Metropolitan Vickers, the Gas Turbine, and the State: A Socio-Technical History, 1935-1960

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Abstract

In 1937 the Manchester Engineering Firm Metropolitan Vickers (Metrovick) were awarded a development contract by the Air Ministry to develop a gas turbine for aircraft propulsion in conjunction with the Royal Aircraft Establishment at Farnborough.

Over the next decade and a half, the company developed a number of gas turbine designs for a variety of applications in the air, at sea, and on land. This thesis examines the gas turbine work of Metropolitan Vickers, and how the company interacted with a variety of partners across both the military and the civilian realms. These included government research establishments such as the Royal Aircraft Establishment and the Admiralty Engineering Laboratory; commercial partners, such as the aero-engine manufacturer Armstrong Siddeley, Yarrow Shipbuilders, and the Great Western Railway, and state institutions such as the Ministries of Aircraft Production and Fuel and Power.

It argues that Metrovick's technical style was formed by the company's existing heavy engineering plant business, which privileged design over development and production engineering. Compared to competitors such as Power Jets and Rolls Royce, Metrovick's progress on aero-engine work was hampered by the lack of a development organisation; though technically advanced, its aircraft engines took a long time to be developed and would not reach production; a factor which was influential in the post-war sale of Metrovick's aero-engine designs to Armstrong Siddeley.

Metrovick did use its gas turbine experience to gain post-war contracts for both naval and civilian gas turbines. The Royal Navy adopted gas turbines for two roles: as lightweight powerplants for short-ranged fast-attack craft, and as part of major warship propulsion systems that were intended to overcome the perceived flaws of the Navy's interwar steam plants. Metrovick was selected as a development partner because of the company's existing naval business, as well as its gas turbine expertise.

In the civilian realm, the company produced gas turbines for a wide range of applications ranging from railway locomotives to electrical power generation. Most of the customers for these designs were state or quasi-state institutions; this thesis argues that the post-war British state's support for the civilian gas turbine shows that it was seen as a crucially British technology that could help improve industrial efficiency, as well as utilising indigenous energy resources.

However, again Metrovick was content to rely on development contracts rather than commit itself to large-scale production. The company's gas turbine designs were somewhat marginal to the wider heavy electrical business, and Metrovick never committed the kind of development resources to the gas turbine division that would have been required to produce successful products, nor did it attempt to sell its designs widely to relevant markets.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright statement

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For Sarah and the twins

Acronyms, initialisms, and abbreviations used

ACA	Advisory Committee for Aeronautics; predecessor of the ARC
ACSP	Advisory Council for Scientific Policy (reporting to the Lord President)
AD	Assistant Director (of Air Ministry directorates)
AEI	Associated Electrical Industries
AEL	Admiralty Engineering Laboratory
AM	Air Ministry
AMDP	Air Member for Development and Production
AMRD	Air Member for Research and Development
AMSO	Air Member for Supply and Organisation
AMSR	Air Member for Supply and Research
ARC	Aeronautical Research Committee
A-S	Armstrong Siddeley
BBC	British Broadcasting Corporation/Company
BTH	British Thomson-Houston
CI	Compression-Ignition
COSAG	Combined Steam and Gas Propulsion
CS(A)	[MoS] Controller of Supplies (Air)
DDRE	Deputy Director of Engine Research
DDSR	Deputy Director of Scientific Research
DDSR1	MAP Deputy Director of Scientific Research responsible for gas turbine research
DDTE	[MoS] Deputy Director of Turbine Engines
DERD	[MAP] Director of Engine Research and Development
DGSR(A)	[MoS] Director General of Scientific Research (Air)
DH	de Havilland Engine Company
DSIR	Department of Scientific and Industrial Research
DSR	Director/Directorate of Scientific Research (depends on context)
DTD	Director/Directorate of Technical Development (depends on context)
EE	English Electric
ESC	Engine Sub-Committee (of the ARC)
FRB	[DSIR] Fuel Research Board
FRS	Fellow of the Royal Society
GA	General Arrangement
GEC	[UK] General Electric Company
GPO	General Post Office
GTCC	Gas Turbine Collaboration Committee
GWR	Great Western Railway
HDA	High Duty Alloys
ICT	Internal Combustion Turbine
IMechE	Institution of Mechanical Engineers
LMS	London, Midland, and Scotland Railway
MAP	Ministry of Aircraft Production
MFP	Ministry of Fuel and Power
MGB	Motor Gun Boat
MoS	Ministry of Supply
MoT	Ministry of Transport

MV	Metropolitan Vickers
MWB	[London] Metropolitan Water Board
NACA	[US] National Advisory Committee for Aeronautics
NGTE	National Gas Turbine Establishment
NPL	National Physical Laboratory
PAMETRADA	Parsons and Marine Turbine Research Association
R&D	Research and Development
RAE	Royal Aircraft Establishment
RAF	Royal Air Force
RDE1	MAP civil servant responsible for Engine Research and Development
RN	Royal Navy
RTO	[Air Ministry] Resident Technical Officer; resident at firms to oversee compliance with airworthiness requirements
SBAC	Society of British Aircraft Constructors
SFC	Specific Fuel Consumption
SGB	Steam Gun Boat
USN	US Navy
YARD	Yarrow-Admiralty Research Department

Introduction

The Second World War is usually described as a 'good' war for British science and technology, having resulted in such national triumphs as radar, penicillin, and the jet engine.[1] With regard to the last, the historiography of the jet engine long portrayed the British programme as the result of a lone, far-sighted inventor who long fought to convince a sceptical government and aero-engine establishment of the practicality of his designs, and who finally after long hard struggle was vindicated. That inventor was Frank Whittle, and this telling of the story fits many of the standard tropes about invention and discovery.[2] It is, of course, a fairy tale.

More recent accounts of the British jet engine have told a different story. Whittle in fact received generous state support, both in terms of funding and in terms of technical support, for what was after all a fairly speculative long-term high-risk project, and turning his vision into a practical aircraft powerplant required the intervention of the existing aero-engine industry so often pilloried as short-sighted in the more popular literature.[3] These more recent accounts have also highlighted the contribution of the Royal Aircraft Establishment (RAE) to the British gas turbine and jet programme; this work had been known about for some time, but had never really entered the public consciousness, and the Establishment's work had not been integrated with the wider gas turbine story, which under-rated its influence.[4] Indeed, the RAE had a gas turbine research programme that predated Whittle's, and it initiated a development programme in parallel with his earliest work. In order to carry out this programme, the establishment sought out a development partner, and it found one in the Manchester engineering firm of Metropolitan Vickers (also known as Metrovick or MV).

Again, though the RAE/Metrovick development programme is not unknown, its full importance has never been fully explored; the aim of this thesis is to do just that, and to show how a close analysis of this collaboration and the company's subsequent gas turbine work can illuminate our existing histories of industry and state in mid-twentieth-century Britain. Metrovick's work is well suited to this, as over the two decades from 1937 onwards, the company produced designs for both aeronautical and naval military use, as well as for civilian industrial uses such as electrical generation or railway power. Of import for existing histories is the way in which government funded both the military and the civilian applications of gas turbine technologies; in the latter case, the economic rationale behind this support gives a picture of a state that is more

[1] Bud (1998)
[2] The narrative of Golley (1986) can be summarised in these terms.
[3] Nahum (2004); Giffard (2011)
[4] Armstrong (1976); Dennis (1999); Bailey (2004)

interventionist than our traditional image[5]. In addition, analysis of Metrovick's work across the various fields and the relative success in each of these areas underlines the importance of factors such as technical style on the way a firm carries out its work. The rest of this introduction will give a brief overview of the existing literatures and historiographies with which I will engage for the rest of this thesis, and will then set out the structure of the thesis as a whole.

Metropolitan Vickers

Metrovick was one of the UK's 'big four' electrical engineering firms, and had a reputation for carrying out unusual amounts of fundamental research for an industrial firm; as a result, certain aspects of the company's business have been well studied. Christopher Niblett's PhD thesis argues that MV did not undertake fundamental research for purely economic benefits, even if these were used as a justification for the maintenance of a research department by its head. The real benefits to MV were as much rhetorical as economic, namely as a source of prestige to the company. Metrovick's' reputation for scientific and technical excellence was partly based on the high-prestige projects it undertook, such as radio, television, and the building of particle physics research equipment. Although these inventions did gain the company money, they also meant that the company was asked to do 'interesting' and 'advanced' research work.[6] In a similar vein, Timothy Cooper's thesis treats the links between MV's research department and academia. He suggests that it was the links forged with academic establishments that were valuable, both for keeping abreast of the state of the art in research, and because of the opportunities to influence university training for engineers. Cooper discusses the relationship between MV and the universities of Manchester and Cambridge in some detail, and links this to the literature on the wider relationship between academia and industry, both for research and education.[7]

The company itself produced two histories of a celebratory nature, commemorating the company's 50th anniversary and the work carried out during the Second World War.[8] More critical is the business history of the company written by two financial journalists after its holding group was merged with GEC.[9] Their focus was mainly on the business failings of the group and its management, as well as the financial dealings behind the scenes; nonetheless, it provides the best account of Metrovick's business strategy available.[10] The only other major work on the company

[5] Whilst David Edgerton's work has looked at state funding for military applications, the funding of the civilian gas turbine suggests an intervention in the civilian economy of a kind that has not been widely studied.
[6] Niblett (1980)
[7] Cooper (2003)
[8] Dummelow (1949); Rowlinson (1947)
[9] Jones and Marriott (1970).
[10] Reich (1992) treats the company's part in an international lighting cartel, but only in passing.

deals with the 1933 'Metrovick Trial', when six Metrovick engineers were arrested in Moscow on charges of industrial espionage. Apart from this, there are a number of works or papers that treat the company's individual projects.[11]

Historiography of the jet engine

Even among the voluminous aviation enthusiast literature, Metrovick's gas turbines are relatively unknown and little studied. This may be in part because Metropolitan Vickers is not seen as an aviation company,[12] but partly also because the company never produced a production aircraft engine. Although Metrovick engines powered a number of prototype and experimental aircraft, none ever went into service, and when the company did produce a 'successful' engine, it was put into production by another firm. As such, the Metrovick engines might be considered 'failures,' and have been erased from most histories of the jet engine.[13] (I will consider the issue of failure and success again below.)This retrospective smoothing of a development path is a not uncommon approach to failures in the history of technology, especially popular histories, in which a Whiggish model of technical progress is an underlying (if often implicit) assumption.

The nature of the initial RAE/Metrovick gas turbine designs also complicates assumptions about technological progress; although fitted with an axial compressor – more 'advanced' and 'efficient' than the centrifugal types fitted to the first British production jet engines - they were not jets. Instead, like the piston engines they were intended to replace, they were designed to produce shaft power to an airscrew – in modern parlance, they were turboprops. Frank Whittle's jet engine was aerodynamically and mechanically simpler, but for its viability as an aircraft power plant relied on the assumption of higher future aircraft speeds. This assumption created what Edward Constant has called a 'presumptive anomaly,' in which the propeller would fail to function efficiently at high speeds.[14] Due to this mechanical simplicity, the first generation of production aviation gas turbines were all jet propulsion designs.[15] Much of the historiography of the jet engine accepts these assumptions; the 'rightness' of the jet choice is conditioned by the eventual success of the technology, and is reinforced by the what-might-have-beens of the Whittle

[11] Eg. Whyte (1977); Smith (1947);

[12] Despite building over 1,000 heavy bombers as a sub-contractor for Avro during the Second World War, which raises interesting questions about the relative status of design and production in regard to what counts as an aviation company.

[13] Or at best passed over in a few lines. Kay (2007) gives perhaps the most detailed account of the Metrovick gas turbines, though it contains a number of errors and does not cite sources; more problematically, the book is essentially a list of projects by nation and company, and offers little or no interpretation.

[14] See Constant (1980)

[15] Although turboprops were soon developed for applications in which fuel economy was of greater importance than speed.

advocates who point out how much earlier the engine could have been developed (Whittle was granted his patent on the jet engine in 1930.) To understand the development of the gas turbine, however, it is necessary to view the gas turbine in context: not as an obviously superior choice, but as merely one of many technical options to be explored. Viewed in this way, the gas turbine is less of a revolutionary break with the past than has sometimes been assumed.[16] The improved compressors and high-temperature materials required for its operation were also technologies that could improve the performance of more conventional piston engines.

Even before the end of the Second World War, the first histories of the jet's invention were being written. The Gloster test pilot John Grierson started work on his book *Jet Flight* in 1944, with the cooperation of the Ministry of Aircraft Production (MAP), and it was published in 1946.[17] This gave brief biographies of early jet workers, and followed a popular heroic inventor's narrative. At about the same time, the first accounts by the participants were published, notably in a series of lectures at the Institute of Mechanical Engineers in 1945 and 1946.[18] One of the lecturers was Frank Whittle, who published his autobiography *Jet* in 1953; written at a time when he was still (not entirely unjustly) bitter at the nationalisation and merger of Power Jets. His tale of the lone inventor fighting against reactionary officialdom was to become the popular narrative of the jet's invention in the UK. In the post-war era, where the jet engine was a potent symbol of Britain's scientific and engineering prowess, Whittle's account was to powerfully influence later histories.

Based on the unpublished narratives written for the Cabinet Office, the UK official history *Design and Development of Weapons* was first published in 1964.[19] Its section on the jet engine echoed some of the criticisms of both government and private enterprise expressed by Whittle's. Neither had appreciated the jet's potential, leading to a delay in getting it into production; a rather Whiggish reading of the history. With Whittle's status as a national hero, many of the difficulties that the Ministry of Aircraft Production had experienced in trying to work with Power Jets did not make it from the unpublished narrative into the official history.[20] Whilst it covered the UK government projects, it did not sufficiently explain the important coordinating role played by the Ministry of Aircraft Production and the RAE in the British jet story.

Another major work that was to have wide influence was the 1950 study *Development of Aircraft Engines and Fuels*, explicitly intended to be a comparative history. It was written for the Harvard

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[16] As Andrew Nahum (2004) has pointed out, Constant's use of the term 'turbojet revolution' fits with his Kuhnian revolutionary interpretation.
[17] Grierson (1946)
[18] Whittle (1945); Constant (1945); Smith (1947)
[19] Postan, Hay, and Scott (1964)
[20] Nahum (2004), 173-5.

Business School by the economist Robert Schlaifer and the aeronautical engineer Samuel D. Heron. Heron had worked in the aero-engine industry for almost half a century, and so the authors had access to many of the key figures as well as company reports. Although in large part unreferenced, it is generally reliable on matters of fact, and contains much information that cannot be found elsewhere. The authors' interpretations have dated less well;[21] their championing of the US free-market approach to development is very much a product of the book's time, place, and publisher. They treated the emergence of jet propulsion as 'the result of a historical accident'; their explanation as to why the US did not develop an indigenous jet engine during the Second World War was simply that the inventors Whittle and Von Ohain were British and German instead of American.[22] In the words of a later historian, this explanation was 'catastrophically inadequate', and much of the later historiography of the jet engine has sought to explain the national patterns of gas turbine development.[23]

This historian was Edward Constant, who published his book *The Origins of the Turbojet Revolution* in 1980.[24] He set out a model for technical change that drew on Thomas Kuhn's work on scientific revolutions. As his unit of analysis, Constant used 'communities of technological practitioners' carrying out most of their day-to-day work on 'normal' technology. He argued that this normal technology was defined by the traditions of technological practice within the community, which were shaped by such factors as education, professional standards, and testing technologies.

Constant notes that the first jet engines were developed in the UK and Germany, countries which had research traditions in 'pure' aerodynamics; this was in contrast to the US, where the National Advisory Committee for Aeronautics (NACA) concentrated on experimental wind tunnel work. In her history of the NACA propulsion laboratory, Virginia P. Dawson argues that Constant's thesis should not be taken to mean that US investigators had an inferior knowledge of theoretical aerodynamics; rather the institutional pressures were to apply this knowledge to development work.[25] The US contexts are discussed in more detail in papers by I.B. Holley and James O. Young. Holley notes that the US Army Air Corps lacked an internal scientific office, and that its technical branch was discouraged from carrying out research work, which was seen to be the preserve of

[21] Though, as Giffard (2011) points out, their insistence on the importance of the engine industry's contribution to jet development has been vindicated.
[22] Schlaifer and Heron (1950), 293
[23] Constant (1980), 271.
[24] Constant (1980)
[25] Dawson (1991)

NACA.[26] However, as Young points out, this very emphasis on empirical development work meant that US companies were very quick to get jet engines into production once they had been made aware of the possibilities.[27]

The influence of local contexts on the design methods chosen for jet compressors is discussed in Brian Nichelson's 1988 PhD thesis.[28] Although it is based in large part on secondary sources, Nichelson describes how the varying national traditions and strengths led to different techniques in different countries. In Germany, a tradition of mathematically-intensive theoretical aerodynamics led to the use of streamline design methods. In the US, NACA's wealth of experience in gaining experimental data on individual aerofoils led to the use of individual-aerofoil methods. In the UK, researchers at the RAE combined the theoretical approach with empirical wind tunnel data from aerofoil cascades. By the end of the 1940s the methods had cross-fertilised, but there still remained national styles in compressor design. Unfortunately Nichelson's treatment of the subject remains mainly at the national level, with little differentiation between projects; he relies mainly on published NACA and RAE technical papers, and on post-war allied evaluations of German aerodynamics, with no archival materials from the various institutions or companies involved. Nonetheless, his discussion of the various national design styles complements Constant's treatment.

Perhaps because of the difficulties in accessing company archives, detailed studies of jet development in the industrial context are very few. One study that goes into more detail for the design process is David A. Mindell and George E. Smith's paper 'The Emergence of the Turbofan Engine,' which discusses the development of turbofan engines in the late 1950s.[29] Their main focus is the development of the first US turbofans, and especially the case of General Electric engines, but they do give a useful historical summary of how axial compressors developed, and give some more detail on the ways in which the various methods of compressor design mentioned in Nichelson's study were unified. They also study some of the ways in which design methods were transferred from NACA to industrial companies, including the publication of design data in a form useful to industrial engineers, and the movement of key personnel from the lab to industry.

Philip Scranton's analysis of US early Cold War jet development shows the ways in which national security imperatives were used to justify the development of multiple service engines, as well as

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[26] Holley (1984)
[27] Young (1999)
[28] Nichelson (1988)
[29] Smith and Mindell (2003)

the concurrent development of follow-up models.[30] As he demonstrates, this policy only worked because of investment on a truly massive scale. Even when 'just' scaling-up engines from existing models, there was no guarantee of timely success; contingency and huge cost and time overruns marked every stage of the process. By these benchmarks, the UK's gas turbine programme was remarkably efficient given the resources invested. [31]

Considering failure

A complicating factor in considering Metrovick's gas turbine projects is that of assessing their failure or success. 'Failed' projects are by their very nature more difficult to uncover, as the relevant records are more likely to have been discarded. Yet the notion of a technology's unitary success or failure is too simplistic: most 'failures' contain successful features, and, like unhappy families, technologies all fail in their own way.[32] Especially when considering technologies sold as commercial products, the most common evaluation criterion is that of market success: did the producer sell enough units at a price that would make a profit or break even? Apart from the fact that what is profitable for a producer may not be suitable for a consumer, many technologies are not produced in a purely commercial environment.[33] Introducing a 1992 symposium on 'Failed Innovations', the historian Hans-Joachim Braun suggested that failures might be grouped into four broad categories:[34]

- Technical problems: can the basic technology be made to work at all?
- Problems of development, production and manufacturing: can the prototype's bugs be worked out, and can the resulting production models be reliably produced at scale?
- Economic power and market considerations: does the technology fit the economics of existing technological systems (or does it successfully disrupt them and become the basis of a new system)?
- Development of rival technologies, moral arguments, and institutional resistance. This is somewhat of a catch-all category; rival technologies may threaten on technical or cost grounds, and moral and institutional arguments must be treated with care to ensure that one attempts to offer a symmetrical explanation for success and failure.

There is obviously a degree of overlap between these categories, and indeed real projects will often encounter interacting issues from multiple categories, but they serve to illustrate the

[30] Scranton (2008)
[31] As indeed Scranton (2011) concludes.
[32] Cf. just about any engineer's story about a 'technically brilliant' project let down by 'marketing' or 'management'.
[33] For example, in military procurement.
[34] Braun (1992); I have slightly adapted his scheme.

complexities of failure. Another factor is that an appreciation of a technology's success or failure is not necessarily universally shared. Braun gives the example of the East German Trabant automobile; a 'commercial' success in a Communist state where supply could not meet demand, it was technically less sophisticated and reliable than its Western contemporaries, and was environmentally 'an outright disaster'.[35] This multivariate view of success and failure meshes well with social constructivist approaches to technology; the various 'relevant social groups' will usually not rank the various factors in the same way, leading to differing judgements about success or failure.[36] In considering the judgements made about the relative success and failure of Metrovick's gas turbine projects throughout this thesis, it is well to bear these caveats in mind.

Technological styles and communities

In comparing Metrovick's gas turbine designs with those developed by other companies, it is helpful to consider the notion of technical style. Similar to the namesake concept in art history, in the words of Thomas Hughes: 'Technological style can be defined as the technical characteristics that give a machine, process, device, or system a distinctive quality.'[37] These technical characteristics are shaped by local, 'cultural', factors, such as 'geographical, economic, organizational, legislative, contingent historical, and entrepreneurial conditions.'[38] Hughes developed his analysis as part of a study of national and regional electricity systems, and much of the work on scientific and technical styles has focused on the national context (such as Nichelson's work cited above).[39] However, one can also apply the concept of style at local levels, such as the individual company or division. Edward Constant argues that the 'social locus of technological knowledge' is in 'communities of technological practitioners'.[40] These are defined by their education, training and conditions of practice, but not necessarily by their disciplinary background; the problems and technologies on which they work are what make communities unique.[41] Constant suggests that the diffusion of inventions out of technological communities, and their adoption as innovations, is controlled by the wider 'cultural' factors suggested by Hughes above. However, at the local level distinct technical styles can arise within communities of

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[35] Braun (1992), 217.
[36] The term is taken from Pinch and Bijker (1987), but the concept is broadly shared across science and technology studies and history of technology.
[37] Hughes (1983), 405.
[38] Hughes (1983), 405.
[39] Treatments of technical styles at the national level are for instance Brown (2000); Lund (1998); studies of national scientific styles include Harwood (1987); Nye (1993); Bloor (2011).
[40] Constant (1984); Constant (1987). These communities should be distinguished from the 'relevant social groups' in Pinch and Bijker (1987); the latter are (mainly) concerned with the shaping of technologies in use, whereas Constant's focus is (mainly) on technological knowledge and invention.
[41] Constant (1987)

technological practitioners by variation-selection within the environment.[42] This thesis will argue that Metrovick's style of gas turbine development was shaped by the company's background in heavy electrical plant manufacture, and will explore the consequences for the progress of its projects.

The state and its institutions

Views of the UK's research-industrial performance in the Second World War have been varied; historians of the 'declinist' school have emphasised the UK's poor industrial performance, as well as criticising its lack of technical and scientific training, and comparing its scientific and technological research unfavourably with both the US and Germany.[43] These analyses have been challenged by more recent histories, perhaps most trenchantly by David Edgerton, who has argued that for most of the twentieth century the UK was a 'Warfare State,' in which much of the country's scientific and technical expertise was concentrated not in universities, but in state (mainly military) scientific establishments. [44]

The establishment with the closest relationship to Metrovick was the Royal Aircraft Establishment; unfortunately there is no single satisfactory history of this institution. As with much aeronautical history, most works are written from a hardware-centric perspective, and institutions are only discussed as places where work takes place, with little or no attempt to place individual projects in their institutional context.[45] There are a number of personal and biographical accounts of staff; these are usually 'insider histories' written for colleagues or fellow enthusiasts. Nonetheless, such accounts can provide detail not found anywhere else, although obviously they must be treated with some caution.[46] In the case of Farnborough, a number of personal accounts were collected in the 1 July 1955 issue of *Flight* for the RAE's 50th anniversary. The 1966 centenary volume of the Royal Aeronautical Society's *Aeronautical Journal* contained actors' accounts alongside historical articles on British aviation. The only history of the Royal Aircraft Establishment is an unpublished narrative written for the Cabinet Office after the Second World War, which was used in the compilation of some of the official histories.[47]This relied heavily on two chronologies published by the RAE, which gave a listing of events up to the end of the Second World War, as well as occasional organisation charts.[48] The Ministry of Supply published a number of pamphlets in the late 1940s and 1950s, but these were celebratory collections of

[42] Constant (1984), 38.
[43] The standard-bearer is Barnett (1986)
[44] See Edgerton (2006); Edgerton (1991) covers similar ground, but specifically with respect to aviation.
[45] Eg. Cooper (2006)
[46] Eg. Baxter (1988)
[47] In NA CAB 102/60
[48] Child and Caunter (1947); Caunter (1949)

vignettes describing individual inventions, with no examination of the institutional context. With regard to the RAE and the jet engine, the work which gives the fullest account of the RAE's importance and the ways in which its role changed during the Second World War is Hermione Giffard's PhD thesis.[49] Giffard argues that existing histories of the jet have over-emphasised the importance of inventors such as Whittle and Von Ohain at the expense of the existing aero-engine industry; concentration on wartime production numbers has also masked the extent to which development work and research were what laid firm foundations for a post-war gas turbine industry.

With regard to the Air Ministry/Ministry of Aircraft Production, there is again no single institutional history. The best overview is to be found in the Official Histories; apart from *Design and Development of Weapons*, the volume on the administration of production gives a helpful overview of the organisation of the various ministries.[50] Published by the Rolls-Royce Historical Trust, the memoirs of the Assistant Director (Engines) at the Air Ministry's Directorate of Technical Development contain much useful information on the running of the Directorate and its relationships with industry.[51] After disagreements with his superior in 1942, Bulman was replaced by Air Commodore Rod Banks; Banks's (somewhat self-aggrandising) memoirs contain an account of his work at the Ministry overseeing jet engines.[52] On procurement more generally, apart from the Official Histories, Andrew Gordon's account of the view from the Admiralty is valuable; for the Air Ministry, Colin Sinnott described the aircraft specification process, and Sebastian Ritchie covers rearmament and procurement.[53]

Structure of the thesis

Metropolitan Vickers's gas turbine projects can be divided into three main areas of application: aeronautical, naval, and industrial. Though there was a great deal of knowledge transfer between the areas –the design department was the same in each case – the requirements and sponsors were different. This study is therefore structured roughly by application area; where multiple strands of the company's work interweave, I have tried to treat them together where possible.

Chapter 1 explains how the Air Ministry came to issue Metropolitan Vickers a development contract for an aircraft gas turbine powerplant. It gives a brief history of the company, and sets out the particular strengths which made Metrovick an attractive development partner. In

[49] Giffard (2011)
[50] Scott and Hughes (1955)
[51] Bulman and Neale (2002)
[52] Banks (1978)
[53] Gordon (1988); Sinnott (2001); Ritchie (1997)

describing the institutions which were involved in the early gas turbine, the chapter gives an overview of the institutional landscape for aeronautical research and development, with particular reference to the Air Ministry, the Aeronautical Research Committee (ARC), and the Royal Aircraft Establishment. By tracing the decision-making in the ARC's Engine Sub-Committee, it shows how the gas turbine was but one technical solution considered to the problem of high-powered engines for air defence, and how Metrovick was eventually chosen to assist with the development of an aircraft gas turbine.

Chapter 2 covers the early gas turbine designs considered by the Royal Aircraft Establishment and Metrovick from roughly 1937 to 1941. The development partners embarked on the manufacture of a number of gas turbine schemes intended to provide shaft power to an aircraft propeller, but only one of these was ever completed, and then in much truncated form. I will seek to explain the reasons for the relative lack of success of these projects by reference to the concept of technical style prevalent in a community of technological practice. I argue that the slow progress of Metrovick's early gas turbine projects was not due to any technical flaws on the company's part; rather it was a consequence of a working style developed with reference to the company's heavy steam plant business.

In 1940, influenced by the progress of other gas turbine projects supported by the Air Ministry, the Royal Aircraft Establishment decided to embark upon the design of a jet engine. Metrovick was eventually chosen as their development partner, and eventually developed a family of jet engines. Chapter 3 traces the decision-making around the RAE's jet propulsion unit, and examines the development of the original RAE design into the Metrovick F.2 engine and derivatives. The F.2 was never put into production; the chapter seeks to explain some of the reasons why, especially in reference to the other UK jet engine projects underway at the time. In examining Metropolitan Vickers' troubled collaboration with Armstrong Siddeley, it will again touch on issues of technical style, showing how despite Metrovick's gas turbine experience, the company's style was still shaped by its heavy plant working style; I will also argue that the company's early lack of commitment to series production meant that it was unlikely to gain this commitment once aero-engine manufacturers entered the gas turbine field.

Post-war, Metrovick attempted to design and manufacture another jet engine, the F.9 Sapphire, but the company directors eventually decided to divest themselves of their jet engine business; chapter 4 seeks to place this decision in the context of post-war British military-industrial strategy, and traces the decision-making at the Ministry of Supply that led to the designs being sold to Armstrong Siddeley. At the same time as this sale was occurring, Metrovick was developing gas turbines for the Admiralty. The gas turbine was adopted as a potential naval powerplant in no small part due to a perceived failure of the RN's previous generation of powerplants; this chapter seeks to explain this perceived failure by reference to the Navy's interwar engineering culture. I will then trace the development of the two strands of Metrovick's naval gas turbine development: as powerplants for fast attack craft, and as boost units for large warships. By comparing naval and aeronautical gas turbine procurement and considering Metrovick's technical style, I will show why it was more successful in the former environment.

The other areas of Metrovick's gas turbine work were all related to industrial and commercial applications; in many cases, this work was supported by government. Even when it was not directly supported, many of its customers were nationalised or quasi-nationalised industries. Chapter 5 gives the political-industrial context for the postwar nationalised industries, and situates Metrovick's civilian business in this environment. It examines some of the institutional struggles for control of civilian gas turbine research, and argues that these show the perceived importance of the technology. State support for the civilian gas turbine was part of a wider effort to mobilise British high technology for national economic gain; I will examine in particular the work of the Ministry of Fuel and Power, which attempted to develop gas turbines that could run on indigenous fuels, and will argue that this fits the post-war pattern of 'defiant modernism'. Though Metrovick made some attempts to use its wartime gas turbine experience, it had no business strategy for the gas turbine, which was relatively insignificant compared to its booming post-war electrical plant business. Shaped by this environment, the company was unable to develop the gas turbine in ways that might have allowed it to create a viable business.

Chapter 1 – Assembling the Gas Turbine: Metrovick, the ARC, and the Air Ministry

The aero-engine lies at the heart of aircraft design, production, and programming.

-Sir Alec Cairncross[1]

In January 1938, the UK's Air Ministry awarded the Manchester engineering firm Metropolitan Vickers a contract to build a gas turbine for aircraft propulsion. The work was to be carried out in collaboration with the Royal Aircraft Establishment (RAE), the state's main aviation research facility. This raises a number of questions: why was the development of a gas turbine necessary at all? Why did the Air Ministry choose a heavy electrical engineering company, with no experience of aero-engine design, to build an aircraft powerplant? What was the relationship, if any, between this government project and Frank Whittle's better-known jet engine? In attempting to answer these questions, this chapter will examine the RAE's gas turbine from its conception through to the awarding of a development contract to Metropolitan Vickers.

In order to understand how the gas turbine project was developed, we must consider the military context in which it was thought of, and the role which the Air Ministry hoped it would fill. I will briefly review the changes to the RAF's air defence doctrine between 1930 and 1940, and will explain how these changes favoured the development of high-powered aero-engines. Secondly, we must understand the organisational geography of aeronautical research; to this end I will give a brief history of the most important institutions involved with engine research and procurement. Many of the important figures in this field were close contemporaries, and had worked together for decades; I will set out the relationships between them. Next, I will consider Metropolitan Vickers, and the particular attributes that made the company seem a promising development partner; in the same way as for the aeronautical research institutions, I will examine the networks of influence that the Metrovick staff were part of. Finally, by looking at the decision-making of the Aeronautical Research Committee's Engine Sub-Committee, I will trace the way that the need for a high-powered engine led to a gas turbine design and a development contract, looking at some of the technological alternatives considered along the way.

[1] Cairncross (1991), 15.

Air Defence

Although engines are a critical technology for all forms of aviation, crucial for improvements in speed, range, and payload, the development of high-powered aero-engines was driven by one customer: the military. Government support for the gas turbine must be seen in the context of a wider effort to produce engines of very high power for air defence. Though the strategic bomber remained at the centre of the RAF's doctrine, during the 1930s air defence gained in importance. In July 1934, in response to the perceived growing threat from Nazi Germany, the Air Ministry proposed the first of eight RAF expansion schemes.[2] The initial plans had a heavy emphasis on bombing aircraft for deterrence, but as international tension grew, the revised schemes placed a greater emphasis on defensive aircraft, not least because they were cheaper. In 1936, to assist in the expansion of production, the Air Ministry started the 'shadow factory' programme, in which it built factories that were to be managed by non-aviation companies.[3]

At the beginning of the 1930s, the RAF's air defence doctrine was based around the use of two types of fighter, the so-called 'Zone' and 'Interception' types. As their names suggested, the former were to patrol in the 'Fighting Zones' that formed a defensive belt to the south and east of London; this required good climb characteristics (to get to patrol height quickly), as well as long endurance (to stay on station for a useful amount of time). As they were to operate both by day and night, Zone fighters were equipped with radio and blind-landing equipment. The effect of these requirements was to reduce their maximum speed. Interception fighters were high-speed day fighters that were stationed at coastal airfields. At the warning of an enemy's approach (in the early 1930s this was usually expected to be from fairly unreliable sound detectors), they were to take off in a pursuit climb. In practice, as was shown in exercises, the Interception fighters were unable to intercept enemy aircraft reliably. As a result, they were moved back to airfields in the fighting zones, fitted with radio, and used as high-performance day fighters, in which role they were more successful.[4]

However, the early 1930s also saw the introduction into squadron service of a new generation of high-performance bombers, the result of advances in engine technology and aerodynamics.[5] In

[2] See James (1990)

[3] The best account of the aerospace industry's expansion is Ritchie (1997). The shadow scheme was inspired by the Great War experience of government-financed factories administered by 'captains of industry', though the government also sponsored the expansion of capacity at aeronautical companies.

[4] Sinnott (2001), 70.

[5] These technologies were introduced in bombers rather than fighters because of procurement cycles rather than for any deep technical reasons.

the RAF's 1931 annual Air Exercises, the defending aircraft – both Zone and Interception types – were unable to catch the new fast attackers (prompting the change in tactics for Interception fighters). In consequence, the next fighter specification to be issued by the Air Ministry (F.7/30, issued September 1931) required the selection of an engine type for maximum performance.[6] This specification led to the RAF's last biplane fighters, the Gloster Gauntlet and Gloster Gladiator; these types retained some of the Zone fighters' concepts, with a nominal night fighting role.

By the mid-1930s, the RAF's process for formulating aircraft operational requirements had changed significantly, including the 1934 creation of an Operational Requirements Section.[7] The section centralised work that had been done piecemeal (or not at all) by other departments, and considered how an aircraft's role would affect its specific technical requirements. For new fighter specifications, it now set aircraft endurance requirements with reference to a hypothetical typical mission profile (that is, takeoff and climb; loiter; combat; and descent and landing). Previously designers had used the cruder measure of the ability to fly for a set time at maximum throttle setting (and thus fuel consumption). Along with lower fuel reserve requirements, these changes lowered total aircraft fuel loads, which improved performance, albeit at the expense of endurance.[8] As the officers responsible for fighting future wars, the Air Staff's approval of these specifications suggests that they were worried enough by the threat of enemy aircraft to 'put maximum speed above all other aspects of fighter performance'.[9]

Fortunately for the RAF, advances in aeronautical technology were taking place in the late 1920s and early 1930s that made higher speeds possible, demonstrated most visibly by the racing aeroplanes that took part in contests such as the Schneider Trophy. The development of superchargers and of high-octane fuels allowed engines to develop more power from the same engine cubic capacity; concurrently, advances in aerodynamics and structures meant that these engines were fitted to streamlined monoplanes, allowing the aircraft to achieve higher speeds. The links between racing aircraft and warplanes can be overstated; despite sharing a designer and engine-maker, the Supermarine Schneider Trophy winners were by no means proto-Spitfires, as they were totally unsuited to anything other than flying round a course at high speed. The engines were also very much racing specials; running on 'witches' brews' of special racing petrol

[6] For reasons of industrial policy, the RAF's production directorate had wanted to choose a different engine design to keep the manufacturer in orders; see Sinnott (2001), 83-4.
[7] Sinnott (2001), 30.
[8] This gave fighter aircraft a greater performance advantage than bombers; whilst fighters could accept lower sortie times, bombers that could not fly to their targets and return were of somewhat limited use.
[9] Sinnott (2001), 102.

laced with alcohol, benzol, and tetra-ethyl lead for no more than an hour at a time, they were not practical for anything but record-breaking. They were, however, influential in showing the potential of supercharging and high-octane fuels. By the mid-1930s all RAF combat aircraft were using supercharged engines running on high-octane fuel.[10]

The move towards engines of very high power had started in the early 1930s, but the mid-1930s development of radar was to revolutionise the air defence environment and give a further boost to engine development.[11] Prompted by a government committee's enquiry into whether 'death rays' were possible, the physicist Robert Watson-Watt and his team carried out the first radar experiments in the UK in 1935, and progress was remarkably rapid thereafter. In September of that year, the government Air Defence Research Committee approved the construction of a radar chain, and in December the Treasury – not a department constitutionally given to profligacy – approved the expenditure of £62,000 for the construction of the first five radar stations.[12] By late summer 1937 these stations were operational, and were being used for air exercises in controlled interception.[13] In conjunction with other technologies, chiefly improved aircraft radio and direction-finding equipment, effective radar promised to have two effects: greatly expanded detection range (thereby giving the defenders more time to react), and freedom from the need for aircraft to carry out time-consuming and expensive standing patrols. The development of better detection and control technologies fortuitously supported the decision to lower aircraft fuel loads in the interests of performance; crucially for the development of the aircraft gas turbine, it also made the development of high-powered engines with concomitantly high fuel consumption a reasonable choice.

Even though some of the work had been carried out by private companies, both the RAF's radar chain and the high-powered engines fitted to its aircraft were the products of UK state research and support. In the interwar period the market for aircraft was overwhelmingly military, and in addition to direct support through aircraft sales, most aeronautical research and development was

[10] Although the Air Ministry had drawn up specification DTD 230 for 87 octane fuel in 1934, 87 octane does not seem to have entered RAF service until 1936. 100 octane fuel was adopted for the RAF in 1937, and entered widespread service in 1940. For further information see Bailey (2008).

[11] This is also the argument of Nahum (1997). I have used the more familiar radar rather than the contemporary British term RDF.

[12] Zimmerman (2001), 89-90.

[13] Zimmerman (2001), 124-7. Interception command and control had been tested the previous summer in the famous Biggin Hill experiments.

paid for by the state.[14] A triumvirate of institutions was responsible for the majority of aeronautical research: the Air Ministry, the Aeronautical Research Committee, and the Royal Aircraft Establishment.[15] The following section will briefly describe the history and roles of these institutions, and show how they were related.

The Geography of Aeronautical Administration

The Air Ministry

Most aeronautical research in the UK, whether civil, military, or 'fundamental,' was funded by the Air Ministry. It was responsible for the RAF as an armed service, as well as for civil aviation and aeronautical research. Accountable to Parliament through the Secretary of State for Air, Ministry policy was set by the Air Council. Headed by the Secretary of State, this was composed of senior RAF officers ('Air Members' with the rank of Air Vice-Marshal or higher), and a number of political appointees. Operational control of the RAF ran through the Air Staff, headed by the Chief of the Air Staff (who had a seat on the Air Council). As the newest and most technologically-based service, from the beginning the RAF placed a high value on matters of materiel and research, with at least one Air Member responsible for R&D matters sitting on the Air Council. These responsibilities were originally combined with those of industrial policy and supply under the Air Member for Supply and Research (AMSR). In 1935, in reaction to the RAF's expansion, this member's workload was lightened by splitting the post into two, creating Air Members for Research and Development (AMRD), and for Supply and Organisation (AMSO). In August 1938, as the RAF expanded further, the AMRD was given responsibility for production, with the position being renamed Air Member for Development and Production (AMDP). He was given two deputies, a Director-General of Research and Development (an Air Vice-Marshal) and a Director-General of Production (a civilian appointment, a former Vice-President of the London, Midland, and Scotland Railway).[16] In 1940, all R&D and production responsibilities were transferred to a new Ministry of Aircraft Production (MAP), although the staff transferred to MAP continued to sit on the Air Council in their old positions.[17]

The administration of R&D work was carried out by Air Ministry directorates, reporting to the Air

[14] See Edgerton (1991), 19-20. In terms of resources expended it would perhaps be better to speak of development and research, as the former is generally an order of magnitude more expensive than the latter.
[15] Other sites tended to specialise in pure research (such as the National Physical Laboratory,) or in operational testing (such as the Aircraft and Armament Experimental Establishment.)
[16] Details for the organisational structure of the Air Ministry are taken from the *Air Force List*, and from Appendix I in Richards (1974), 401-403.
[17] I will discuss the creation of MAP in more detail in Chapter 3.

Member responsible for research. Initially there was a single Directorate of Research (DSR - under the Air Ministry's Director of Research), which was responsible for both research and development. In 1924 this system was modified in response to calls for more fundamental research (as discussed below). The aeronautical engineer Harry Wimperis was appointed as Director of Scientific Research (also DSR), and the Directorate of Research was split into two directorates: a Directorate of Technical Development (DTD), headed by the Director of Technical Development (an RAF officer) and a Directorate of Scientific Research, headed by the new Director of Scientific Research. The directorates were mainly staffed by career civil servants (as noted, the DTD was headed by an RAF officer, and the DTD as a whole had a higher proportion of service personnel, being closer to the 'end user'). One advantage of this system was that the staff overseeing development contracts were not military officers due to change postings every few years; in the interwar period there were only three people in the job of overseeing aircraft development, and two in the job for aero-engines.[18] This continuity meant that the same person could oversee a project from its inception through to introduction into squadron service, a process that might take five or six years. It also meant that because of the personal relationships built up over time, engine companies felt that they could start development contracts on a handshake, secure in the assurance that funds would be forthcoming, which saved time.[19] One factor in the closeness of the relationship was that in order to ensure the survival of a military aeronautical industry in the interwar period, the Air Ministry operated a closed 'ring' or 'family' of companies which would be given military contracts; orders were where possible spread around companies, who knew that the Air Ministry had a stake in their long-term health.[20] There were other advantages to the DTD's civilian status; civilians could argue with senior military officers uninhibited by rank differences, in ways that their service colleagues perhaps could not.[21]

Procurement

Interwar procurement had to fulfil a variety of needs; as well as providing new equipment for the RAF, the Air Ministry had the secondary goal of ensuring the health of the aeronautical industry as a whole. As noted above, this was done by spreading orders and development work among companies; in other cases, the Air Ministry set production standards so as to enforce the use of

[18] With a civil service rank of assistant director (AD), for engines these were Lt-Col LFR Fell (until 1927) and GP Bulman; the ADs (Aircraft) were JS Buchanan, H Grinsted, and WS Farren. Data taken from the *Air Force List.*

[19] These advantages were noted by Schlaifer and Heron (1950), 70-74, especially in comparison to the US system.

[20] In the case of aero-engines the four companies were Rolls-Royce, Bristol, Napier, and Armstrong Siddeley. As noted above, industrial policy could be one factor in the choice of engine for new aircraft types.

[21] As noted by the AD(Engines) in his memoirs; see Bulman (2002), 124.

modern manufacturing methods.[22] Procurement processes differed for aircraft and engines; in the case of aircraft, the Air Staff would draw up an operational requirement, which would be translated into an Air Ministry specification. The specification would be issued to selected aircraft manufacturers, who would then submit tenders. From these paper designs the Air Ministry would select a number (usually two or three) to be built as prototypes. After competitive flight testing, if the performance was good enough the Ministry would order the winning aircraft into production.[23] The Air Ministry covered the costs of prototype production and development, with a fixed profit margin for the manufacturer.

Another option for manufacturers was the 'private venture'; here they would develop a prototype aircraft at their own expense, to be submitted either as a candidate for an existing specification, or directly to the Ministry to fulfil an unmet operational need. The company would then hope to make its money back in royalties on production aircraft. In practice, even private ventures were usually developed in close collaboration with the Air Ministry, which would then fund most or all of the development costs. For example, the Supermarine Spitfire, often described as a private venture by Vickers-Supermarine, evolved from a disappointing prototype to specification F.7/30. Though Supermarine's chief designer Reginald Mitchell decided to begin a new design not to any existing specification, this decision was supported by the AMRD Hugh Dowding, who was able to fund it as part of a high-speed research programme. The Spitfire prototype was ordered under specification F.7/34, and the initial production aircraft under specification 16/36.[24]

In contrast, engines were not ordered to Air Ministry specifications; rather almost all engine development work was funded by Ministry development contracts.[25] As noted above, the Assistant Director (Engines) in the Directorate of Technical Development was a career civil servant who was able to build close working relationships with the designers and management at aero-engine manufacturers. Development programmes were generally agreed collaboratively, based on the projected needs of the RAF. In contrast, because of the more rigid US system of engine specifications, American aero-engine companies preferred to fund their own development,

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[22] Examples included the 1928 decision that henceforth the RAF would only order metal-framed aircraft, and would run down its woodworking trades, or the 1933 decision to award a multi-year production contract to Avro on the condition that the company upgrade its production tooling and jigging. See Sinnott (2001), 38; Ritchie (1997), 27

[23] For more on the Air Ministry Specification process, see Meekcoms and Morgan (1994); Sinnott (2001) Occasionally more than one type would be ordered, either to spread orders around, or to provide a backup aircraft type in case of project failure.

[24] See Sinnott (2001), which also qualifies the 'private venture' status of the Hawker Hurricane and the de Havilland Mosquito.

[25] A factor which may be responsible for the relative lack of documentation about engine procurement; Sinnott (2001), 39, makes a similar point.

recouping costs by charging this as an overhead on production sales.[26] In the UK, a limited number of private venture engine projects were started, but their 'private' status often meant that work had been started on a handshake in advance of Ministry funds being available, with only a very few being developed at private expense.[27] For example, in the case of Rolls-Royce, their Kestrel engine was inspired by Fairey Aviation's importation of Curtiss V-12 engines to power their Fairey Fox fast bombers. Fairey sought support for license production of the Curtiss engine in the UK, but the Air Ministry was unwilling to add another aero-engine company to the 'ring'. Instead the AD (Engines) approached first Napier (who declined) and then Rolls-Royce to design a similar engine. The resulting Kestrel was to be one of the RAF's major engines of the 1930s.[28] Anticipating the need for greater power, Rolls-Royce's 'P.V.12' project began as a private successor to the Kestrel, but it soon became clear to them that the development costs would be more than they were willing to bear, at which point the AD(Engines) was only too willing to step in and provide funds.[29] The resulting Merlin was to be probably the most important British aero-engine of the Second World War.

Although there was considerable overlap between the two, the DTD was responsible for the development of aircraft equipment and the testing of equipment for service acceptance, whereas the DSR was responsible for longer-term research. The 1924 split of the Directorates had been the result of worries that fundamental research was being crowded out by an emphasis on development. This was partly a function of the costs involved; development was a more expensive activity, and it was largely carried out by industrial companies.[30] The DTD's Assistant Director for Engines estimated that by 1937 he was spending over £1M on development contracts in industry per year.[31] By contrast, most of the scientific work was carried out at government laboratories or in universities, although some work was carried out at research associations or by independent consultants (particularly on fuels). However, the single most important site for aeronautical research in the UK was undoubtedly the RAE, or Royal Aircraft Establishment, to which I will now turn.

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[26] Schlaifer and Heron (1950) discuss the relative merits of the US and UK funding systems in detail. Though the Air Ministry charged royalties for the sale of commercial engines based on state-funded military designs, these seem to have been fairly nominal.
[27] See again the discussion in Schlaifer and Heron (1950), and the personal anecdotes in Bulman and Neale (2002)
[28] Pugh (2000), 159-60 suggests that the Kestrel was based on an engine under consideration by Rolls-Royce at the time, the 'FX', but it is unclear how far the design had progressed before the Air Ministry stepped in.
[29] Bulman and Neale (2002), 199-200.
[30] Another factor was that as the results of development were more immediately obvious to the Air Force user, this activity got more feedback than longer-term research.
[31] Bulman (2002), 168.

The RAE

The Royal Aircraft Establishment at Farnborough was one of the world's largest aeronautical research centres; by the late 1930s, it had over 500 research staff in an Establishment of a few thousand people, spread across sixteen departments.[32] Its role was as 'a full-scale aeronautical laboratory for the Air Ministry,' including: 'i) Development work on experimental Aircraft and Engines, ii) Testing of experimental instruments and accessories, iii) Development of special flying instruments for which there is little commercial demand.'[33] The RAE's departments thus fell into two categories: those that mainly performed research and experiments, offering advice to industry (Aerodynamics, Structures, Materials), and those that were mainly design-based (Wireless, Instruments, Electrical and Ignition, Armaments). The Engine Department was somewhat unusual in that it had both research and design functions: it provided scientific and engineering advice to engine companies on matters such as vibration, fuel chemistry, and cooling (thereby supporting the Air Ministry's development programme in industry), but it also designed engine accessories such as superchargers and carburettors.[34] Wherever possible RAE designs were handed over to a commercial firm for production, as the Farnborough workshops were not geared towards large-scale manufacture.[35]

There was a tension here between research and design/engineering work that had existed from the RAE's creation. The Establishment had been founded before the First World War as the Royal Aircraft Factory; as the name suggested, it was intended to be a state arsenal for the design and production of aircraft and aero-engines, as well as a site for research.[36] This role soon brought it into conflict with the nascent aircraft industry, which complained that the Factory had a monopoly on designs for the Royal Flying Corps, which was inefficient and suppressed private enterprise. During the First World War the issue came to a head, and the government decided that the Factory should be purely a research and experimental establishment, with no aircraft design functions. Many of the Factory's design staff left for senior posts in industry (see Table 1.1), which helped improve relations between the two. In light of the claims of the Factory's inefficiency, it is

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[32] Precise numbers are hard to come by; by 1939 there were over 1,100 salaried employees at the RAE, of whom at least half were research and technical, but many of the support staff would have been hourly-waged; by comparison, during the First World War the Establishment employed about 5,000 people.

[33] As affirmed by the Air Ministry's Director of Technical Development in 1924, quoted in Caunter (1949), 50.

[34] For examples of carburettor design see Freudenberg (2003).

[35] Although the workshop staff were very skilled, getting experimental equipment made up was a slow process and a source of some frustration to experimenters; for an example see Postan, Hay, and Scott (1966), 185-6; For a more personal account, see Baxter(1988).

[36] Before the Royal Aircraft Factory it had been the Balloon Factory, which had been founded supporting the Royal Engineers' ballooning units. For more on the politics around the Factory's creation, see Driver (1997), and Hare (1990)

interesting to note that these staff had been paid a total wage of £6,000 at Farnborough, compared to some £40,000 in the private sector.[37]

Table 1.1 – Post-1916 Royal Aircraft Factory staff moves to industry

Name	Role	Moved to
G. S. Wilkinson	Engine Designer	Napiers
S.D. Heron	Engine Designer	Siddeley Deasy
F.M. Green	Engine and Aircraft Designer	Siddeley Deasy
H.P. Folland	Aircraft Designer	Nieuport
H. Bolas	Aircraft Designer	Parnall
P.L. Teed	Materials Scientist	Vickers
J.S. Irving	Engine Designer	Sunbeam
J. Kenworthy	Aircraft Designer	Austin Motors
F Bennell	Aircraft Designer	Boulton and Paul
J Lloyd	Aircraft Designer	Armstrong Whitworth
W.S. Farren	Aerodynamicist	Armstrong Whitworth

On 1 April 1918, the Royal Air Force was formed by the merger of the Royal Flying Corps and the Royal Naval Air Service.[38] To avoid confusion, and to reflect its change of role, in July 1918 the Royal Aircraft Factory was renamed the Royal Aircraft Establishment. In the post-Armistice demobilisation, the RAE shrank by 75% from its wartime peak, down to 1,380 staff.[39] Having lost its production and design tasks, the Establishment's future purpose was somewhat unclear. However, it continued its wartime research and development programmes in areas such as engine and fuel research, and aircraft stability and control.[40]

The RAE's organisation remained essentially similar throughout the interwar years; in the 1930s, the Establishment was headed by the Chief Superintendent, who was appointed by the Air Ministry. From 1928-1941 this was the Cambridge-educated engineer AH (Arthur Henry) Hall.[41] Under him were a Chief Accountant (responsible for the RAE's administrative departments); an Engineer in Charge of Production (in charge of the Establishment's central workshops; during the interwar period this was GB Turner); and a Superintendent of Scientific Research and a

[37] Child and Caunter (1947), 23.
[38] The date remains a source of continuing amusement to the senior services.
[39] Caunter (1949), 37.
[40] As evidenced by the post-war annual reports of the Aeronautical Research Committee.
[41] Not to be confused with the RAE Aerodynamicist (and post-war director) AA (Arnold Alexander) Hall.

Superintendent of Technical Development (in 1939 these were Harold Roxbee Cox and Andrew Swan respectively). The latter two reported to their respective directorates at the Air Ministry and worked out a research programme with the RAE's experimental departments. However, the relationship between Farnborough and the Ministry was less subordinate than the formal organisation might suggest. The Superintendent was a member of the Aeronautical Research Committee (ARC), which oversaw research at Farnborough. (I will return to the ARC below, as it played a crucial role in this history.) In addition, many of the ARC's sub-committees had RAE experts as members, who could seek official sanction for research programmes via that route. Finally, many of the Air Ministry staff and ARC members were themselves ex-Farnborough researchers, and were always willing to listen to research suggestions.[42]

'Pure' research work in aerodynamics was supposedly the domain of the National Physical Laboratory (NPL), but in practice this was not always a clear distinction, with RAE staff also conducting research on theoretical methods in aerodynamics.[43] However, the RAE often acted as what Takehiko Hashimoto has called 'scientific middlemen,' translating the scientific data and theories of such places as the NPL and the universities into forms that were useful for designers in industry.[44] This could take the form of transforming the mathematical analysis of a problem into data sheets or graphs that allowed designers to find solutions without having to solve complex mathematical models; useful for an industry still dominated by empiricist 'practical men.'[45]

Indeed, of the Air Ministry's research sites, the RAE had the closest links with the aviation industry. From 1922, the RAE had the responsibility for checking that civil and military aircraft designs met the statutory airworthiness requirements. By 1928, it was felt that using trained RAE staff to check manufacturers' calculations was not an efficient use of their time, and a Resident Technical Officer (RTO) scheme was started. The RTOs were seconded to 'approved' firms as liaison officers, and oversaw the firms' procedures. This freed up the Airworthiness Department to do research into aircraft structures and to shape the requirements for future aircraft, whilst being kept informed of what was happening in industry.[46] Apart from carrying out their own programme of research, the RAE's departments were also there to offer advice to aeronautical companies

[42] See the history by JD Scott compiles as part of the civil series of the Official Histories: NA CAB 102/60 - The Royal Aircraft Establishment: Organisation and Administration, ¶68.

[43] Indeed, the NPL's Aerodynamics Department was mainly funded by a grant from the Air Ministry (the NPL itself was funded by the Department of Scientific and Industrial Research.)

[44] Hashimoto (2007)

[45] Scott and Hughes (1955), 373.

[46] CAB 102/61 - Aeronautical Research Council, JD Scott, Part IV.ii

when requested, as well as placing their experimental and test facilities (such as wind tunnels or specialist engine test benches) at the service of manufacturers.

The technical competence of industry was also improved by the movement of staff from the RAE to private firms. The most dramatic example was the exodus during the First World War, but individuals moved at other times as well, often with the tacit approval of the RAE and Air Ministry. Although junior staff salaries at Farnborough were comparable with those in industry, civil service pay for more senior technical and scientific staff was significantly lower than in the private sector.[47] In the late 1920s Farnborough's supercharger specialist James Ellor was being courted by a US engine manufacturer, and the Air Ministry DTD convinced Rolls-Royce to make Ellor a comparable offer. Ellor left the RAE and joined R-R, where he worked on Air Ministry supercharger contracts.[48] He designed the supercharger for the Rolls-Royce Kestrel, which had an efficiency of over 70%, and was involved with the design of the 'R' racing engines fitted to the Supermarine Schneider Trophy racing aircraft.[49] At around the same time, a number of the engine department's testing staff moved to the Bristol Engine Company, where Harvey Mansell was to head its cylinder test department.[50] This movement also had the effect of improving informal contacts between the RAE and industry.

Yet some of the tensions of the Royal Aircraft Factory's relationship with the aeronautical industry remained after it became a research establishment. Industry fears about Farnborough usurping their design role remained, with complaints being made in the early 1920s that the RAE was doing too much development and engineering work that could be carried out by private companies. As the industry journal *Flight* put it, the work of the Air Ministry's Directorate of Research was 'about one-fifth research and four-fifths engineering', and the 'concentration of research and experiment' at the RAE should not lead to 'more designing and constructional work than would be good for the country or the industry'.[51] As noted above, these complaints led to the reorganisation of the Air Ministry's research organisation into separate Directorates of Scientific Research and of Technological Development, and the appointment of a Director of Scientific Research. During the late 1930s there were supposedly complaints from industry about sharp

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[47] See eg the complaints in Baxter (1988); the issue is also noted in Schlaifer and Heron (1950)
[48] Pugh (2000), 300-301.
[49] This was a period when superchargers were becoming more widely-used, being used to boost power at sea-level as well as at height.
[50] Gunston (1978)
[51] *Flight*, 5 Oct 1922, 570.

practice in the patenting of work done by the RAE's Engine Department.[52] The Department's development of a gas turbine engine must be seen against this background, as it represented a departure from the tendencies of the past two decades towards research, and a move back towards the design of engines. As I will show below, this departure was driven by the urgent needs of air defence.

The Aeronautical Research Committee and the Engine Sub-Committee

As mentioned previously, work at Farnborough was overseen by the Aeronautical Research Committee (ARC); formed as the Advisory Committee for Aeronautics (ACA) before the First World War, its aim was to advise government on aeronautical science, with a view to the consequences for the national defence. It had an elite scientific character, comprising mainly theoreticians with few engineers or experimenters.[53] With the outbreak of the First World War, the ACA was called upon to advise on a wide range of aeronautical problems, and to deal with the volume of work a number of permanent sub-committees were formed to deal with subjects of interest.[54] These sub-committees gave the ACA the flexibility to enquire into most issues that the Air Board (forerunner of the Air Ministry) passed to the committee. One of the earliest was the Engine Sub-Committee (ESC), formed in 1916. Like its parent committee, it contained representatives of the armed services, state research institutions, and independent experts.

After the Air Ministry's formation in 1918, the ACA submitted its reports to the Secretary of State for Air rather than the Prime Minister, and in March 1920 it was expanded and renamed the Aeronautical Research Committee. Though it retained its advisory role, its remit was expanded, and representatives of the aeronautical industry were included as members. It was given the authority to administer research work proposed to it by the Air Ministry, as well as to initiate its own research work, and was provided with funds by the ministry for this purpose.[55] The committee's funding was split between the Department of Scientific and Industrial Research (DSIR) and the Air Ministry. The DSIR would be responsible 'for the provision of independent research for the advancement of science, even though it may ultimately tend to the advancement of aeronautics.' The Air Ministry would be responsible for 'research aiming exclusively at

[52] As noted in Banks (1978), 132; however, Freudenberg (2003)'s account of the engine department's work gives no hint of these tensions. There seems to have been some personal animus between Franks and the RAE's patent agent, which may explain the tone of his account.

[53] See Driver (1997); Bloor (2011); as aeronautics developed as a discipline, the proportion of aeronautical engineers rose, but the committee retained its elite character.

[54] For one-off issues, the ACA also formed smaller expert panels.

[55] Its expanded terms of reference are given in the Technical Report of the ARC for 1920-21.

advancement in aeronautics, except as regards work done at the NPL.' [56] As noted previously, as the work done at the NPL's Aerodynamics Department was almost entirely of an aeronautical nature, in practice it was funded by the Air Ministry.[57]

From 1924 onwards the ARC attempted to get the Air Ministry to place more emphasis on research rather than development. The Committee had pressed for the appointment of a Director of Scientific Research, as it felt that the Ministry was concentrating on development to the detriment of fundamental research, and that more general research would be more effective than 'prize money for limited lines of attack on the problems of flight'.[58] The aircraft industry representatives were removed from the ARC, industry liaison instead being carried out by twice-yearly meetings with the Society of British Aircraft Constructors (SBAC); more generally, the Air Council decided that membership of the Committee should 'be confined solely to members appointed in virtue of their scientific standing rather than as representatives of definite interests'.[59] 'ARC research' encompassed work carried out at the NPL at the direct instruction of the committee; at the RAE at the suggestion of, or merely with the approval of, the Committee; and research on an ARC-funded programme carried out in University laboratories. The support of the ARC's Engine-Subcommittee members for a gas turbine engine would be crucial for the development of the technology; it is to some of these people that I will now turn.

As is not uncommon with committees, much of the ARC's power came through the influence of its members rather than through its formal responsibilities; as most of them were on the committee due to their scientific eminence and their positions elsewhere, they had the power to smooth the path of decisions taken in committee. More united these men (and they were all men) than their common membership of the ARC. They had similar social backgrounds, leading to what Andrew Nahum has called, in relation to the creation of the air defence system of the late 1930s, 'Clubland at War'.[60] On the main committee, a majority of the members were Fellows of the Royal Society; on the Engine Sub-Committee, the proportion was lower, but was never less than about 40%.

[56] NA CAB 102/61 – Aeronautical Research Council, J.D. Scott, ¶22.

[57] E.g. the 1928 Air Estimates show a grant of £30,000 to the NPL.

[58] Technical Report of the ARC for 1922-23, 1; similar sentiments are to be found in the Report for 1923-24. The content of the ARC's reports does not seem to have changed significantly across this period, possibly because they were already research-oriented.

[59] The quote is from the Technical Report of the ARC for 1924-25, 2; see also NA CAB 102/61 – Aeronautical Research Council, J.D. Scott, ¶27. The SBAC was the industry's trade body.

[60] Nahum (1997), 325. The particular club in this case was the Athenaeum, not coincidentally also a favoured haunt of Royal Society members. For more on the importance of the self-presentation of 'insider scientists' as 'gentlemanly professionals', in the interwar period, see Chaston (1997).

There were also close personal links of shared experience, especially those relating to service in the First World War. Many of those involved in aeronautical research policy had been part of 'Hopkinson's Gang,' working under the Department of Military Aeronautics' head of supply and research Professor Bertram Hopkinson FRS. As can be seen from Table 1.2, there was considerable overlap within this group alone.

Table 1.2 – Selected members of 'Hopkinson's Gang' – post-war affiliations	
Charles Galton Darwin	FRS (1922); Christ's College, Cambridge; ARC; Head of NPL (1938)
William Scott Farren	FRS (1945); Head of Aerodynamics at RAE; University of Cambridge; Deputy DSR at Air Ministry, Director of RAE; ARC
Frederick Lindemann	FRS (1920); Clarendon Laboratory, Oxford; Air Defence Research Committee; Scientific advisor to Winston Churchill
David Pye	FRS (1937); fuel research, University of Cambridge; Deputy DSR, Air Ministry; DSR, Air Ministry
Harry Ricardo	FRS (1926); Air-Ministry-funded fuel and engine research; ESC
Richard Southwell	FRS (1925); Superintendent Aeronautics Dept, NPL; Trinity College, Cambridge; Professor of Engineering Science, Oxford; various ARC sub-committees
Geoffrey Ingram Taylor	FRS (1919); Cavendish Lab, Cambridge; ARC and sub-committees.
Henry Thomas Tizard	FRS (1926); Fuel research, Oxford; Assistant Secretary, DSIR; Permanent Secretary, DSIR; Rector, Imperial College; ARC; Chairman, ARC (1933)

In terms of overall influence, Henry Tizard was the undisputed leader of this group; as Philip Chaston has pointed out, his combination of education and training made him the perfect 'insider scientist', able as a 'gentlemanly professional' to interact with politicians and civil servants as an equal, to and negotiate state committee business with ease.[61] Trained as a chemist, he had joined the ARC after the First World War, becoming its chairman in 1933 (he was chair of the Engine Sub-Committee from 1925). Intimately familiar with government and scientific policy-making, he had been largely responsible for the creation of the DSR's post at the Air Ministry; indeed, it had originally been expected that he would take the position, but Tizard elected to stay in his current position at the DSIR, and Wimperis, a wartime colleague of Tizard's – and an Athenaeum man – got the job.[62] After leaving the DSIR to take up the rectorship of Imperial College, he remained committed to his committee work; described as a 'stimulating chairman' and a 'master of the searching question,' he was able to cut to the heart of difficult technical issues.[63] In 1934, when Wimperis suggested to the Secretary of State for Air that an independent scientific committee should be formed to consider the problem of air defence, Tizard was the immediate choice to chair it. Tizard was therefore one of a very small circle aware of the possibilities of radar detection in the mid-to-late 1930s, which influenced his views on engine development.

The other senior civil servant on the Engine Sub-Committee was David Pye, who was the Director of Scientific Research at the Air Ministry (until 1937, Deputy Director). In the early 1920s he and Tizard had worked with their wartime colleague Harry Ricardo researching fuel chemistry for internal combustion engines, work which contributed to the eventual election of all three as Fellows of the Royal Society.[64] Ricardo was a brilliant consulting engineer who continued to do research on internal combustion engines and fuels throughout the 1920s and 1930s, experimenting with the effects of various fuels, engine cycles, and technologies such as the sleeve valve. His consultancy firm did large amounts of research work under contract to the Air Ministry, as well as working with aero-engine manufacturers such as Rolls-Royce and Bristol.[65] Crucially for the evolution of the RAE's gas turbine projects, he had an existing relationship with Metrovick. One of his closest colleagues had been a college apprentice with Metrovick's predecessor company British Westinghouse, and during the First World War MV had built piston engines for tanks and submarines under license to Ricardo's designs. He had also carried out consultancy work

[61] Chaston (1997)
[62] J. E. Serby, 'Wimperis, Harry Egerton (1876–1960)', rev. John K. Bradley, Oxford Dictionary of National Biography, Oxford University Press, 2004 [http://www.oxforddnb.com/view/article/36973, accessed 20 June 2010]; the only full-length biography of Tizard is Clark (1965)
[63] The quote is from G. J. Piller, 'Tizard, Sir Henry Thomas (1885–1959)', Oxford Dictionary of National Biography, Oxford University Press, Sept 2004; online edn, Jan 2008 [http://www.oxforddnb.com/view/article/36528, accessed 25 June 2010]
[64] Including work on predetonation and what would now be called octane rating.
[65] Pugh (2000) notes that during the 1930s Rolls-Royce paid Ricardo a £500 yearly retainer.

for Metropolitan Vickers on combustion.[66]

Like its parent committee, the Engine Sub-Committee had members to represent the interests of the Air Ministry, the Admiralty, and the Royal Aircraft Establishment.[67] The most frequent Air Ministry representative (and vice-chairman of the sub-committee) was Pye, but the Directorate of Technical Development's engine representative, G.P. Bulman, was also often present; other Air Ministry Staff occasionally attended. The RAE representatives were usually senior members of the Engine Department; in the mid-1930s the head of department was Andrew Swan, who was often joined by his subordinates AA Griffith (who was to become head of department after Swan left the RAE) and Hayne Constant.

Griffith was awarded a first-class degree in mechanical engineering by the University of Liverpool in 1914; he also won a scholarship which allowed him to remain there for a further year to do postgraduate research work. In 1915 he joined the Royal Aircraft Factory's Physics and Instrument department, becoming a Senior Scientific Officer in 1920. An early piece of work, was with the physicist Geoffrey (GI) Taylor (one of 'Hopkinson's gang' and later an ARC member), was on analogues for the stresses in bars in torsion. [68] He also carried out research on aircraft propellers, which led him to apply aerodynamic theory to turbines and compressors. In 1926 Griffith produced the RAE report 'An aerodynamic theory of turbine design,' in which he analysed axial compressors and turbines as rotating aerofoils rather than (as had previously been the case) as passages forming turbine nozzles, suggesting that far higher efficiencies could be achieved in this way.[69] Experiments at the RAE confirmed that more efficient compressors could be built in this way, but there was not seen to be any immediate utility for the work, and in 1928 Griffith moved to head the Air Ministry Laboratory in South Kensington, returning to Farnborough in 1931 when the Laboratory was merged with the RAE. He continued to take an interest in gas turbines, and in 1936 gained approval to construct a test axial compressor which would build on the experimental wind turbine work on blade cascades carried out at Farnborough. In 1939, Rolls-Royce hired Griffith to work for them as a research engineer.[70] He was elected FRS in 1941.[71]

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[66] See the minutes for the MV Board Executive Committee for 22 Sep 1936 and 20 Oct 1936, items 1487 and 1517, MOSI 1996.139/1/3/3. For more on Ricardo's consultancy work and career in general, see Reynolds (2008); Ricardo (1992)

[67] The main committee also had members representing the War Office, the NPL, and the DSIR.

[68] Rubbra (1964), 119.

[69] The nozzle approach came from steam turbine practice; though it gave good results for turbine designs, it was unsuited to the design of axial compressors.

[70] For more detail on Griffith's early turbine work see Armstrong (1976); see also Hawthorne (1991) and

Griffith's successor was Hayne Constant, who had read Mechanical Sciences at Cambridge and joined the RAE's Engine Department in 1928 after a postgraduate year researching torsional vibration. He left Farnborough in 1934 to take up a lectureship at Imperial College, but found teaching not to his liking. Imperial's Rector – Henry Tizard – suggested that he might find the work at Farnborough more interesting, and he returned to the RAE to head the Engine Department's Supercharger Section.[72] The section was doing research on compressors using Griffith's methods of analysis, and Constant was involved in the design of a test compressor based on Griffith's theories. Shortly after his return to Farnborough, Constant was given the task of writing a feasibility report on the gas turbine. It marked a point about which the personal networks of the aeronautical research field would coalesce in support of the technology; the report would confirm the ARC Engine-Sub-Committee's interest in the gas turbine, and would be instrumental in the selection of an industrial development partner for the RAE's gas turbine research programme: the Manchester engineering firm of Metropolitan Vickers.

Metropolitan Vickers

Prestige and profits

The Metropolitan Vickers Electrical Engineering Company (Metrovick) was among the UK's premier heavy engineering companies; indeed its staff considered themselves the 'aristocracy' of electrical engineering.[73] As one of the big four firms 'dominating the British electrical industry' (along with GEC, English Electric, and British Thomson-Houston) the company was a major supplier to the National Grid, awarded some 30% of the generation and transmission plant contracts.[74] Founded in 1899 as the British Westinghouse Electrical and Manufacturing Co., Metrovick had a reputation for scientific and engineering excellence that was bolstered by its large research department. The department was relatively unusual in that it spent much of its time on fundamental research; the department's head, APM Fleming, claimed this would lead to 'new industries arising from discoveries made in the research department.[75] Though some of the

Dennis (1999).

[71] Proposed and seconded by Harry Ricardo and David Pye respectively.

[72] William Hawthorne, 'Constant, Hayne (1904–1968)', rev. Oxford Dictionary of National Biography, Oxford University Press, 2004; online edn, May 2006 [http://www.oxforddnb.com/view/article/32534, accessed 10 December 2009] The RAE was also doing theoretical and practical work on more conventional superchargers, which Stanley Hooker at Rolls Royce was to use to improve the Merlin's performance.

[73] Jones and Marriott (1970), 148.

[74] Jones and Marriott (1970), 63; Cooper (2003), 77.

[75]Quoted in Cooper (2003), 69.

research did lead to profitable products (such as the discovery of very low vapour pressure oils and greases) the benefits to the company were as much reputational as directly economic.[76]

The research department also forged mutually beneficial relationships with university researchers; the most famous of these was probably that with Cambridge University's Cavendish Laboratory. By forging links with institutions such as the Cavendish at universities, the Metrovick research department was able to keep in touch with cutting-edge science relatively cheaply, suggesting future lines of research, as well as generating prestige for the company. No less than nine of the research department's staff were elected Fellows of the Royal Society; a unique achievement for an industrial research lab.[77] The company's engineering departments were equally prestigious in their fields, with reputations for mathematical sophistication and for innovative design practices.[78] Metrovick's Mechanical Engineering Department design staff were awarded a number of professional honours for advances in steam turbine practice, which bolstered the company's reputation for technical competence.[79]

However, the flip-side of this prestige was that pride in the company's engineering prowess could lead its engineering staff to take on projects that made little commercial sense. The heavy electrical plant business was based on large bespoke solutions, which led to a privileging of design expertise over production engineering within the company.[80] Engineers were often given license to develop their own projects at company expense without regard to utility: for instance, one of the company's electrical engineers was given license to develop an automatic gearbox for automobiles based on an idea of his.[81] At other times, projects seem to have been accepted based mainly on whether they were technically interesting or not.[82] Systems of cost control were weak

[76] See also Niblett (1980). Cooper (2003) suggests that Metrovick's R&D spend was probably comparable with that of other electrical engineering companies – due to differing accounting practices it is hard to be certain – but that it resulted in a higher profile due to its fundamental nature and links with other institutions. For more on interwar industrial R&D, see Edgerton and Horrocks (1994)

[77] Cooper (2003), 76. It is unclear whether this includes staff who worked with the research department; if not, there were at least two more FRS's in the company.

[78] Terry Burnett, personal communication, Jan 18 2010. Though this seems to have held company-wide, certainly the Mechanical Engineering Department's design staff were unusually mathematically sophisticated for the industry, as evidenced by the awards and prizes won by them for the development of analytical design methods. See eg. Smith (1933).

[79] For example, the IMechE's Hawksley medal was awarded to both Karl Baumann and Henry Guy during their MV careers.

[80] I will return to these issues of technical style again in chapter 2.

[81] See the IEEE oral history interview with Charles Flurscheim at http://www.ieeeghn.org/wiki/index.php/Oral-History:Charles_Flurscheim, accessed 10 Jun 2012; another similar

[82] A suspicion which is strengthened by some of the projects depicted in Rowlinson (1949), such as a bottle-

or non-existent, and some sections of the business made significant losses.[84] For example, Metrovick's consumer electricals subsidiary Metrovick Supplies made a loss of £100,000 in 1928, and was sold off. In the same year, Metropolitan Vickers was merged with their arch-rivals British Thomson-Houston (BTH) under the holding company Associated Electrical Industries (AEI), though the companies continued to be run essentially independently; if anything, their rivalry was made more bitter.[85]

Metrovick was embedded in many networks of power and influence; apart from its involvement in the UK's national grid, the company had large overseas sales, both in the British Empire and elsewhere.[86] Though its core business was in steam turbines and electrical generation, MV was also linked to rail transportation networks, both by supplying them with electrical generating plant, and through its traction business; this included the sale of both complete electric locomotives and of traction gear.[87] In the UK, Metrovick's most prominent customers were the LMS and Southern Railways, and the London Metropolitan Railway (and later London Underground).[88] Overseas contracts included electrification projects for Indian and South African main line railways, as well as for commuter lines in New South Wales and Brazil. The company also produced light transport equipment for trams and trolleybuses, and by the late 1930s it produced some 40% of the trolleybus equipment in the UK.[89] An offshoot of its steam turbine work was the supply of geared steam turbines to shipbuilders, though the interwar shipbuilding slump meant that this was never a major part of its business.[90] The company also had interests in broadcasting; its light bulb subsidiary Cosmos had been turned over to radio valve manufacture during the First World War, to help meet the demand for military radio equipment. After the war, Metrovick continued to manufacture radio components, and was one of the original shareholders in the British Broadcasting Company (providing one of the directors). In conjunction with the research department's high-voltage experiments, Metrovick also developed continuously-evacuated valves

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making plant for a whisky distillery.

[84] Many of these failings are documented in Jones and Marriott (1970).

[85] For a fuller account, see Jones and Marriott (1970)

[86] Although as a member of both British and international electrical cartels, there were some restrictions on export territories.

[87] That is, propulsion machinery that was fitted to the customers' choice of chassis and coachwork. In the UK, the main national railway companies all had their own coachbuilding works.

[88] Although Southern's mid-1930s electrification plan standardised on English Electric equipment. EE was headed by a former MV executive, and according to one authority, he offered MV the chance to join a joint project, but was rebuffed in part due to the Manchester firm's wounded pride. See Jones and Marriott (1970)

[89] Dummelow (1949), 159.

[90] Dummelow (1949), 65; 104; 145.

of very high power, which were used by the General Post Office (GPO) for their radio stations, and by the BBC for their early television transmission apparatus.[91]

By the mid-1930s, then, Metrovick was a company with a wide range of interests and with a reputation for engineering competence; factors that would be important as the UK's rearmament programmes began to encompass ever wider swathes of the country's manufacturing sector. In particular, the company's experience of advanced steam turbine development coupled to its research reputation would lead it to be an attractive partner for the RAE's gas turbine development programme.

Military contracts

As David Edgerton has suggested, the UK's 'Warfare State' was able to draw on expertise throughout the economy in order to build defence systems; indeed the UK spent more on defence-related R&D than any other nation during the interwar years.[92] Yet despite the company's wide range of products, Metrovick's business strategy seems to have ignored the military and service ministries as potential customers; during the 1930s the company appears to have concentrated on the manufacture of electrical power generation and transport equipment.[93] Despite this, MV was awarded a number of specifically military contracts during the 1930s.

Their broadcast electronics expertise was the reason that MV became one of the first companies in the UK to become directly involved with the radar effort. As noted above, the company had provided high-powered valves to the BBC and the GPO, and the earliest proof-of-concept radar experiments had used GPO transmitters in order to provide a signal for the radar return.[94] In late 1936, the Air Ministry asked the company to quote for a number of large valves for high-powered transmitters; the Air Defence Research Committee then recommended that Metrovick be awarded a contract to produce radar equipment.[95] Because of radar's secrecy and the company's international contacts (and patent-sharing agreements), there was some reluctance on the part of the Air Member for Research and Development to sanction this. The issue was eventually resolved by awarding a contract for transmitters to MV; the receivers were built by Cossors, and ancillary electrical equipment was manufactured by a third company, with integration being carried out by

[91] Dummelow (1949), 138-9.
[92] Edgerton(2006); see also Ferris (1989)
[93] Especially for export. Unfortunately the MV archives do not hold detailed financial information, so this must remain speculative, based on contemporary advertising and on the company's own history.
[94] Buderi (1996), 57-8.
[95] Dummelow (1949), 139; Zimmerman (2001), 125-6.

the Air Ministry's researchers.[96] In overcoming its reluctance to give the contract to Metrovick, the Air Ministry must have concluded that there was no other company with the transmission expertise available.

Metrovick also had links with the Royal Navy. In the mid-1920s, as Westinghouse's UK licensee, MV received royalty payments from the Admiralty for the RN's use of radio equipment that used the Westinghouse radio patents.[97] However, after the production of materiel during the First World War, MV's first Admiralty contracts were in the early 1930s; a contract for signalling projectors (i.e. lights) for warships.[98] By the end of the Second World War, the company had produced almost eight and a half thousand. The Army soon followed the Navy with an order for searchlights and mobile sound detectors for air defence; from 1936 the company produced over 1,200 searchlights and over 560 sound detector units. In 1937, as the Army's re-equipment programme got underway, Metrovick was also awarded contracts to build gun carriages for artillery pieces and anti-aircraft guns.[99]

The largest pre-war contracts, however, came from the Air Ministry. Apart from the order for radar transmitters, in December 1936 the ministry placed an order for 3,750 autopilots. These were for the planned expansion of the RAF's heavy bomber forces, and had been designed at the Royal Aircraft Establishment. Metrovick assisted in adapting the design for volume production, and continued to manufacture autopilots throughout the Second World War.[100] The final – and largest – Air Ministry contract came in 1938, when MV was chosen to build and manage a 'shadow' factory for the production of Avro Manchester bombers. As noted above, the shadow factory programme drew on the First World War experience of the Ministry of Munitions, which had used private-sector industrialists to manage war production.[101] The Air Ministry initially set up shadow factories for aero-engines (in 1936) as it became clear that the engine manufacturers could not meet the demands of the RAF's expansion; these factories were built with government money and

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[96] Zimmerman (2001), 126. Metrovick later provided transmitters for the first AI aircraft radar sets; see Zimmerman (2000), 215-7.
[97] See item 5610 of the minutes of the MV board for 10th June 1936, MOSI 1996.139/3/2. The patent referred to in the discussion is presumably US patent 1,414,717, for improvements to radio receivers. Lee and Hogan (named on the patent) worked for NESCO, which was taken over by Westinghouse in 1919.
[98] Though it is possible – indeed likely – that MV provided electrical equipment of a general nature to the services.
[99] The figures are taken from Rowlinson.
[100] Rowlinson (1947), 47. Although the history does not state this explicitly, Metrovick's instrument and metering department's experience of electromechanical devices must have been a factor in the choice of the company.
[101] Gordon (1988)

managed by existing engineering firms.[102] In 1938, the scheme was expanded to cover aircraft as well as engines. The first turf for the new Metrovick factory was cut in April 1939; by 1945 it had produced over a thousand aircraft for the RAF.[103] The variety of work that the company undertook suggests that customers both military and civilian had a high opinion of its engineering competence.

People and influence

Though the majority of its production was ostensibly civilian, Metropolitan Vickers clearly had substantial links to the supply ministries and the military. At the company itself, the three members of staff most influential in its gas turbine work were Karl Baumann, the chief engineer; Henry L Guy, head of the Mechanical Engineering department; and David M Smith, a turbine engineer who was in charge of the gas turbine team. In the company's research department, the metallurgist R.W. Bailey also contributed his expertise.

Baumann had joined the company in 1909, having previously studied under and worked with Professor Aurel Stodola of the Swiss Federal Institute of Technology in Zurich. Stodola was a world authority on steam turbine theory, and when British Westinghouse asked him to recommend a turbine engineer, he nominated Baumann.[104] Baumann quickly rose in influence at the company, and was appointed the company's chief engineer in 1912; somewhat retiring, he seems to have run the engineering departments with quiet authority. His deputy was HL Guy, who had joined British Westinghouse shortly after Baumann, also to work on steam turbines; by 1918 he was the head of the Mechanical Engineering department. Often described as forceful, Guy seems to have been somewhat difficult, but he put his energy to good use; outside the company he was heavily involved with the activities of the Institution of Mechanical Engineers (IMechE), including work on steam nozzle testing methods for its Steam Nozzle Research Committee.[105] He was also involved with the Royal Society, being elected FRS in 1936 due to his research and design work on steam

[102] Government ownership was partly because manufacturers were loath to invest in productive capacity that would be surplus to requirements in peacetime. Non-aero firms were used because they had a supply of skilled workers and managerial talent; it was seen as easier to use this rather than to try and expand the workforce at aviation companies. For more on this issue, see Ritchie (1997).

[103] Though it should be noted that Avro took a fairly hands-on approach to the management of the MV shadow factory, something that was no doubt helped by the fact that it was based locally (personal communication, Nick Forder, 12 Jun 2012.) The contracts listed in this section were the major ones issued before the outbreak of war; during the conflict itself, like most British industry, Metropolitan Vickers was engaged in a full range of war production. See Rowlinson (1947) for an exhaustive list.

[104] Dummelow (1949), 42.

[105] Work that used similar methods to the cascade testing of aerofoils in aeronautical research; see Guy (1939)

turbines.[106] During the latter half of the 1930s committee work at the learned institutions began to take up an increasing amount of his time, and in 1941 he resigned from his position at Metropolitan Vickers to take up the position of Secretary to the IMechE. During the Second World War he was active in a wide variety of committees related to engineering, and in 1944 was appointed to the Advisory Council on Scientific and Industrial Research.[107]

The head of the engineering metallurgy group in the research department was RW Bailey, who worked closely with Guy. One of his particular research interests was the high-temperature creep behaviour of metals, and as a result he had good connections to specialist steel and alloy foundries. Interestingly, there appears to have been a disciplinary split in the Metrovick research department; Bailey saw his main duty as supporting Metrovick's engineering departments, and worked particularly closely with Baumann and Guy, whereas the rest of the department was dominated by staff with interests in electrical engineering and physics.[108] Whatever the intra-company politics, Bailey clearly contributed to the image of Metrovick's expertise in metallurgy, which was an important factor in the selection of the company to assist on the internal combustion turbine (ICT). During the 1920s he had investigated the possibilities for the industrial gas turbine, but had come to the conclusion that its fuel consumption would be uneconomical without higher-temperature materials.[109] He had suggested a gas turbine design to Metrovick's Manchester Committee of the Board in 1935, but it does not seem to have been developed further.[110] As will be seen below in the sub-section on compressors, gas turbines were under consideration by a number of companies at this time, as they held out the promise of greater efficiencies than steam; however, in order to achieve these, materials with better high-temperature performance would be required.[111] Bailey's expertise in high-temperature materials was therefore of importance.

[106] His proposer for election as FRS was the combustion chemist Sir Alfred Egerton; Tizard was the seconder.
[107] Guy's RS obituary is Smith (1966). Given their similar contributions to steam turbine research, it is interesting that Baumann was never made FRS. Following Chaston (1997), this might be explained by his foreign birth and reserve, which would have meant Baumann would not have easily fitted into the milieu of the 'gentlemanly professional.'
[108] Smith (1958), 16; see also the letter from G. McKerrow to H. Tizard, 18 September 1938, IWM archives HTT 69
[109] Smith (1958), 17.
[110] See the meeting minutes for the Manchester Board Meeting of 19 Feb 1935, MOSI 1996.139/5.2. Unfortunately the board papers and records of the wider discussion have not survived.
[111] Indeed, the theoretical potential of gas turbines had long been recognised; in the UK, the Air Ministry Laboratory's WJ Stern produced a report in 1920 considering the gas turbine as an aircraft powerplant, but noted that it would not be viable with contemporary materials science and component efficiencies. See Constant (1980), 143-144.

The final Metrovick employee involved in the company's early gas turbine investigations was David Macleish Smith, who joined Metrovick as a college apprentice in 1919 after a science degree at Glasgow University. His analytical talents soon became apparent; one of the shop stewards supposedly bet Baumann and Guy that Smith would be able to answer any technical question they could come up with, and won.[112] He was soon put to work in the Mechanical Engineering department, where he developed a number of numerical methods to work out blade stresses and vibration modes in turbines.[113] Though shy and retiring, his talents meant that by the late 1930s he was one of the turbine department's senior engineers, and would be chosen to head the team that would collaborate with the RAE in developing a working gas turbine. The following section will now consider the origins of this project in the context of the various technologies that were being considered by state research organisations.

Origins of the gas turbine

As has been noted above, the operational environment of the late 1930s meant that high-powered engines were needed for interceptor aircraft. The gas turbine was but one of the potential powerplants that might be useful for this goal; other options suggested ranged from free-piston gas generators through aircraft diesel engines to developments of the conventional Otto cycle. The following section will consider the range of technologies considered by the experts of the ARC's Engine Sub-Committee (ESC).

Technological variety

The ESC had discussed the gas turbine before; in 1930 one of its panels had considered a research proposal by AA Griffith for the construction of an experimental turbine rig, based on his work at Farnborough.[114] However, in the mid-1930s the sub-committee returned again to the subject, and began to consider the development of actual powerplants as opposed to research testbeds. As might have been expected given the importance of defence to the operational environment, the discussion of military engines in the ESC was overwhelmingly in reference to the needs of fighters. However, the first turbines considered for aircraft power by the ESC were steam rather than gas turbines, and were considered in relation not to fighter aircraft, but in relation to long-range seaplanes! This was in response to a 1935 request that the sub-committee investigate the possibilities for engines of very high power (on the order of 10,000 HP). Introducing the issue to the ESC, Tizard noted that the sub-committee 'should not confine itself to the internal combustion

[112] Saunders (1987), 606.
[113] Smith (1933)
[114] The panel approved of Griffith's proposal, and the Engine Sub-Committee itself gave its approval in May 1930, but no experiment at Farnborough was forthcoming; see Constant (1980), 111.

engine if other types of prime mover appeared to be more hopeful.'[116] The discussion centred on whether the use of a turbine with a high-temperature working fluid would be practical, but after calculation AA Griffith informed the committee that the efficiencies would be too low; Tizard noted that 'it disposed of the possibility of the vapour turbine for aircraft purposes.'[117]

In discussing the state of high-powered piston engine design, the committee's conclusion was that there was an upper limit on practical cylinder size (and thus on power per cylinder). A high-powered engine would therefore require a method of drawing power from a large number of small cylinders. Tizard suggested that successfully building such an engine might take 10 years; given that the CI [Compression-Ignition, or diesel] engine could be built with larger cylinders than a petrol engine, the CI might be a superior choice for a shorter timeframe.[118] Indeed diesels were to be a recurring alternative to conventional engines in the ESC's discussions; later that year, the ARC sponsored a conference with aircraft and aero-engine constructors to discuss future aeronautical progress.[119] In preparation, the ESC was asked to look at a list of discussion points relating to engines; one point was the diesel engine's suitability for civil use, because of its fuel economy and the lower fire risk of diesel oils compared to aviation petrol.[120]

One point made in the committee was that in future there might be a divergence between military and civil engine requirements. At this time, most commercial aircraft were powered by versions of military engines de-rated for longer life and reliability, but as Griffith put it: 'in the near future military machines would no doubt be required to have a speed of some 300 m.p.h. and fuel economy would become of minor importance'.[121] For high-powered engines, the question of fuel economy and fuel type was of particular interest to the Chairman; as noted previously, Tizard had trained as a chemist, and his major contribution as a researcher had been an investigation of petrol composition.[122]

At a later meeting in February 1936, Tizard asked to what degree fuel consumption might be

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[116] 91st ESC meeting, 26 February 1935, 1097, NA DSIR 22/61.

[117] 93rd ESC meeting, 14 May 1935, 1143-4, NA DSIR 22/61. The major point of discussion was whether high enough rates of heat transfer could be achieved. Interestingly, the use of a Velox boiler was suggested; this was a form of gas turbine, albeit one that provided little or no useful power.

[118] 91st ESC meeting, 26 February 1935, 1103, NA DSIR 22/61.

[119] Following the removal of the industry members from the main committee, such events were one of the ways that the ARC attempted to keep abreast of the needs of the aeronautical industry.

[120] 95th ESC meeting, 24 Sep, 1935, 1172, NA DSIR 22/61.

[121] 95th ESC meeting, 24 Sep, 1935, 1172, NA DSIR 22/61.

[122] See Clark (1965)

disregarded if the Air Ministry desired to develop a 'sprint engine for Home defence'.[123] In private discussions Tizard and Ricardo had concluded that a two-stroke engine was a possible contender, provided fuel consumption was not a primary concern. Tizard asked the RAE and Ricardo to submit their suggestions for maximum power possibilities given this relaxed constraint, stating that:

> 'The subject provided not only an interesting research problem but a question of very great practical importance. Defence machines were likely to be in the air for comparatively short periods of time and hence fuel consumption was of much less importance than the development, when required, of the utmost possible power output and the maximum excess of speed over that of the opposing machine.'[124]

As noted above, Tizard was the chair of the Air Ministry's Committee for the Scientific Survey of Air Defence, which had supported the earliest radar experiments. By now he would have been aware that this technology offered the chance for defensive aircraft to be directed to intercept attackers from takeoff, and that fuel consumption therefore no longer had the same importance.[125]

The major advantage of using high-octane fuels in existing engines was the ability to use high boost pressures at low altitudes without causing detonation. The major effect on performance would be to raise climb rates at heights below the full-throttle altitude (i.e. the height at which the supercharger could maintain ground-level atmospheric pressure), but above this height, the fuels would be mainly 'superfluous.'[126] It was clear that for higher overall engine powers, new designs would be required. Ricardo's suggestion was a two-stroke design could achieve higher powers from existing 87-octane fuel, due to its better detonation resistance; he had some experience of two-stroke performance, having carried out single-cylinder tests for the DSR.[127] Ricardo did note that the benefits of the 2-stroke might be lessened if 100-octane fuel were used. Following the committee's positive discussion, Tizard suggested that Pye and Ricardo should make further arrangements themselves. In the event, this engine was further developed by Ricardo and Rolls-Royce, but never entered production, as its development was outpaced by more conventional engines using high-octane fuel. Nonetheless, the support given to this unconventional design suggests the importance given to high-powered engines by the Air Ministry.[128]

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[123] 98th ESC meeting, 25 Feb 1936, 1229-30, NA DSIR 22/61.
[124] 98th ESC meeting, 25 Feb 1936, 1229-30, NA DSIR 22/61.
[125] The influence of Tizard's chairmanship of the CSSAD on the ESC discussions is noted in Nahum (1997).
[126] 98th ESC meeting, 25 Feb 1936, 1237-38, NA DSIR 22/61.
[127] 98th ESC meeting, 25 Feb 1936, 1230, NA DSIR 22/61.
[128] For a fuller account of this project, see Nahum (1997).

Compressors

One of the crucial auxiliary engine technologies discussed by the ESC was the engine supercharger or compressor, which compressed the intake air (or 'charge'). Until the late 1920s, superchargers had been mainly used to give higher power at altitude; as the air got thinner, compression of the intake charge was required to maintain the same amount of oxygen per cylinder. However, from this period, engines began to be designed to use superchargers to boost the engine's power at all heights, including ground level. High-powered engines required large mass flows of air (in order to burn large amounts of fuel); achieving these mass flows in a reasonably small volume (and thus lower engine weight) required compression of the intake air by a supercharger.[129] This had been tried in the Rolls-Royce Schneider Trophy racing engines, and was introduced into service aircraft in the Rolls-Royce Kestrel. The major drawback of this method of power boosting was that it increased the sensitivity of the engine to detonation, and therefore required the use of higher-octane fuels – hence Tizard and the ESC's concerns about fuel supply. It was supercharger technology that first brought Metrovick to the committee's attention.

By the mid-1930s, the best current superchargers gave a compression ratio of about 2, but it was clear that for the high-powered engines then being conceived this would have to be raised. The RAE's experts suggested that maximum blower compression ratios would be 3 for an exhaust-driven compressor, and about 2.5 for one driven off the engine.[130] At a meeting in March 1935, the ESC went over the supercharger problem at greater length, with Pye giving an overview of the latest work being done under the auspices of the Air Ministry. He informed the committee that the Bristol Engine Company was working on a two-stage radial supercharger, and that the RAE had also been doing research on two-stage blowers (i.e. two compressors in series to give higher pressures).[131] In addition, Rolls-Royce had asked the Swiss electrical engineering company Brown Boveri & Cie. to design them 'a multi-stage axial blower for one of their newest high powered engines'.[132]

In the mid-1930s, Brown Boveri was internationally the company with the greatest experience of axial turbomachinery; like Metrovick, the company manufactured steam turbines, but they also had extensive experience of building axial fans and blowers. Working with the eminent aerodynamicist Professor Jakob Ackeret of the Swiss Federal Institute of Technology, Brown Boveri had built the compressors for the Institute's high-speed wind tunnel. Building on the

[129] Also known as a blower.
[130] 98th ESC meeting, 25 Feb 1936, 1235-36, NA DSIR 22/61.
[131] 99th ESC meeting, 31 Mar 1936, 1253, NA DSIR 22/61.
[132] 99th ESC meeting, 31 Mar 1936, 1253-4, NA DSIR 22/61

compressor experience gained through the collaboration, the company went on to manufacture a number of industrial turbocompressors. Not initially intended for power generation, as 'Velox' boilers they were designed to be compact units providing very high rates of heat transfer; as blowers in oil refineries they were to provide large amounts of compressed air for the petroleum cracking process.[133] Their Rolls-Royce supercharger had a design pressure ratio of 2.5, and Brown Boveri were 'confident that it would have a good efficiency.' In addition, they were said to be working on an exhaust-driven blower.[134]

At Tizard's prompting, Ricardo mentioned that Metropolitan Vickers were considering some gas turbine designs with 'superchargers giving delivery pressures of 3 or 4 atmospheres at ground level', and that the company were 'very keen on the solution of the blower problem'.[135] As noted above, Ricardo had an existing consulting relationship with Metrovick, and had recently worked with the firm on combustion problems; he was clearly aware of their proposed projects. Unfortunately no Metrovick documentation about these designs survives, but the company must have been aware about the growing interest in gas turbines by other turbomachinery companies such as Brown Boveri (especially as they were by now being used commercially as compressors in oil refineries); as noted previously, RW Bailey had been considering gas turbine designs some time previously.

Perhaps surprisingly, given his previous support for the axial compressor at the RAE, Griffith expressed some reservations about the type's possible drawbacks. He argued that if it was designed to run efficiently at its operating conditions, it would encounter aerodynamic problems during start-up. These would persist in running, limiting its efficiency to some 55%. This assertion was challenged by some of the other aerodynamicists on the committee, who asked to see further data.[136] Tizard moved the discussion along by stating that if developing an efficient blower of high compression ratio was of importance – as it seemed to be - then it seemed to be equally important to get 'somebody fresh to go into the problem,' suggesting that 'the matter might be taken up with Metropolitan-Vickers.' Pye suggested that BTH might also be approached, as they

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[133]Constant (1980), 114-5; 145-6. After development, both the Velox boilers and the refinery blowers produced small but useful amounts of power, and Brown Boveri began the design of an industrial gas turbine for electrical power generation; this was to be completed in 1939.

[134] 99th ESC meeting, 31 Mar 1936, 1254, NA DSIR 22/61.

[135] 99th ESC meeting, 31 Mar 1936, 1254, NA DSIR 22/61. It is unclear who Ricardo had been in contact with at Metrovick, and whether the gas turbine mentioned was RW Bailey's paper study.

[136] 99th ESC meeting, 31 Mar 1936, 1254-5, NA DSIR 22/61.

had links to GE in the US, and ‘a wide experience.’[137] The RAE’s Andrew Swan made the point that engine designers should be involved in the project, ‘so that due regard could be paid to engine design and air cooling problems.’ [138]

Returning to the Rolls-Royce blower, Tizard asked whether the Brown Boveri design’s pressure ratio could be increased to 4, whilst still retaining a reasonable efficiency. Griffith responded that if he had to aim for that ratio with a low risk of failure he would choose a two-stage centrifugal blower, but for the highest possible efficiencies he would go for the axial type, albeit at a heightened risk of failure.[139] In response, Swan suggested ‘that if the Committee desired to pursue the axial flow type it might be a good plan to call in a firm such as Metropolitan-Vickers as consultants’; Tizard suggested that Metrovick should be asked to manufacture the compressor, but should be ‘allowed to use the R.A.E. as consultants.’[140] Ricardo pointed out that the design of a turbine blower for the diesel engine was ‘practically the Metropolitan-Vickers problem.’[141] Given the Metrovick interest in gas turbines, Tizard suggested that the firm’s ‘[interest] in the aero engine problem [be] stimulated,’ and that a consultation with the RAE should be arranged.[142] Summing up, he stated that the committee all agreed that producing a blower with a pressure ratio of 4 was a matter of importance, and suggested that Pye think about the best way for the Air Ministry to support this goal and report back to the committee. Clearly the experts of the ESC saw Metrovick as a viable partner for the development and production of aeronautical turbomachinery.

Consequences

Despite the ESC having discussed both turbines and compressor technologies, it would be misleading to suggest that the jet engine was a natural conclusion of their deliberations. This position is sometimes taken by those who point out that Frank Whittle had been thinking about jet engines since the late 1920s, and had been granted a patent on the jet engine in 1930.[143] This ignores a number of factors: firstly, a working gas turbine suitable for aviation use was clearly some way off; the only existing gas turbines at the time were industrial units weighing many tons.[144] Secondly, the gas turbines that had been considered by Griffith and the RAE were all, like

[137] 99th ESC meeting, 31 Mar 1936, 1255, NA DSIR 22/61.
[138] 99th ESC meeting, 31 Mar 1936, 1255, NA DSIR 22/61.
[139] 99th ESC meeting, 31 Mar 1936, 1256, NA DSIR 22/61.
[140] 99th ESC meeting, 31 Mar 1936, 1256-7, NA DSIR 22/61.
[141] 99th ESC meeting, 31 Mar 1936, 1257, NA DSIR 22/61.
[142] 99th ESC meeting, 31 Mar 1936, 1257, NA DSIR 22/61.
[143] E.g. Golley (1996); Gunston (1997).
[144] And indeed, designs producing practical amounts of power were not developed before the late 1930s.

the industrial units, designed to drive a power shaft rather than to produce a propulsive jet. Finally, it ignores the fact that the technologies the Engine Sub-Committee was considering – improved superchargers and fuels – were capable of giving great performance improvements to existing piston engines, and as such had a utility beyond solely being progenitors of the gas turbine.

Indeed, the piston engine was itself not as monolithic a technology as comparisons with the jet engine would imply. Throughout 1936 and 1937, the committee discussed the development of various types of piston engines, using a number of different fuels, and employing a number of different engine cycles. The aircraft diesel engine was seen as a particularly promising type; although heavy, it had good fuel economy and promised reasonable power from low-octane fuels. The committee pressed for a joint research programme between the RAE and Harry Ricardo, with Tizard expressing the view that work was 'not worth doing on a small scale if the C.I. Engine[... was] to catch up with the petrol engine and if £100,000 could be well spent on the project in the next two years it would be worth spending.'[145] As late as summer 1938 – after decisions had been taken to fund a number of gas turbine projects – the ESC was considering the merits of using a free-piston gas generator to drive a power turbine.[146]

In order to discuss a potential diesel programme, Ricardo went to the RAE, where the issue of supercharger development was raised. Ricardo must have raised Metrovick's experience again, as reporting on the discussion to the Engine Sub-Committee, Pye 'stated that the position in regard to superchargers had been reviewed and arrangements made for Dr. Griffith and Mr. Constant to visit the works of the Metropolitan Vickers Company and discuss with them any of their supercharger proposals.'[147] Pye also gave further details for the proposed Brown Boveri- Rolls-Royce axial compressor, as well as for the other firms that were developing blowers. One of these was the British Thomson-Houston Company; Pye noted that 'no recent progress had been made although that firm was building a compressor for a client at Cambridge.'[148] The client was Power Jets, and the compressor was for Frank Whittle's first jet engine.

Discussing gas turbines

Both Pye and Tizard would have been aware of Whittle's work. The Air Ministry had signed an agreement with Power Jets permitting him, a serving RAF officer, to serve as the company's chief

[145] 101st ESC meeting, 16 Jun 1936, 1311, NA DSIR 22/62.
[146] 113th ESC meeting, 28 Jun 1938, 1566-7, NA DSIR 22/62.
[147] 102nd ESC meeting, 29 Sep 1936, 1325, DSIR 22/62.
[148] 102nd ESC meeting, 29 Sep 1936, 1326, NA DSIR 22/62.

engineer, had placed him on the special duty list, and continued to pay his salary. In addition, Tizard had been asked to give an opinion on the feasibility of Whittle's design, and had passed this on to the RAE.[149] Tizard clearly saw the gas turbine as a possible powerplant for the future; discussing the committee's Future in February 1937, he noted:

> The Sub-Committee would be of much more use if it took definite account of such problems as the provision of high powers and the possibilities of the internal combustion turbine and of jet propulsion. Scientific interest in the petrol engine was now concerned with (1) fuel, (2) lubricants, and (3) materials, but there it ended. Jet propulsion and the internal combustion turbine, however, offered a much bigger scope to Committee members. Further, in problems of this type it was necessary to envisage expenditure on a large scale if results were to be obtained in a short enough time to make them of competitive value.[150]

With regard to the ICT, by now the RAE's Constant had done some calculations that suggested an overall efficiency of 20% was achievable.[151] As Tizard put it, 'for certain duties [i.e. fighter interceptions] a high powered machine of 20 per cent. efficiency might be of more use than a lower powered machine of 30 per cent. efficiency'.[152] When the RAE staff presented their analysis of the Whittle scheme, they agreed that it seemed feasible, but that fuel consumption at sea level and 300 mph was almost four times that of a piston engine. Griffith explained that this was due to both losses resulting from the jet efflux's speed, and due to Whittle's assumption of a relatively low compressor efficiency of 65%; these factors would also give relatively poor take-off performance.[153] However, as the Deputy DSR, W.S. Farren, pointed out, Whittle had designed his engine with flight speeds of 400-500 mph and altitudes of up to 60,000 feet in mind. Tizard pointed out that at 400 mph and over, the plant's efficiency was 'impressive,' and Griffith agreed that if the take-off issue could be overcome, this was the case. Another point made was that the engine had the 'great advantage' of being able to run on diesel oil; a point which linked back to the previous discussions about fuel supply.[154]

The discussion then turned to the components of the Whittle scheme. Griffith estimated that the radial compressor's estimated efficiency might be improved by some 5%, but suggested that the

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[149] Nahum (2004), 28-37.
[150] 105th ESC meeting, 2 Feb 1937, 1403, NA DSIR 22/62.
[151] The note on the Whittle scheme coming as a result of Tizard's involvement with Power Jets.
[152] 105th ESC meeting, 2 Feb 1937, 1404, NA DSIR 22/62.
[153] 106th ESC meeting, 16 Mar 1937, 1413, NA DSIR 22/62.
[154] 106th ESC meeting, 16 Mar 1937, 1413, NA DSIR 22/62.

axial blower would 'fit in better, be lighter, and give a higher efficiency.'[155] He advised that recent experiments at the RAE had indicated that the start-up and stalling problems of axial compressors were less severe than previously anticipated.[156] Griffith also suggested that replacing the jet exhaust with a turbine to drive a propeller would give superior performance in every case except at the highest speed and altitude considered. Before moving on, Tizard stated that the Whittle scheme had great promise: it was simple to manufacture, and efficient at high speeds. Simplicity of manufacture was not an unimportant consideration; the expansion of engine production under the shadow schemes was stretching the aero-engine companies' management skills to the limits, and it was not clear whether there would be any experienced excess capacity to build gas turbines.[157]

When Hayne Constant presented his report on 'The Internal Combustion Turbine as a Powerplant for Aircraft' to the committee, his most important conclusion was that the ICT could give specific weight and economy as good as or better than contemporary piston engines, except at low altitudes. The design favoured by the RAE was rather complicated, with a two-stage turbocompressor used as a gas generator for a power turbine.[158] Though the assumed component efficiencies were quite high, Constant stated that his efficiencies were based on experimental results achieved by Rolls-Royce. The RAE had carried out preliminary experiments on combustion length (important for the overall size of the engine), and the Farnborough drawing office had done some preliminary layouts and weight estimates.[159]In these earliest discussions about the aircraft gas turbine, there is clearly a sense of the interpretative flexibility of the gas turbine.[160] For Frank Whittle, it was a powerplant that promised excellent aircraft performance at speeds and altitudes beyond anything achievable at the time. Its use of jet propulsion meant that it could use components of lower efficiency, but that the powerplant as a whole would only be efficient at high speeds. For the RAE staff, on the other hand, it was a device to replace the high-powered piston engine, giving much greater power at comparable fuel consumption. Toward this end they were willing to accept a more complicated design than Whittle.

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155 106th ESC meeting, 16 Mar 1937, 1414, NA DSIR 22/62.

156 At this time the RAE was building the test axial compressor 'Anne'; and had conducted wind tunnel tests on blade cascades.

157 See Ritchie (1997). As inexperienced companies would find out to their cost, the gas turbine's ease of production turned out to somewhat of a chimera, but at first sight it was certainly mechanically simpler than a piston engine. See also chapter 3 below.

158 106th ESC meeting, 16 Mar 1937, 1416, NA DSIR 22/62.

159 106th ESC meeting, 16 Mar 1937, 1416-7, NA DSIR 22/62.

160 In the sense used by Pinch and Bijker (1987)

Tizard's argued that there was 'a very strong case for the vigorous development of a device which should result in a very fast machine driven by a jet or a combination of jet and airscrew'. He suggested that the turbine schemes considered were superior to reciprocating engines in that they could use any type of fuel oil, and they promised to be easy to manufacture in quantity; again linking the gas turbine to previous worries about fuel supply and production, he suggested that there should be a 'concentration of effort and large scale manufacture' on these schemes.[161] Improvements in compressors were also needed for more conventional engines; even if the ICT came to naught, the development of better compressors would give the desired improvement, although Griffith warned that if development of the turbine was to go ahead, then one should not 'cramp' it by trying to satisfy petrol engine requirements.[162]

The RAE's estimate of the staff required for the development of a gas turbine meant that external partners would be needed, as the Establishment did not have the necessary resources. Griffith suggested that Metropolitan Vickers would be a good choice, as a steam turbine manufacturer would have useful knowledge and experience; the necessity for rapid development outweighed the security concerns of bringing in an external partner.[163] This arrangement would be similar to the already-existing one between Whittle's Power Jets and British Thomson-Houston. Metrovick's interest in gas turbines was underscored by Harry Ricardo, and the decision was made to approach the company's research department. Another factor in the approach was that the department might have creep data on potential high-temperature materials for the ICT, as the NPL did not have any.[164] Though there was some concern that Metrovick might not give a small-scale research project the full attention that it would need, Tizard suggested that 'the Air Force might want 2 million H.P. and this should be worth catering for'.[165] Whether this was communicated to potential partners is uncertain; none of the early correspondence with Metrovick mentioned production numbers, and as will be seen in chapter 2, the initial contracts only mentioned experimental work. Nonetheless, given the informal links between the ESC men and Metrovick staff such as Guy, it is quite possible that quiet words about potential production numbers were passed to the Manchester firm. No mention was made of the established aero-engine companies, which would suggest that the ESC saw the ICT as requiring turbine expertise more than aero-engine

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[161] 106th ESC meeting, 16 Mar 1937, 1417, NA DSIR 22/62.
[162] 106th ESC meeting, 16 Mar 1937, 1417, NA DSIR 22/62.
[163] 106th ESC meeting, 16 Mar 1937, 1418 NA DSIR 22/62. Partly because of the separation between experimental and theoretical departments, there were often delays in getting experimental equipment built in the Farnborough workshops.
[164] 106th ESC meeting, 16 Mar 1937, 1419-20, NA DSIR 22/62.
[165] 106th ESC meeting, 16 Mar 1937, 1418-9, NA DSIR 22/62.

experience.[166]

Tizard's summary of the discussion was that the committee should support a 'vigorous policy of development of the turbine and airscrew – with or without jet,' and that it should support the Whittle scheme to bring it to a successful conclusion. The committee agreed to recommend to the Air Ministry that it should assist the Whittle Scheme in order to evaluate its performance as quickly as possible, and that the RAE should be brought in to oversee the tests.[167] The ESC was soon given more detail on the Power Jets engine, which had had its first test run, although a number of teething troubles were being experienced. Negotiations were underway with Power Jets for the Air Ministry to provide funding to the project.[168] Hayne Constant also set out the RAE's proposed ICT development programme, and concluded that a low-efficiency ICT could be constructed 'immediately in the light of existing knowledge'; he suggested that such a turbine should be built to gain knowledge for a future high-efficiency turbine.[169] This low-risk ICT was to have a two-stage centrifugal compressor; concurrently, the axial compressor programme was to be continued with the aim of developing a higher-efficiency ICT compressor.[170] Metrovick had been approached about the turbine's development, and once the ICT's layout had been finalised RW Bailey planned to investigate suitable materials. Whilst MV was willing to undertake the manufacture of the ICT, the company would require the assistance of someone to oversee the scheme, and of a draughtsman or two. Tizard asked whether Metrovick was aware of 'the magnitude of the business' that might arise from their participation; the DDSR replied that the point had been made in the discussions.[171]

Alternatives

Yet for all the importance that the ESC clearly attached to the gas turbine, it was by no means their main concern at the time, or even the only novel technology being considered. In the same meeting where Tizard was pressing to ensure that MV understood the potential markets for the new technology, the committee had an extended discussion of bi-fuel systems and the possibilities for water injection for raising the power of conventional piston engines; a matter that

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[166] Though another factor may have been that the engine companies had their hands full with the expansion of their existing piston-engine production.

[167] 106th ESC meeting, 16 Mar 1937, 1421, NA DSIR 22/62.

[168] 106th ESC meeting, 16 Mar 1937, 1437-8, NA DSIR 22/62.

[169] A copy of this RAE report E.3550 'Programme of Research for the Development of the Internal Combustion Turbine' by Hayne Constant can be found in the Tizard archives, IWM HTT 204.

[170] Although the compressor programme was not solely directed toward the ICT; the report noted that the RAE had designed an axial compressor of a size suitable for a piston engines supercharger.

[171] 107th ESC meeting, 29 Jun 1937, 1444-5, NA DSIR 22/62.

was to be discussed at meetings up until the outbreak of war.[172] Nor were all the members of the committee particularly enthusiastic about the ICT's design. At the September 1937 meeting, the Admiralty representative, Engineer-Commander W.G. Cowland, raised some objections to the RAE scheme based on his naval steam turbine experience. In particular, he suggested that the losses due to leakage, bearing friction, and other unavoidable effects had been neglected. Cowland recommended that steam turbine designers should be brought in to advise on the project, but the DDSR pointed out that the RAE was collaborating with Metropolitan Vickers partly for that very reason, again underscoring the favourable way in which the Air Ministry viewed the company's turbine expertise.[173] Farren also pointed to the performance figures for Brown Boveri industrial gas turbines, which suggested that there were no fundamental difficulties with the concept. The committee's decision was to continue with the project; on the 13th December 1937 a team of Metrovick staff travelled down to the RAE to begin the detailed design discussions for their gas turbine.

With hindsight, many commentators have blamed the Air Ministry for tardiness in supporting the gas turbine, but although it had obvious potential – recognised by the experts at the Air Ministry and the RAE – it was equally obviously a longer-term project. The Air Ministry's attention was on the expansion of current production and the improvement of existing designs; for the medium term it was considering the development of more exotic piston engines such as Ricardo's 'sprint' two-stroke engine.[174] It is ahistorical to think of this concentration on piston engines as a sign of a resistant pre-jet mentality; in reality it was a pragmatic response to an environment in which a major conflict was imminent.[175] Equally, the Engine Sub-Committee did not lack imagination; they strongly supported the development of gas turbines, as well as other novel technologies. Even as the Power Jets and RAE/MV teams were working on their projects, the Engine Sub-Committee was examining hybrid turbine technologies such as turbines being driven by exotic free-piston gas generators.[176] Even if they were never developed, the fact that these alternatives were being more or less seriously considered clearly suggests that at the time the gas turbine was not seen as so overwhelmingly superior as to preclude other options.

[172] In the event, a reliable supply of 100 octane fuel meant that bi-fuel systems were not needed, although in the latter half of the war some engines were fitted with water injection for overload boost usage.
[173] 106th ESC meeting, 16 Mar 1937, 1453-7, NA DSIR 22/62.
[174] For more on which see Nahum (1997).
[175] For an elegant exposition of this point see Nahum (1997) and Nahum (2004), 173-177.
[176] See, for example, NA DSIR 22/62, Minutes of the 115th ESC Meeting, 15 Dec 1938, p. 1591-1604.

Conclusion

In the military-operational environment of the 1930s, high-speed aircraft were required for air defence, which in turn created a need for lightweight engines of great power. By the mid-1930s, changes to RAF operational requirements and the emergence of radar technology meant that high fuel consumption need not be an issue. The gas turbine was an attractive potential solution to this problem, as it promised higher power output from a lightweight engine. In addition, at a time when wartime high-octane fuel supplies were not guaranteed, its ability to use low-grade fuels was an advantage, as was its perceived ease of manufacture.

If the immediate spur for the RAE's gas turbine project was the Whittle scheme, the former was not merely a copy of the latter, but rather grew out of many years' research at Farnborough. In addition, it was a rather different project in conception, designed to drive a propeller, and using a more complicated layout and compressor design. Both Whittle and the RAE chose a steam turbine manufacturer to help them develop their design: In Whittle's case, he chose British Thomson-Houston, and the RAE chose to work with Metrovick.[177] In choosing to work with the Manchester firm, the RAE and Air Ministry were influenced by a number of factors. Metrovick was a company with a reputation for technical excellence in turbine design, and with a highly-regarded research department with expertise in high-temperature metallurgy. It had already been investigating gas turbine designs in-house, and it had the design expertise and resources to work with the RAE on a research project of this type. Metrovick was already a military supplier, and so would be familiar with the requirements of an Air Ministry contract. Above all, the company was linked into networks of influence such as the Royal Society and the IMechE, and through these to the Engine Sub-Committee and Air Ministry decision-makers; the firm also had some direct links to ESC members such as Harry Ricardo, who was a consulting engineer to Metrovick.

Of course there was a degree of contingency in the choice of partner: the pressures of rearmament were such that established engine companies had no spare capacity to devote to the development of speculative external projects, and although the RAE could design and build its own engine accessories, it did not have the resources to develop its own gas turbine. However, the expert consensus within the ARC's Engine Sub-Committee was that a turbine manufacturer of MV's reputation would be an eminently suitable partner for the RAE's ICT project. The collaboration would expose the different working styles of the research establishment and the

[177] Whittle had unsuccessfully tried to interest BTH in his jet designs in 1930; Aero-engine companies had been no more forthcoming. See Whittle (1953), 30; 38; 49. There is some irony in the different gas turbine projects choosing development partners who were rivals under the AEI holding company.

industrial heavy plant supplier, but for now, in the winter of 1937, the axial gas turbine project was underway.

Chapter 2: Proliferating Projects.

As discussed in chapter 1, by late 1937 the RAE had begun discussions with Metropolitan Vickers to start the design of a gas turbine. This chapter will examine the early collaborations between the RAE and Metrovick in more detail. It will look at the various designs that the collaboration produced – the 'B', 'C', and 'D' schemes – and the way in which the RAE's 1940 decision to design a jet propulsion unit affected these projects. It seeks to answer two questions: why did the number of schemes that the RAE and Metrovick were collaborating on expand, and to what extent was the slow progress of these designs compared to other gas turbine projects a result of the technical characteristics of the two development partners? In order to answer these questions, I will draw on Edward Constant's notions of technological communities and of technical style, and will apply these to Metrovick and the RAE respectively. I will show how the two development partners were members of distinct technical communities, and that the RAE's research orientation and Metrovick's steam turbine design expertise led them to adopt a particular style that militated against speedy development. In order to do so, I will first review Constant's schemas, and will then show how the RAE and Metrovick began to work together. I will examine the gas turbine designs developed in more detail, and will show how the technical style of the two partners affected both the designs and their progress.

Communities and style

As noted in Chapter 1, part of the gas turbine's appeal was its supposed simplicity and ease of manufacture. Yet given that the ultimate goal of the RAE-Metrovick collaboration was an aircraft engine, progress in producing even a proof-of-concept test rig was slow; the time from initial design to first run of the B.10 test rig was almost three years, and this was for a design whose scope had been much reduced from the initial conceptions (a rough benchmark for a piston engine was between three and four years from design to series production). Although early discussion of the gas turbine had emphasised the production benefits of the engine, the RAE do not seem to have thought about actual aircraft powerplants, apart from in the abstract.[1] The RAE had brought in Metrovick as an industrial partner to help with development, but the Farnborough staff still treated the designs as one-off research units; actual aircraft engines were for the somewhat nebulous future. In turn, Metrovick's attitude to engineering development was shaped by the company's heavy plant experience, and this affected the company's approach to building an aero-engine. Of course, the fact that a heavy plant manufacturer's working practices were

[1] As noted in Chapter 1 above, the gas turbine's supposed ease of production had been a point in its favour during the Engine Sub-Committee discussions.

different from those of an aero-engine company should not be surprising; however, an analysis of the differing environments and communities in which they operated provides explanations for the particular ways in which they differed.

As noted in the introduction, this thesis uses Edward Constant's analysis of 'communities of technological practitioners', which argues that these are 'the primary locus of what is called technological progress'.[2] These communities are defined by, and are 'tautological with' common traditions of practice, which comprise 'complex information physically embodied in the community, and the hardware and software of which they are masters.'[3] This knowledge is inculcated by the training, education, and professional standards present in the community, as well as a certain amount of 'learning by doing.' However, like Thomas Hughes's notion of a technological system, much of the power of the idea of a technological community comes from its precise application – the analytical value of the concept is lost if it is so large as to encompass everyone, or so small that it does not allow for comparison.[4] Clearly, also, individuals may be members of multiple communities at different levels; it is indeed at these boundaries that differences between groups can become apparent.

The two major communities represented in the RAE-Metrovick collaboration were the aeronautical community and the mechanical engineering community – more specifically, research engineers working in aerodynamics and on internal combustion engines, and steam turbine engineers. Both groups had institutional links to other technical communities; in the case of the RAE, these links were to aero-engine manufacturers, as well as to the community of military users. In the case of Metrovick, the links were with electrical engineers, as well as with the sub-specialities required for turbine design, such as specialists in ball-bearings, alloy forgings, and power measurement. Though, as noted previously, disciplinary allegiances are not necessarily indicators of membership of a particular technical community, in the case of the RAE-MV collaboration the professional identities of the two communities were distinct; the Metrovick staff were mainly members of the Institution of Mechanical Engineers, whereas the RAE staff were members of the Royal Aeronautical Society.[5]

Another important technical community involved in the internal combustion turbine programme was that of metallurgists. The ICT would require sustained high-temperature operation; although the service life of an engine was only envisaged as being some 300 hours, the centrifugal forces

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2 Constant (1984), 28.
3 Constant (1980)
4 Hughes (1983) sets out his ideas on large technical systems in detail.
5 I owe this point to Nick Forder.

on the turbine wheel would lead to creep deformation of the blades and eventual failure.[6] As a major application for creep-resistant alloys was steam plant, it was unsurprising that Metrovick should be familiar with the field. Indeed, as noted in chapter 1, RW Bailey's section in the research department was mainly interested in high-temperature metallurgy. Both Bailey and the RAE's chief metallurgist were participants in the earliest meetings between Metrovick and the Farnborough staff, where turbine materials were an important subject of discussion. Bailey was able to make good use of his links with other metallurgists; he was the first point of contact within Metrovick for people such as WH Hatfield of Vickers-Firth or D.A. Hansard at High Duty Alloys. Hatfield's fellowship of the Royal Society provided another link to MV via his fellow FRS Henry Guy. During the various delays and troubles encountered in producing forgings for the experimental gas turbines, a quick phone call or a note to a personal contact was a valuable channel to urge completion of an order, or simply to get an update direct from the forge. As shown in the previous chapter, this metallurgical expertise was crucial in the selection of Metrovick as a development partner.

The concept of technological 'style' (somewhat analogous to the namesake notion in art history) can be useful in describing local differences in approach by members of the same community (at least at higher levels of analysis). Styles can be national, in response to different political-economic contexts; examples might be electrical power systems, or even the differing approaches to engineering drawing and blueprinting.[7] Yet even at lower levels of the technological hierarchy, within what might be considered a single technological community, distinct local styles can often be identified. As Constant describes it, 'identity does not imply homogeneity of practice, only a well-winnowed tradition which grossly matches the relevant environment'.[8] Local styles at (say) the company level can develop by 'fine tracking' within the environment; different engineers will have differing appreciations of the worth of particular performance parameters, and so will make slightly different design choices. Over time, these divergences will lead to the emergence of distinct and recognisable local styles.[9] I will return to this point later, but first I will consider how the collaboration between Metrovick and the RAE got underway.

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[6] The figure of 300 hours had been used in the ESC's discussions of engine life, and was also mentioned in Smith's notes for his meetings with the RAE staff on 8 Mar 38, MOSI 1996.3235/1/1

[7] For electrical systems, see Hughes (1983); for engineering drawing, see Brown (2000).

[8] Constant (1984), 38.

[9] Constant gives an example from the US auto industry: Compared to Chevrolet's engines, Ford's V-8 engines were heavier, less fuel efficient, had lower specific output, and ran at lower RPM. They were also nigh-indestructible. Once a company style arises, positive feedback in hiring and training will tend to reinforce it. Even if the initial differences were purely stochastic, one would still expect to see the rise of distinct styles because of this feedback mechanism.

Approaching Metrovick

At the same time as Hayne Constant was presenting the RAE's proposed ICT research programme to the ARC's Engine Sub-committee, Andrew Swan, head of the RAE's Engine Department, was asking Griffith to draw up estimates for the numbers of staff needed to carry it out, and for information on 'the position regarding manufacture and any necessary co-operation with outside firms.'[10] Swan also requested a note for the DSR on the ICT's high-temperature material requirements. The RAE first formally approached Metrovick in conjunction with this request, with the RAE's Superintendent of Scientific Research contacting RW Bailey of MV's research department. He noted Bailey's considerable experience in the field of high-temperature creep behaviour, and asked whether a meeting could be arranged with the RAE's staff to discuss 'this and other matters.'[11] Bailey agreed and arranged to visit Farnborough on April 2, where he discussed both high-temperature metallurgy and more general turbine issues.[12]

In April 1937, at one of the RAE's regular engine conferences, Constant presented his planned programme for the development of the gas turbine, and the RAE's chief metallurgist discussed the materials research required.[13] The programme was based on the manufacture of a simple gas turbine of medium efficiency, as Constant felt that it was important to gain experience of development and test running quickly.[14] The minutes of the conference note that the decision was taken for the engine department to start on the general design of an ICT; once the design was sufficiently advanced, the question of manufacture would be investigated. With their specialised welding experience, Metrovick seemed to be the best people to tackle the problem; the RAE's chief superintendent told the conference that Metrovick had been informed of the project, and that the firm was willing to accept a development contract.[15] The next day the head of the engine department sent a memo authorising the drawing office to start work on the general design, and noted that Metropolitan Vickers would be receiving a development contract once a suitable stage

[10] Memo A Swan to AA Griffith, 19 March 1937, NA AVIA 13/1408

[11] Letter from RS Capon to RW Bailey, 23rd March 1937, NA AVIA 13/1408. Capon was the RAE's Superintendent of Scientific Research; the letter was signed on behalf of the RAE's Chief Superintendent, even though it was presumably drafted by one of the Engine Department. RAE policy seems to have been to send letters out under the authority of the superintendent or director.

[12] Letter from RW Bailey to RS Capon, 1 April 1937, NA AVIA 13/1408; Letter from HL Stevens to Metropolitan Vickers, 14 May 1937, NA AVIA 13/1408

[13] H. Constant, RAE Note E.3550, 'Programme of research for the development of the Internal Combustion Turbine,' April 1937, NA AVIA 13/1408; H. Sutton, RAE note M.4758, 'Note on materials for Internal Combustion Turbine,' 12 April 1937, NA AVIA 13/1408. The engine conferences were regular events held to discuss all the engine work being carried out at Farnborough.

[14] H. Constant, RAE Note E.3550, 'Programme of research for the development of the Internal Combustion Turbine,' April 1937, NA AVIA 13/1408.

[15] 'Extract from minutes of engine conference held at R.A.E., 12th April, 1937,' NA AVIA 13/1408

had been reached.[16] The RAE's Chief Superintendent (AH Hall) gave the Air Ministry the Farnborough staffing estimates for the ICT in late April, stating that an extra four senior drawing office staff would be required for the design of the ICT and its test equipment. These extra staff had not been discussed with the Treasury representatives who had visited Farnborough in February, but Hall suggested that they be assigned directly to the Engine Department; with a phrase no doubt born of years of civil service experience, he noted smoothly that this was 'not to set a precedent or be extended', and that he proposed to review the arrangement in a year's time.[17]

In late May the DSR informed Farnborough that the ARC had endorsed its sub-committee's recommendation: 'The Air Ministry should take up the question of the development of the internal combustion turbine as a matter of urgency and make all possible arrangements for its production at the earliest possible moment. The Sub-Committee consider that this will probably require the co-operation of turbine builders and recommend that the possibilities in this direction should be explored without delay.'[18] A comment on the letter noted that no formal Air Ministry approval had been received as yet; beneath it Swan pencilled the laconic aside: 'Acknowledge receipt. This can be taken as approval I suppose.' A fortnight later, Farnborough's Chief Superintendent replied to the Air Ministry, asking them to open an account for the project, and suggested that a token allotment of £1,000 be made 'in the first instance.'[19] Meanwhile, the RAE had taken further steps towards co-operation with turbine builders, and had visited Metrovick. On June 3rd, Griffith, Constant, and Dr. Sutton, head of the RAE's metallurgy department, visited the Trafford Park works, along with the Air Ministry Deputy DSR, W.S. Farren. They were met by Baumann, RW Bailey, and other technical staff, to discuss how Metrovick might be able to assist the RAE.[20] The company's expertise in working high-temperature steels was noted, but the Metrovick staff noted the difficulties of taking on large amounts of work, due to their existing commitments.[21] Metrovick were not the only firm to be approached by the RAE; Griffith and Constant visited the works of the Fraser & Chalmers company (a GEC subsidiary) to investigate their facilities. The Farnborough men judged that the firm seemed to be more advanced than

[16] "Extract from Mr. Swan's note of 13th April 1937 to sections," NA AVIA 13/1408. April 13th is also the date that WR Hawthorne (who worked on gas turbines at the RAE during the Second World War) gives for the start of drawing office work on the ICT, although he does not give sources; see Hawthorne (1991).
[17] Letter from AH Hall to DSR, Air Ministry, 29 April 1937, NA AVIA 13/1408
[18] Letter from WS Farren (DDSR, Air Ministry) to Chief Superintendent, RAE, 25 May 1937, NA AVIA 13/1408
[19] Letter from AH Hall to Secretary, Air Ministry, 17 June 1937, NA AVIA 13/1408
[20] The Metropolitan Vickers correspondence file does not have a record of this meeting, as it starts in December 1937, but the RAE file contains a brief report giving the names of some of those present. See "Conference at Metropolitan-Vickers", n.d., NA AVIA 13/1408
[21] "Conference at Metropolitan-Vickers", n.d., NA AVIA 13/1408. The Metrovick representatives did not elaborate on whether the existing commitments were for military orders or for general production.

Metrovick in aerodynamics, but 'not so far ahead on materials.'[22] In light of these considerations, the RAE decided that Fraser & Chalmers should concentrate on axial flow compressors.[23] Supporting comments made later by Constant, this suggested that the RAE team were more worried about the mechanical and material problems of the gas turbines than the aerodynamic.[24] What is interesting about this concern is that it complicates the picture of the RAE staff as theoreticians only concerned with ideal efficiencies and ignoring practicalities; with regard to building a complete gas turbine plant, issues of mechanical design and materials science were clearly important factors in their thinking.[25] Swan also asked Constant to keep in touch with Frank Whittle's work at BTH, and asked him to provide a list of the test data that was to be supplied to the RAE and Air Ministry by Whittle.[26] The RAE preferred to give manufacturing contracts for items that could not be manufactured by their own workshops, or to supervise work at other locations; the Metrovick work was unusual in that the company was being approached as a development partner due to its in-house expertise. This suggests a number of things: that the RAE were aware of the development issues that would arise in the manufacture of a complete gas turbine, in that it was not enough to hand over a design to a manufacturing contractor, and that the Establishment had a good opinion of the Manchester firm's engineering competence, and especially their metallurgy and materials expertise.

By the autumn of 1937 the RAE had definitively settled on MV as their gas turbine design and development partner, although there were some problems with the financial arrangements; the Air Ministry's Finance Department objected strongly to the use of 'time and lime' (i.e. cost-plus) payments.[27] However, as the DDSR wrote soothingly to the RAE, these problems would be overcome 'with patience on both sides.'[28] By mid-November, the RAE had a number of schemes that it was proposing to take to Manchester and show to Metrovick.[29] Progress had also been made in a financial sense; £828 of the RAE's original £1,000 project allocation had been spent,

[22] "Notes on discussion with Messrs. Fraser and Chalmers Ltd., on internal combustion turbine", n.d. (but presumably late July 1937), NA AVIA 13/1408

[23] Fraser & Chalmers went on to manufacture the research compressor 'Ruth' to an RAE design in 1939.At about the same time the RAE placed an order with C.A. Parsons for the research compressor 'Alice,' which also ran in 1939.

[24] Constant (1945), 418.

[25] This criticism is often aimed particularly at Griffth and his contraflow schemes; see the discussion of Scheme C below.

[26] Swan to Constant, 10 Jun 1937, NA AVIA 13/1408.

[27] Quite why this was unacceptable is unclear, as most if not all Ministry development contracts were issued on a cost-plus basis.

[28] Letter from WS Farren to Chief Superintendent, RAE, 25 October 1937, NA AVIA 13/1408. Eventually the Finance Department must have been vanquished, as later contracts were (at least in part) cost-plus.

[29] Letter from AA Griffith to Secretary, Air Ministry, 18 November 1937, NA AVIA 13/1408

and AH Hall asked the Air Ministry for another £2,500 be allocated to the project account for the rest of the financial year.[30]

The requisite patience was presumably shown by both sides; by late February 1938 the Air Ministry's financial controllers had overcome their distaste for cost-plus contracts, and had issued Metropolitan Vickers with a 'Schedule for designing, constructing and supplying an Internal Combustion Turbine Aero-Engine'. The terms of the agreement were that the Air Ministry would bear the actual cost of work done by the company up to a limit of £10,000, and would pay the company a management fee of £2,000, with another £2,000 to be paid if the contract extended for more than one year.[31] Though the contract title suggested that the Air Ministry (or at least its finance department) expected to receive an aero-engine, the RAE had already decided that the gas turbine would be a testbed, rather than an aircraft engine; in any event, the authorised sum was unrealistically low for the development of a working engine, even if (as revealed in the ESC's discussions) it was hoped that the gas turbine would be cheaper and easier to manufacture than piston engines.

Meanwhile, even before the gory financial details were settled, the collaboration continued. The first major technical meeting between Metrovick and the RAE was held in December 1937, where the Farnborough staff laid out the three main gas turbine schemes that they wanted to consider. All consisted of gas generators to power a separate power turbine; scheme 'A' was to use radial compressors[32]; scheme 'B' used axial compressors; and scheme 'C' consisted of a contraflow axial compressor.[33] The RAE representatives noted that axial compressor performance was still uncertain, but said that they had built a small axial compressor that they planned to test in the New Year. This was the compressor 'Anne,' which had been designed by Constant on his return to the RAE from Imperial in 1936. With 8 compressor stages running at over 20,000 RPM, the RAE team hoped to achieve a pressure ratio of 4. They also noted that they had information on a Swiss gas turbine, which the Brown Boveri company had designed in conjunction with Jakob Ackeret, Professor of Aerodynamics at the Swiss Federal Technical University in Zurich. The RAE had ordered one for evaluation purposes; its testing at the Brown Boveri works had been viewed by the RAE's staff, and it would be re-tested at Farnborough once delivered.[34] They considered its

[30] Letter from AH Hall to Secretary, Air Ministry, 12 November 1937
[31] 'Schedule for designing…', 21 February 1938, NA AVIA 13/1408
[32] Although the notes made by the MV Mechanical Engineering representative suggest that a mixed axial-radial compressor was being considered; see the sketch in DM Smith, 'Report on Conference with RAE Engineers,' 16 December 1937, MOSI 1996.3235/1/1
[33] In which the turbine and compressor rings were concentric on a single drum; due to its theoretical advantages (see below) this was a favourite design of Griffith's.
[34] Among the staff that visited Switzerland were Constant and AD Baxter; see Baxter (1988).

efficiency ‘disappointingly low’, but claimed there were ‘several interesting design features about the machine, not least the extensive use of welding.’[35] With these preliminaries out of the way, the partners were ready to begin work on their own designs.

Mechanics of collaboration

As noted above, the collaboration with Metrovick departed from usual Air Ministry practice insofar as it was a partnership between the company and the RAE. The RAE had not designed engines since the First World War; their relationships with engine manufacturers consisted mainly of one-off assistance with their problems, and with the testing of proposed service engines for the Air Ministry’s Directorate of Technical Development. Where the RAE did design engine accessories (such as boost controllers, carburettors, and the like) they were handed over to specialist manufacturers for production as a finished design. This was generally also the case where experimental equipment had to be manufactured elsewhere, with the external contractor being treated as an extension of the Farnborough workshops.[36]

In the gas turbine case, the relationship was far more collaborative; although the RAE staff had drawn up some preliminary designs, based on their aerodynamic theories, they realised that these would require a great deal of development, which would require facilities beyond those available at Farnborough. They also hoped to benefit from Metrovick’s experience in turbine design. As a result, design work was shared between the RAE and Metrovick; the initial design RAE design was checked and re-calculated by Smith’s team, and then the design was iterated at Metrovick, with input from (and some double-checking of the calculations by) the RAE. In order to assist with the initial transfer of the designs, two RAE staff were seconded to the MV works; they were MAA Allfrey, an RAE Scientific Officer who had been taking over detail design work on the schemes from Constant, and LT Whitehead, the designer-draughtsman responsible for most of the stress calculations on the schemes.[37] They were to lead the MV staff through all the calculations which the RAE had performed relating to cycle efficiencies and stresses, and arrived at Trafford Park in January 1938. Allfrey left Trafford Park in late June 1938, and Whitehead returned to Farnborough a few weeks later.

As Harry Collins has shown, this kind of personal contact can be needed to transfer techniques even within what is ostensibly a single community, but the interactions between the RAE and

[35] DM Smith, ‘Report on Conference with RAE Engineers,’ 16 December 1937, MOSI 1996.3235/1/1
[36] Such as was the case with the compressors ‘Ruth’ and ‘Alice’; although some of the mechanical details were left to the contractors, the aerodynamic design was all the RAE’s.
[37] DM Smith, ‘Report on Conference with RAE Engineers,’ 16 December 1937, MOSI 1996.3235/1/1

Metrovick show how their different communities approached the same technical problem.[38] One of the subjects common to both the RAE and Metrovick was the fluid dynamics of the gas turbine, but the differences in their approaches to the subject were the result of their parent communities. The turbine engineer's approach to axial turbomachinery was to treat each stage as a series of passages through which the flow would accelerate; the aerodynamicist's approach, pioneered by Griffith and used by the RAE, was to treat each stage as a blade cascade (essentially rows of blades arranged like a Venetian blind) and to work out flow deflection angles and pressure rises on this basis. In practice, at least for turbines, the working methods do not seem to have been that different – certainly the collaborators were able to follow one another's calculations without too much difficulty. For instance, details such as calculated blade angles generally matched closely between the RAE and Metrovick, whatever the method used. Where there was disagreement between the partners, it mainly arose from differing assumptions, for instance discussions over what kind of piping losses to expect (as discussed for the 'B' scheme below), or in which – essentially arbitrary – reference pressure should be used for calculating pressure coefficients.

Metrovick seem to have generally adopted the RAE's methods for compressor design, and treated Constant and the engine department staff as the experts. For instance, when Smith found that he was not getting the same values for blade lift coefficients as the RAE, he asked Farnborough for clarification, giving the formula he had been using.[39] Their reply was that the method Smith had previously been given was not applicable to the new highly-cambered blades that were under consideration, and that Constant would be sending an 'applicable method' shortly.[40] Similarly, when some of the company's staff developed an analysis of the flow through cascades, they sent it to Farnborough for checking and approval.

This was unsurprising, as the RAE were the acknowledged experts in the field, but there is other evidence to suggest that the Metrovick mechanical engineers – even ones working on fluid problems such as turbines – were less familiar with aerodynamic conventions than might be expected. For instance, in a report on one of the Metrovick visits to Farnborough there is a reference to the Reynolds number (a ratio of the inertial to viscous forces in a flow) in the typescript. In Smith's hand there is a marginal note giving the formula for this quantity, which would suggest that it was not immediately familiar to him, whereas it was standard knowledge

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[38] Collins (1985) gives a personal account of the work required to get a laser experiment to work using the description from another physics department; in some sense of course one might consider these to be separate communities of 'laser-using' and 'non-laser-using' physicists.
[39] DM Smith to RAE, 4 Jul 1938, MOSI 1996.3235/1/1
[40] RAE to MV, 12 Jul 1938, MOSI 1996.3235/1/1

among the aeronautical engineers.[41] In other cases mechanical engineering practice prevailed, such as in the display of compressor characteristics. Workers at the RAE had developed methods of dimensional analysis applicable to compressors in the early 1930s, which could be used to compare data from scale models to the full-size case. Yet similar methods do not seem to have been widely used in mechanical engineering; when the National Physical Laboratory aerodynamicist Arthur Fage read a paper on 'aerodynamical research and hydraulic practice' to the IMechE in 1935, much of the discussion suggested that though ingenious, the methods did not have much to offer working engineers.[42] Metrovick's reports presented test data in the dimensional form, though generally corrected to standard atmospheric pressure. Some of the problems encountered during the collaboration, however, were not merely due to the communication difficulties between different technical communities, such as unfamiliarity with particular methods or symbology, but were due to the particular technical styles of the parties involved. I will now give an overview of the gas turbine schemes developed during the early collaboration, and how they were affected by local technical styles.

Designs

As mentioned previously, the RAE's initial proposals consisted of three gas turbine schemes, 'A', 'B', and 'C.' Scheme A was quickly abandoned, as the RAE staff did not now think that it would achieve sufficiently high efficiencies with its centrifugal compressors. The other two schemes were thought more promising, with the RAE staff expressing their preference for the contraflow 'C' design from an aerodynamic point of view. As each of the contraflow gas turbine's rotors rotated independently on the shaft, the various stages could run at their optimum speed, allowing for theoretically better matching of turbine and compressor stages, giving easier starting and promising higher operating efficiency. However, the RAE team appreciated that the contraflow turbine would involve serious mechanical and constructional difficulties. These included differential expansion of the rotors (each containing a cold compressor section and a hot turbine section), and the problems of providing an airtight gas seal between adjacent rotors. As a result, the partners decided that Metrovick's initial efforts should be concentrated on the 'B' scheme, but that the company should also do some experimental work on the contraflow type to see if the 'mechanical objections' could be overcome.[43]

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[41] DM Smith, 1 Jul 1938, MOSI 1996.3235/1/1 It is unclear what degree of training in hydro- or aerodynamics Smith had received; he had started work in the mechanical engineering department on winding gear for mines. Nick Forder, personal communication, 7 Jul 2012. As the collaboration continued, the MV staff adopted aerodynamic methods; see eg. DM Smith's letter of 1 Jan 1941, MOSI 1996.3235/1/4.

[42] Fage (1935)

[43] DM Smith, 'Report on Conference with RAE Engineers,' 16 December 1937, MOSI 1996.3235/1/1.

Scheme B

The proposed gas turbine was to have an overall compression ratio of 5 to 1; as it was known that the off-peak performance of a single compressor deteriorated as its pressure ratio was increased, the RAE staff suggested that it might be better to have two axial compressors in series. The first gas turbine was to be purely experimental, and 'it would never be put into an aeroplane'.[44] The partners did not consider it worthwhile to test the turbines separately (with high-temperature steam), but planned rather to test the plant as a whole. They argued that vibration (and thus the forces on the unit) would be dependent on the load on the compressor and turbine when running as a complete plant.[45]

By the next progress meeting in early February, the Farnborough staff seconded to MV had led Smith and his colleagues through the RAE's design calculations and had settled in. The Metrovick staff had been concentrating on the design of the turbines; as well as this being their particular area of expertise, the RAE had not yet tested its experimental compressor or the ordered Brown Boveri ICT.[46] The experimental compressor 'Anne' had been under construction since mid-1936, but due to delays in the Farnborough workshops had not been completed until late February 1938.[47] Unfortunately for the RAE's researchers, a bearing failure on its first run caused it to strip its blading, and it was not rebuilt and producing useful data until October 1938.[48] This meant the MV team had limited practical information to go on; the Farnborough staff hoped to achieve efficiencies of 85-90%, but admitted that this figure was only a guess.[49] The RAE team also reported some results from their latest centrifugal compressors, stating that they were keeping the type in mind 'in case the axial flow compressor should prove unsuccessful.'[50] Although they had no experience with multi-stage centrifugal compressors, Farnborough's single-stage designs had achieved efficiencies of 75-80%, and the RAE staff hoped to be able to improve on that.

In the meantime the partners were reliant on blade cascade wind tunnel tests for their compressor design data. Cascades had been a characteristic part of the RAE's approach to axial compressor design from Griffith's earliest researches. In a ring of compressor blades, each blade had two neighbours, and acted like one of the middle blades in a cascade (at least to a first

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Confusingly, the project was given the internal Metrovicks designation of 'Turbo Compressor "A".'

[44] DM Smith, 'Report on Conference with RAE Engineers,' 16 December 1937, MOSI 1996.3235/1/1

[45] DM Smith, 'Report on Conference with RAE Engineers,' 16 December 1937, MOSI 1996.3235/1/1

[46] Although Griffith at least had visited the Brown Boveri works in 1938, the gas turbine was not to be delivered to Farnborough until November 1939

[47] Most of the RAE's early compressor projects were given women's names: Anne, Alice, Betty, Doris, Ruth, Freda, and Sarah.

[48] Constant (1945), 411-414; Roxbee Cox (1946), 18.

[49] DM Smith, 'Report on Conference – 1st February 1938,' 3 February 1938, MOSI 1996.3235/1/1

[50] DM Smith, 'Report on Conference – 1st February 1938,' 3 February 1938, MOSI 1996.3235/1/1

approximation). By measuring the actual flow deflections created by the cascade, empirical correction factors could be discovered for the calculation of pressure changes across compressor stages. This was in contrast to German compressor practice, where a tradition of mathematical aerodynamics led to the use of sophisticated streamline design methods, and the USA, where the National Advisory Committee on Aeronautics' wealth of aerofoil experimental data led to the use of individual blade design methods.[51] Following the RAE's approach, Metrovick began construction of their own cascade tunnel.[52]

The RAE staff did note that information from 'other sources' would become available in the course of time – presumably via their contacts at Brown Boveri – and that they would pass on any relevant information to Metrovick.[53] Constant visited Switzerland in the summer of 1938, and returned with some rules of thumb for compressor design. These suggested that flow breakaway from the compressor drum would happen if the lift coefficient at the blade roots was too high. As this was a three-dimensional effect, it would not show up in blade cascade tests; another case where the RAE's lack of test data from completed compressors was a drawback.[54] Unfortunately this information also had the effect of increasing the RAE's caution with regard to the compressor design, and they recommended an increase in the number of compressor stages (and thus in compressor weight) to lower the blade lift coefficients. [55] In the absence of any comparative data, it was hard to tell how accurate some of the Swiss advice was; the recommendation that axial blade clearances should be greater than a third of the blade width was later shown to be unnecessary, decreasing compressor performance.[56]

In the absence of compressor test data, Constant agreed that the Metrovick team should initially concentrate on their turbine calculations. [57] He had been doing performance analyses of the plant under varying speed and atmospheric conditions, but this was 'very involved work'. Constant had been investigating the effect of dual turbo-compressors, and suspected that independent compressors would have better average compressor efficiency under varying load and running conditions. As these loads were typical of those which would be encountered in an aircraft plant,

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[51] For more on this argument, see Nichelson (1988); the German tradition of mathematical physics – *'technische Mechanik'* is examined by Bloor (2011).
[52] See Todd (1945).
[53] DM Smith, 'Report on Conference – 1st February 1938,' 3 February 1938, MOSI 1996.3235/1/1
[54] DM Smith, 'Discussion at Farnborough 29th June, 1938,' 1 July 1938, MOSI 1996.3235/1/1. As noted above, this information was used to redesign 'Anne' after the first failure.
[55] DM Smith, 'Discussion at Farnborough 29th June, 1938,' 1 July 1938, MOSI 1996.3235/1/1
[56] See the comments in Constant (1945), 412.
[57] DM Smith, 'Report on Conference – 1st February 1938,' 3 February 1938, MOSI 1996.3235/1/1

he supported the choice of a multi-compressor scheme. [58] The Metrovick staff had been examining sample blade sections for the turbine wheel, and that that they were laying out configurations that would shortly be manufactured and tested in the company's wind tunnel.[59]

Over the next few months, the Metrovick team laid out a number of plant schemes, with varying types of turbines and layouts (see Table 2.1 below). At the same time, the company's Mechanical Department was investigating the manufacturing methods required for the production of gas turbines. The Mechanical Department's Superintendent (MV's senior production engineer) reported that the blades would require more accurate machining than was possible with the machine tools currently installed at Trafford Park, and so he would have to acquire new plant to manufacture blades and other parts to the required tolerances.[60]

Table 2.1 – Turbine schemes considered by MV up to August 1938[61]

Scheme A		Arrangements involving centrifugal compressors
Scheme B		Arrangements involving axial compressors
Scheme C		Arrangements involving contraflow compressors with independent wheels
B.1		3 reaction turbines, 2 compressors, L.P. turbine driving airscrew
B.2	Feb 1938	3 reaction turbines, 2 compressors, H.P. turbine driving airscrew
B.3	Feb 1938	1 impulse + 2 reaction turbines, 2 compressors, H.P. turbine driving airscrew
B.4		2 reaction turbines, 1 compressor, H.P. turbine driving airscrew
B.5	Mar 1938	1 turbine (impulse wheel + reaction stage), 1 compressor
B.6		As B.5 but with higher upper temperature limit
B.6a		As B.6 but with larger heat drop in impulse wheel
B.7		As B.5 but with lower pressure ratio

[58] DM Smith, 'Report on Conference – 1st February 1938,' 3 February 1938, MOSI 1996.3235/1/1
[59] DM Smith, 'Report on Conference – 1st February 1938,' 3 February 1938, MOSI 1996.3235/1/1. MV's existing tunnel was used mainly to test steam turbine blade profiles.
[60] DM Smith, 'Report on Conference – 1st February 1938,' 3 February 1938, MOSI 1996.3235/1/1
[61] Data largely from HG Rhoden's 'Appendix – List of Schemes' (n.d., but c. 3 September 1938), MOSI 1996.3235/1/1

B.8	Jul 1938	Turbocompressor test unit; turbine to same dimensions as I.P. of scheme of B.2 (4-stage reaction), special 6-stage compressor, single combustion chamber
B.9		Turbocompressor test unit; turbine as B.8, special 9-stage compressor, twin combustion chambers
B.10	Aug 1938	Turbocompressor test unit; turbine as B.8, redesigned 9-stage compressor, single combustion chamber

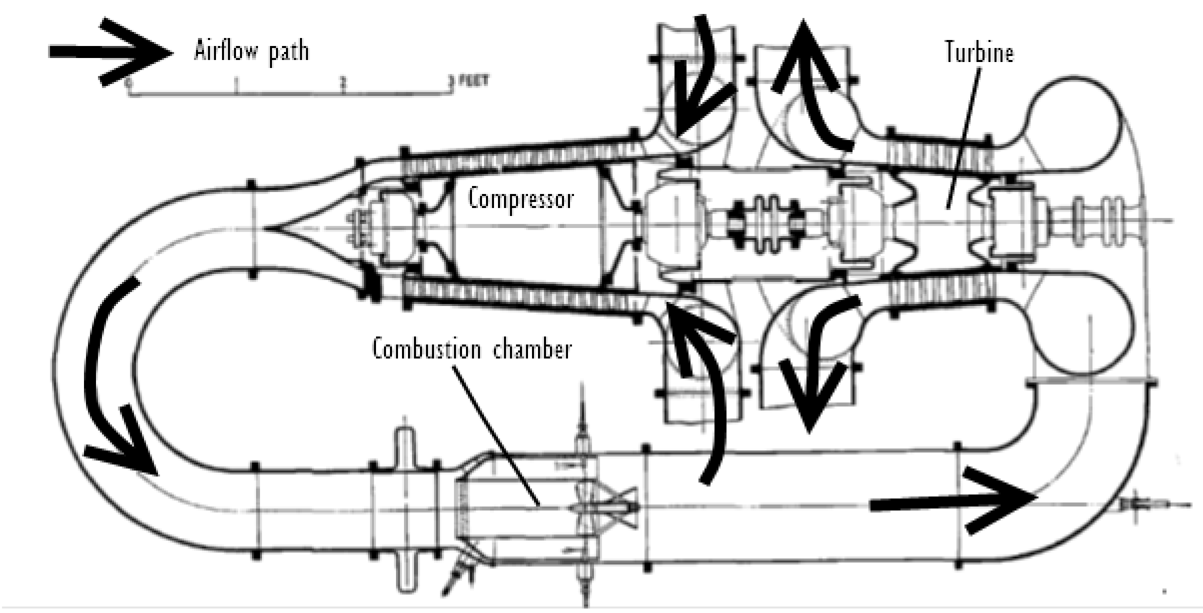

Figure 2.1 - General arrangement of B.10[62]

By late February 1938 Smith had completed a set of cycle calculations for the B.2 scheme, and estimated that it would have a thermal efficiency of 12.85%, giving a power output of some 1200HP.[63] However, it was clear that the turbine's operating conditions would be outside normal experience: the response Smith obtained from ball-bearing manufacturers was that the combination of operating speeds and temperatures, combined with the loads on the bearings, was unprecedented, and the bearing companies could not guarantee that any of their existing products would be suitable.[64]

As the design process went on, it became clear that the Farnborough staff and the turbine engineers had made different assumptions in their calculations. Some of these were down to

[62] Adapted from Smith (1947)
[63] DM Smith, 'Scheme B2: (IV): Overall cycle performance,' 23 February 1938, MOSI 1996.3235/1/1
[64] See eg. Letter from Hoffman to Metrovick, 28 February 1938, MOSI

simple misunderstandings – such as whether efficiencies quoted were for overall sections or for individual components – but there were more serious disagreements over the pressure drops to be expected in the plant pipework, with the RAE's estimated losses far lower than Metrovick's.[65] This was again due to differing technical culture; bend and piping pressure loss calculations were part of everyday steam turbine practice, but were less common in the design of aero-engines.[66] Both parties agreed that multiple smaller compressors in series were more aerodynamically efficient; the smaller number of stages in each compressor meant that each stage ran at a speed closer to its optimum. However, Metrovick favoured mechanically simpler schemes than the RAE, arguing that the lower piping losses incurred in a single-compressor scheme would offset the lower compressor efficiency.[67] Based on their axial compressor experience, the RAE staff questioned whether it would be possible to design a single compressor for a pressure ratio of and still retain suitable operating characteristics. However, they indicated that they were willing to try a single compressor with a pressure ratio of 4 if the lower piping losses would give the same overall performance. [68]

Perhaps because Griffith and Constant were realising how long it would take to manufacture the complete test plant, in March they asked Metrovick to manufacture an experimental reaction turbine to be tested with high-temperature steam. This was in order to gain manufacturing experience and reliable test data for gas turbines; although this was to be based on one of the intermediate-pressure designs from the B schemes, it was not intended to form part of a final plant.[69] However, this decision was soon revised. Neither the RAE nor Metrovick had been able to find a suitable dynamometer to test the turbine's performance; as manufacturing or commissioning a custom test piece would be both time-consuming and expensive (and possibly of dubious accuracy), they decided to return to testing a compressor and a turbine in tandem. In order to obtain a test unit within a reasonable time, the partners decided to scale their design back to a single turbocompressor, based on the intermediate-pressure section of the B.2 scheme.[70] This would also give them the opportunity to test a combustion chamber; although the partners did not mention this in their discussions, the combustion experimenters at the RAE were finding it a more difficult problem than had perhaps been expected.[71] By late August 1938, the

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[65] "Report on visit to Messrs. Metropolitan Vickers Ltd. Manchester," 8 March 1938, NA AVIA 13/1408
[66] Or at the very least on a different scale.
[67] 'Report on Conference – 8th March, 1938', 10 March 1938, MOSI 1996.3235/1/1
[68] 'Report on Conference – 8th March, 1938', 10 March 1938, MOSI 1996.3235/1/1
[69] 'Report on visit to Messrs. Metropolitan Vickers Co Ltd, Manchester', 8 March 1938, AVIA 13/1408; decision confirmed at an Engine conference held at the RAE 10 March 1938
[70] DM Smith, Notes on conference at RAE, 19 April 1938, MOSI 1996.3235/1/1
[71] See Baxter(1988), 160-164.

turbocompressor design had been frozen as the B.10, consisting of a 9-stage axial compressor and a 4-stage reaction turbine. Although the unit would give useful test data for both turbine and compressor, it was not intended to produce any useful output; the turbine's power was to be entirely absorbed by the compressor.

There was a tension between the turbocompressor's similarity to a viable aircraft powerplant, and the increased cost, complexity, and development time that greater similarity would entail. Although from the very beginning of the collaboration the 'B' unit was to be for test purposes only, and would never fly in an aeroplane, the complexity of the initial schemes suggested that the RAE had hoped to achieve power-plant-like performance in a single bound. Though going for a full working engine would make the accurate determination of individual components' performance difficult if not impossible, there was a benefit to be had from looking like an actual engine. Though the B.10 was clearly not an aircraft plant, producing no useful shaft power, Constant was at some pains to emphasise that it be made to look like a practical aero-engine. As historians of technology such as Donald Mackenzie have shown, the credibility of technologies under test is based on the ability to make trustworthy similarity judgements between experiment and the final article; making the turbocompressor look like an engine helped reinforce its potential as one.[72] At a conference in June 1938, in advance of a visit by the Air Ministry DSR, Constant pointed out that the current design's 'excessive frontal area would have an unfortunate propaganda effect on many persons viewing the test unit,' and that it would be 'extremely desirable' to have all the piping in a single plane, 'so as to indicate that such units could be placed in a wing with few difficulties as to frontal area'.[73] Nonetheless, by this point it was becoming clear that the losses inherent in the 'B' scheme's many right-angled bends were going to be significant. This had initially been disputed by the RAE, whereas as noted above, Metrovick's steam turbine experience led them to believe that the pressure losses would be high.[74] By the autumn of 1938, RAE had carried out more of its own tests on piping losses, and the partners agreed that these high levels might make the difference between a viable powerplant and a failure.[75] For a full aircraft plant, a different approach would be needed. There was, however, the possibility of finally having some experimental data to draw upon, as the RAE's compressor was close to being run with its new blading.

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[72] Mackenzie (1990)

[73] DM Smith, 'Discussion at Farnborough 29th June, 1938,' 1 July 1938, MOSI 1996.3235/1/1

[74] Although the magnitude of these losses was initially disputed by the RAE, who thought Metrovick's estimates rather pessimistic; see for example "Report on visit to Messrs. Metropolitan Vickers Ltd. Manchester," 8 March 1938, NA AVIA 13/1408, and DM Smith, 'Discussion at Farnborough 29th June, 1938,' 1 July 1938, MOSI 1996.3235/1/1

[75] HG Rhoden, 'Report on I.C. Turbine' (n.d., but c. 3 September 1938), MOSI 1996.3235/1/1

Over the next year, manufacture of the B.10 components began, yet it was to be December 1939 before the compressor – the first completed component – was ready to be tested. The slow progress of the RAE's turbine schemes caused some concern at the Air Ministry and in the ARC's Engine Sub-Committee. Before the committee's June 1939 meeting, Tizard spoke to Pye and discussed the gas turbine programme. Tizard felt that Metrovick's progress was slow, and that 'there was no real drive behind it.'[76] At the meeting itself, at which Constant reported on the RAE's gas turbine work, Tizard asked whether the test programme could be accelerated.[77] Constant replied that it was 'as fast as possible, considering the original nature of the work.'[78] He did, however, point out that there might be a 'psychological' reason for the slow progress, in that Metrovick 'were accustomed to the design of power station turbines where the utmost reliability was essential. They [MV] had therefore felt it to be desirable to check the R.A.E. conclusions before proceeding to the design work.'[79]

'Psychology' and technical style

As Constant suggested, Metrovick's 'psychological' slowness was a matter of technical style rather than of ability; a style which was shaped by the company's core business. Although Metrovick had its own experimental test department for turbine components, it did not have a separate development organisation.[80] Steam turbines were not mass-production items, and were made to order for a particular client; they were too large and expensive to perform the trial-and-error development methods more common in other sectors. As a result, the company put a premium on careful design up front, helped by its staff's proficiency with analytical design methods; any problems revealed in service had to be tackled on site at the turbine installation. This was in contrast to aero-engine practice, where initial research might be carried out on single-cylinder test units, but following this extensive development was carried out on (usually multiple) experimental engines. The apotheosis of this approach could be found at Rolls-Royce, where multiple prototype engines were run to breaking point; any failed parts were replaced and strengthened, and the process was repeated. Although not cheap, requiring dedicated development teams and multiple engines on test, this approach allowed Rolls-Royce to constantly improve the output of the company's designs, in some cases more than doubling the rated horsepower of an engine type over its service life.[81] It was noticeable that the engine companies

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[76] HT Tizard, 'Note on a conversation with Mr Pye about the Engine Committee,' 5 Jun 1939, IWM HTT 11/27
[77] NA DSIR 22/62, Minutes of the 118th ESC meeting, 6 Jun 1939, 1667.
[78] NA DSIR 22/62, Minutes of the 118th ESC meeting, 6 Jun 1939, 1667.
[79] NA DSIR 22/62, Minutes of the 118th ESC meeting, 6 Jun 1939, 1667.
[80] At least until 1942, when a development section was set up to help with the gas turbine designs.
[81] Whyte (1978), 1-2.

which did not carry out such extensive development either produced engines that were considered second-line or that suffered from a reputation for poor reliability.[82]

Steam turbines were long-lead items, requiring large forgings and castings, which militated against the development of methods to produce large numbers of components quickly (apart from turbine blading, which was one of the reasons Metrovick had been tasked with the manufacture of a gas turbine). This in turn meant that the adoption of a more engine-like development cycle was difficult, as it was not possible to manufacture and test components with any kind of speed. But even in the case of initial manufacture before development Metrovick's progress was slow. It is perhaps instructive to consider Armstrong Siddeley's manufacture of a test contraflow compressor to the RAE's designs, which went from order to delivery in roughly a year (though the RAE then carried out its own development work at Farnborough getting the compressor to run).[83] Similarly, the research compressors built for the RAE by Fraser & Chalmers and Parsons seem to have been completed and tested significantly more quickly than the B.10 compressor. This may of course have been due to the fact that these designs were manufactured to the RAE's designs rather than designed in collaboration with the RAE, and as such were not subject to the vagaries of changing specifications and ideas about how the compressor should be designed.

One case where the approaches of the RAE and Metrovick differed was in regard to weight. Aeronautical practice put a premium on lightness, often at the expense of other factors such as durability (and cost). This was certainly the case in military service, where engines would be overhauled every few hundred hours. These constraints did not apply to turbine practice; steam turbines were expected to run for thousands if not tens of thousands of hours without major repairs. As a result, many of the Metrovick designs were rather on the heavy side. The initial design life of the 'B' test unit was only 300 hours, but the gearbox that MV designed to test the B.10 compressor was more like a piece of steam turbine equipment. Constant noted that the proposed design looked large and heavy, something suited for continuous use; he had rather something in mind 'like an aero-engine unit, with a life of roughly 500 hours'.[84] Metrovick's attitude carried over to the gas turbines themselves; as AD Baxter, one of the RAE's engineers, put it, 'nothing less than half inch nuts and bolts ever seemed to be contemplated'. According to his

[82] As might have been said of Armstrong Siddeley and Napier respectively.
[83] See the section on Scheme 'C' below. It was also a smaller unit than the B.10.
[84] DM Smith, 'Report of Mr Constant's visit,' 1 Nov 1938, MOSI 1996.3235/1/1 By comparison, when Rolls-Royce was designing the supercharger for their Vulture engine, they changed the blading design because it was easier than redesigning the gearbox; personal communication, Nick Forder, 12 Jun 2012.

memoirs, he had difficulties in convincing the Metrovick engineers to make greater use of lightweight fasteners and sheet metal construction, as opposed to heavy bolts and castings.[85]

In bridging these technical styles, the RAE attempted to assist Metrovick as far as possible by seconding LT Whitehead, an experienced designer-draughtsman, to Trafford Park as one of the two staff sent there at the beginning of the project. When Whitehead was due to return to Farnborough in summer 1938, the Air Ministry DDSR stated that 'he would endeavour to let [Metrovick] have the services of one other draughtsman accustomed to aero engine scantlings'.[86] This proved harder than anticipated, and by August Henry Guy wrote to Constant that 'in view of the difficulty you are experiencing in getting an aero engine draughtsman for us, I will not press this unduly. I think you and your associates at Farnborough will be able to keep us straight on all points that are likely to arise, although this may need additional reference to you'.[87] Given the discrepancies between what Metrovick and the RAE considered acceptable, overcoming the weight of local technical style and tradition was clearly no easy matter.

There was perhaps also a hint in Guy's reply of Metrovick's generally measured approach to the ICT. Though technically interesting, and despite Tizard's predictions of a large potential market, the gas turbine remained one project among many in a company that was heavily committed to war production. Though Smith and his team were spending most of their time working on the project, Guy and the firm's higher management seem to have been happy for it to continue at its own pace without attempting to harness extra resources.

On 3 September 1939, the long-feared war broke out. The immediate impact on the Metrovick gas turbine programmes was a loosening of the collaboration between the company and the RAE. With the increased pressure of work at both sites and with wartime travel restrictions, it became harder to arrange face-to-face meetings. As a result, the RAE emphasised to Metrovick that they should try and do as much independent work as possible and not wait for Farnborough's approval.[88] The B.10 compressor was finally tested in December 1939, and demonstrated a high efficiency of over 85%, although the maximum pressure ratio achieved was only about 2. The unit's turbine was run by July 1940, and the complete unit was assembled in September/October 1940, and run successfully in December 1940. The B.10's test programme was then relatively short, with the final report on the B.10 being sent to the Ministry of Aircraft Production in late

[85] Baxter (1988), 157-8.
[86] DM Smith, 'Report of Conference – 19th May, 1938,' 23 May 1938, MOSI 1996.3235/1/1
[87] HL Guy to H Constant, 3 August 1938, MOSI
[88] Letter WL Taylor to MV, 15 Sep 1939, MOSI 1996.3235/1/2

March 1941.[89] This may have been because the B.10 had taken so long to bring to the test stage that much of its value was now more or less academic: its compressor was highly efficient but was conservative in terms of stage pressure rises, and as a proof-of-concept turbocompressor the layout of the plant had been superseded by more recent designs. On the other hand, some of its design features had proven trouble-free enough to be adopted by later designs without the need for extensive further testing, such as the drum construction of the compressor and turbine.[90]

Why, then, the two-year delay from design to manufacture? On the one hand, there were real problems in finding materials suitable for the gas turbine; sufficiently heat-resistant alloys proved to be very difficult to forge and machine. The B.10 turbine forgings were originally ordered in June 1938, with an expected delivery in August that year, but it was to be September before the first successful forgings were produced, and spring 1939 until all of the turbine parts were produced. Even at this point, there was about a further six months' slippage in all parts of the schedule. Manufacturing the hundreds of blades needed for one compressor and turbine proved to be a more difficult endeavour than had initially been realised. On the other hand, delays were also in part due to diversion of effort to other gas turbine projects, in particular one that was to be more like an aircraft engine: scheme D.

Scheme D

In early November 1938, Constant reported that the Air Ministry urgently desired the production of a complete plant more representative of an aircraft engine. The project's urgency was such that it should be developed without waiting for the test results of the B.10. As a result he had drawn up the outline of a coaxial scheme, to be known as scheme D. Again there were mechanical issues to be considered; although Constant favoured dual compressors for aerodynamic reasons, he agreed that this would cause mechanical difficulties.[91] By the next progress meeting, Metrovick had examined his proposals for the scheme, and had come to similar conclusions. Smith did, however, point out the mechanical advantages of a single compressor, and the participants discussed various options that might allow a high pressure ratio to be achieved in a single compressor: blowing off air in intermediate stages on startup, variable stators, altering the low-pressure blading, or even de-clutching compressor stages on running-

[89] Letter DM Smith to DSR, Ministry of Aircraft Production, 29 Mar 1941. The Ministry had taken over research and development work from the Air Ministry upon its formation in 1940; for more detail see chapter 3.

[90] This novel feature had been adopted to ensure that the thermal expansion of the turbine matched that of the casing, and was remarkably successful.

[91] DM Smith, 'Report of Mr. Constant's Visit,' 4 November 1938, MOSI 1996.3235/1/1

up.[92] Constant asked Smith to consider these options further, noting that he considered blow-off the most promising.

A few days later, the Farnborough staff were able to write to Metrovick, giving further details of Anne's performance on test. Although some of the compressor's stages were operating in a stalled condition at low speeds, giving rise to a low operating efficiency, these would unstall as the compressor was accelerated to its operating speed. This made 'the possibility of obtaining high pressure ratios from a single unit appear much more hopeful.'[93] As a result, Metrovick laid out preliminary designs with both single and double compressors. By January 1939, the RAE had decided that the D scheme should be a single-compressor design, with a separate power turbine to drive an airscrew. Yet it was still not entirely clear whether the unit should be suitable for aircraft use, or whether the scheme was to be for ground test only. This was settled the following month, when Constant informed MV that the plant would not be installed in an aircraft, but would be run at ground level on a test bench. The scheme was, however, to be laid out so as to approximate the installation in an actual aircraft as much as possible, including such points as a diffuser for the aircraft exhaust. As the design of the unit was to be optimised for ground running, the partners agreed that it was to be designed 'as for an aeroplane which would have to fly at low altitudes only'.[94]

Table 2.2 - Evolution of the D scheme[95]

D.1	November 1938	RAE Proposal; 2 compressors, 800 °C Maximum temperature, impulse & 2 reaction turbines
D.2	December 1938	MV calculation and layout based on D.1
D.3		As D.2, but HP section to run at 8000RPM instead of 7500 RPM
D.4	January 1939	Single compressor (7500 RPM), 800 °C maximum temperature. 2-wheel impulse HP turbine & reaction LP turbine
D.5	February	Single compressor (9000 RPM), 900 °C maximum temperature. Single-stage

[92] DM Smith, 'Visit to R.A.E.,' 10 December 1938, MOSI 1996.3235/1/1.
[93] Letter from Chief Supt. RAE to MV, 14 December 1938, MOSI 1996.3235/1/1
[94] DM Smith, 'Visit from Mr. Constant,' 24 February 1939, MOSI 1996.3235/1/2.
[95] Data taken from note by DM Smith, 'Scheme D – Co-axial Arrangements of Complete Plant', 9 May 1939, MOSI 1996.3235/1/2

	1939	impulse HP turbine & reaction LP turbine
D.6		Single compressor (7500 RPM), 750 °C maximum temperature. 2 reaction turbines.
D.6a		As D.6, but with LP turbine modified for lower leaving loss.
D.7		RAE Proposal; Turbocompressor carried on 2 bearings, 750 °C maximum temperature
D.8	April 1939	MV layout with same blading as D.6, but with turbocompressor supported on 3 bearings.
D.9		Similar to D.8, but with blading to MV design.
D.10	April/May 1939	Similar to D.9; designed for pressure ratio of 5:1, but to be capable of overspeed if needed to achievespecified output of 2000HP
D.11	May 1939	Similar to D.10, but with revised blading.

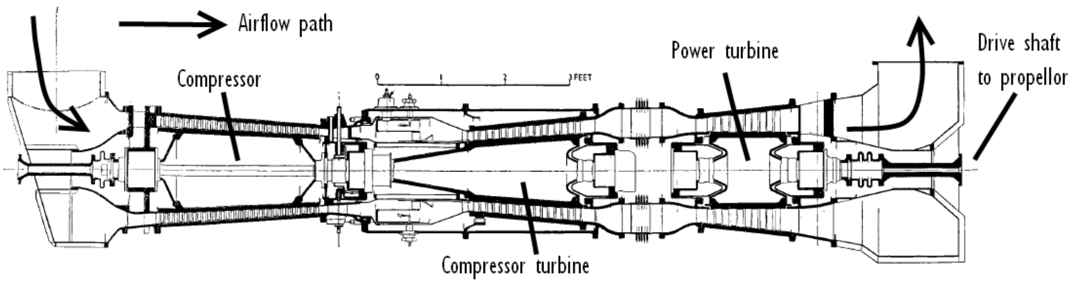

Figure 2.2 - D.11 arrangement[96]

There was clearly some urgency in the RAE and Air Ministry's appreciations of the D scheme, even though the B.10 test plant was not currently expected to be completed before the autumn.[97] At the end of March, Constant informed MV that the Air Ministry was prepared to have the company order up long-lead items such as castings and forgings for the D scheme in advance of test data from the B.10; the Ministry was prepared to accept the extra expenses that would probably be incurred due to design changes being required at a later date.[98] This was underlined by the Air

[96] Adapted from Smith (1947)
[97] And, as previously mentioned, did not run as a unit until late 1940.
[98] DM Smith, 'Visit to Farnborough, 29th March 1939,' 3 April 1939, MOSI 1996.3235/1/2

Ministry's DSR when he visited Trafford Park to view the B.10 under construction and to discuss the full plant scheme. [99]

No reference was made in these discussions to the other gas turbine research that the Air Ministry was funding. In mid-1938 the Air Ministry had agreed to fund the reconstruction of Frank Whittle's test engine after a turbine blade failure, and running had resumed in October of that year. The RAE's staff must have been well aware of its progress; from the initial evaluation reports on the scheme in 1937, Constant had been following the progress of the project, and the engine department had provided advice when necessary, including assistance in 1938 with the combustion difficulties that the Whittle Unit was experiencing.[100] By the time that the basic D.11 design was being finalised, Constant was starting to think that Whittle and Power Jets might have the basis for a viable aircraft engine (though the RAE position was still that propeller power was more efficient).[101] Whether the DSR was using the Power Jets engine as an explicit comparator is uncertain – he did not personally view it on test until June 30 – but he seems to have felt that the MV project could do with more drive. In mid-May he asked Griffith to prepare a note for the Air Ministry on how the work at Metrovick 'might be accelerated.'[102] As noted previously for the B.10. the sense that urgency was lacking was shared by Henry Tizard. In terms of concrete direction, the Air Ministry was pushing for the D.11 scheme; in late June, Metrovick was told to order up material and forgings for the unit once the drawings were ready. After a number of discussions with the supplier for the turbine forgings, Metrovick placed orders for these long-lead items in August 1939.

However, issues around Metrovick's technical style were again raising their head. Weight had not been a great concern for the B.10, but the D.11 was intended to be more like an aircraft engine, and here the RAE had some worries. Metrovick's initial weight estimate for the plant was some 4,000 lbs.; at the D.11's design power rating of 2,000 HP, this would give a specific power of 0.5 HP/lb, or roughly half that of the best current piston engines. Given this high weight, Constant was confident that it could be 'substantially reduced without much difficulty.'[103] A fortnight later, the RAE sent a letter to Metrovick stating that the engine department had made a rough weight estimate for the D.11, which had come out 'at about 3,000 lb.'[104] They noted that they were 'unable to account' for the difference between their number and the Metrovick weight, which the

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[99] DM Smith, 'Visit from Mr Pye and Mr Constant,' 14 Apr 1939, MOSI 1996.3235/1/2
[100] Baxter (1988), 163. The RAE was to provide continuing support with combustion problems to Power Jets over the next few years.
[101] Whittle (1953), 87; Bailey (2004), 18.
[102] Letter from DR Pye to AA Griffith, 16 May 1939, NA AVIA 13/1410
[103] DMS 17 Oct 1939, MOSI 1996.3235/1/2
[104] Letter RAE to MV, 30 Oct 1939, MOSI 1996.3235/1/2

RAE considered 'excessive'.[105] Smith responded that he would re-check the estimates once detail design was further advanced.[106] Although the Metrovick engineers appreciated the importance of weight reduction, their method of reducing weight at the end of the design process was alien to aeronautical practice, where it was a concern from the very beginning. The differing values the technical communities of turbine engineers and aero-engine engineers placed on weight and reliability can be seen in the response of the Director of Engine Research and Development at the Ministry of Aircraft Production to Metrovick's engines; he noted that they must be too heavy, as they never broke down on their first test![107]

The production of the D.11 suffered from many of the same problems as the B.10, in that there were problems in the production of forgings and in the supply of material for the plant. In addition, on the night of December 23 1940, the *Luftwaffe* attacked Trafford Park as part of the 'Manchester Blitz'. The Metrovick works were heavily bombed, with major damage to the tool room and the machine shops.[108] Among the items that suffered damage or were destroyed were large numbers of D.11 jigs and some of the turbine parts.[109] Although the compressor was tested in January 1941, assembly of the turbine was delayed due to damage to the production gauges.[110] Tests of the D.11 compressor showed that it had very low efficiency, due to unforeseen Mach and 3-D flow effects; as a result, work on completing the plant was effectively abandoned. The part-completed unit and its spares were finally shipped to Farnborough in July and August 1943, where it seems to have been used as an instructional unit.[111] As was the case with the B.10, by the time manufacture was underway the RAE's interest had moved on – in this case to jet propulsion. Even as Metrovick was starting work on the D.11, the RAE was involving the company in another turbocompressor project: the contraflow scheme C.

Scheme C

The contraflow scheme C was among the original designs considered by the RAE, and was in many ways the favoured design of the RAE's staff; AA Griffith especially had been proposing similar designs since he first began to work on gas turbines. The contraflow design consisted of a number of mechanically independent wheels, each of which contained a ring of compressor blades and a ring of turbine blades comprising a single stage of the compressor or turbine. In theory this meant

[105] Letter RAE to MV, 30 Oct 1939, MOSI 1996.3235/1/2
[106] DM Smith to RAE, 1 Nov 1939, MOSI 1996.3235/1/2
[107] Whyte (1978), 2.
[108] Dummelow (1949), 180-1.
[109] See the listing in the memo from B Reynolds to DM Smith, 31 Jan 1941, MOSI 1996.3235/1/4. The B.10 escaped major damage.
[110] NA AVIA 13/1412, 'ICT Progress Statement G.O. 16782: Report No. 36 covering January 1941, ' n.d.
[111] See the letter by DM Smith to the RAE, 7 July 1943, MOSI 1996.3235/1/6

that each stage could run at its optimum speed; in practice the design combined both mechanical and aerodynamic complexity with the added problems of thermal distortion. Although they were sanguine about its advantages – they estimated a 20% weight saving over scheme B – the RAE staff did appreciate the difficulties in manufacture and operation that would be associated with the scheme.[112] Initially then, Metrovick's involvement with contraflow schemes was limited to the consideration of manufacturing methods for the kind of double-tier blades and blade rings envisaged for the scheme.[113] With the company doing work on the B scheme, the contraflow idea was relegated to the background. Yet the RAE clearly retained an interest in the design, and continually returned to the question of whether Metrovick could carry out design calculations for it.

The company had clearly carried out some work by early May 1938, when the design staff showed Constant some general calculations and a layout for a contraflow design.[114] Constant noted that the design pressures should be chosen so that air leakage was always from the cold side to the hot side, which would cause smaller losses than the other way around. The Metrovick staff undertook to carry out some more detailed stage calculations, but these were put on hold following Constant's June 1938 visit to Switzerland. In light of the information obtained on his visit, Constant suggested that the C scheme would have to be re-calculated, and said that he would shortly be providing an updated method for the calculations.[115] In the meanwhile, he suggested that the contraflow scheme should be second in priority to the B.8 currently under design. Metrovick seem not to have made much progress on the design, and by mid-August, Smith noted that Constant's enthusiasm for the contraflow '[appeared] to be diminishing'.[116]

The next serious consideration of the contraflow concept occurred concurrently with the birth of the D.11 scheme. In mid-October 1938, Griffith asked the Metrovick staff whether they would be prepared to make an immediate start on the design of a contra-rotating scheme.[117] However, in early November, the RAE staff announced that they considered the development of a coaxial scheme (scheme 'D') to be their highest priority. Although Constant reiterated his interest in the contraflow scheme, he stated that it would have to come second to the coaxial plant.[118] As a

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[112] DM Smith, 'Report on Conference with RAE Engineers,' 16 December 1937, MOSI 1996.3235/1/1
[113] This may well have been because of the similarities between long-span steam turbine blades and the large blade rings required for scheme C.
[114] DM Smith, 'Report of Conference – 19th May, 1938,' 23 May 1938, MOSI 1996.3235/1/1
[115] DM Smith, 'Discussion at Farnborough 29th June, 1938,' 1 July 1938, MOSI 1996.3235/1/1
[116] DM Smith, 'Visit from Mr Constant', 22 August 1938, MOSI 1996.3235/1/1
[117] Letter AA Griffith to MV, 19 October 1938, MOSI 1996.3235/1/1. Perhaps related to the renewed interest is the fact that Griffith became head of the RAE's engine department in 1938.
[118] DM Smith, 'Report of Mr. Constant's Visit,' 4 November 1938, MOSI 1996.3235/1/1

result, Metrovick did minimal work on the contraflow scheme until the following year. At the RAE, with Griffith now at the head of the Engine Department, interest in the contraflow design revived again, and in February 1939 the Establishment placed an order for a research unit with the aero-engine manufacturer Armstrong Siddeley. This was a relatively small 9-stage design with a maximum diameter of 11 inches.[119] In May Constant was able to report to Metrovick that the Air Ministry would shortly consider placing an order for a contraflow turbocompressor in addition to this unit, and asked whether the company would 'be in a position to undertake this work'.[120] He suggested that the Air Ministry would probably consider this project of higher priority than the development of the ground test D.11 plant into a flight engine; a curious statement, given that the DSR had just visited Metrovick and stressed the urgency of the company's existing projects.[121]

This resurgence of interest in the contraflow concept was somewhat surprising. Griffith had been courted by Rolls-Royce since early 1939, and he started work there as a gas turbine consultant on 1 June.[122] Given that the Air Ministry had expressed a desire to get a working turbocompressor as soon as possible, and that the RAE must have known about Griffith's impending departure, it is unclear why there was a push for a project that would add to the multiplicity of designs under consideration by the RAE and its partners, especially a project whose main patron was just leaving the Establishment. The most plausible explanation seems twofold: firstly, given Griffith's prestige and influence in the engine department – he had been at the RAE for almost a quarter-century – his advocacy of the contraflow engine held great weight.[123] Secondly, the RAE's ethos privileged this kind of technically interesting research work over the development of existing designs.

Some accounts of early British gas turbine development have stressed the low level of support given; yet in financial terms, Farnborough was not as resource-starved as some accounts of the interwar period might suggest – and certainly not in the boom years of late 1930s rearmament. However, with the ethos of a research establishment seems to have come a certain measuredness of pace.[124] However, in the case of the gas turbine development, the problem seems not to have

[119] Details of the unit are sketchy; the RAE staff described it variously as a turbocompressor and as a supercharger. A brief description and photo are given in Roxbee Cox (1946).
[120] DM Smith, 'Visit of Mr. Constant,' 12 May 1939, MOSI 1996.3235/1/2.
[121] It is unclear quite what he thought the Air Ministry would do with the D.11.
[122] Rubbra (1964), 125. Bailey (2004) suggests that Griffith's move may have been partly motivated by pique at the Air Ministry's reluctance to fund his contraflow design; certainly Griffth's first designs for Rolls-Royce were of this type.
[123] Indeed, he may well have left for Rolls-Royce because they would allow him to develop his contraflow ideas in a way that the RAE would not. (Personal communication with Frank Armstrong, August 2012)
[124] On the financial support for Farnborough see Edgerton (20 06); on the interwar RAE and its ethos, see Baxter (1988)

been a lack of interest in the ICT, but rather a near-boundless and undirected enthusiasm.[125] Apart from the test compressor ‘Anne,’ built in the Farnborough workshops, the RAE sponsored a profusion of compressor designs, with at least five gas turbine and four compressor projects being initiated before the first turbocompressor was successfully run.[126] Although many of these projects differed significantly in their design assumptions, each seems to have been initiated based on new aerodynamic theories or on individual pieces of empirical evidence, rather than as part of a comprehensive test programme. The consequence was that new projects could not fully benefit from the experience gained on existing designs.[127]

A further explanation for the profusion of projects might be that many of the initial gas turbine projects (as opposed to the research compressors) were intended as much to give an insight into the mechanical, material, and manufacturing problems of the gas turbine as to prove aerodynamic theory. By training the Engine Department staff were mostly mechanical engineers, so mechanical matters of alloy creep and ball-bearing operation loomed as large as the aerodynamic issues of pressure rise per stage and stage efficiency, a point later confirmed by Constant.[128] He attributed this in part to the fact that the RAE’s engine department was experienced enough in mechanical design to anticipate problems in this area, but did not foresee the aerodynamic issues that would arise; as he put it, the ICT section ‘plunged lightheartedly into the aerodynamic morass from which more experienced aerodynamicists might have recoiled.’[129] Perhaps a final factor in the proliferation of projects was the divide at the RAE between theoretical and experimental researchers, of which Griffith and Constant were the former. Due to the delays in getting experimental equipment manufactured in the RAE’s always-busy workshops, theoretical work could run ahead of the test results that would provide a check.[130] Similarly, theoretical researchers’ knowledge of development difficulties was always more of an intellectual appreciation than the daily routine of the experimentalists.[131]

Whatever the cause, a few weeks later, the contraflow design seemed to have been put on the back burner, with Constant noting that it would be ‘at least two months’ before the Air Ministry

[125] Henry Tizard had noted with respect to Hayne Constant that he was ‘liable to be too optimistic’; see Tizard’s letter to DR Pye, 30 March 1938, IWM HTT 77
[126] The compressors Anne, Alice, Ruth, and the E.5; for turbines, the RAE contraflow, the B.10, the D.11, the C.6, and the F.2.
[127] Not least because there were so few completed designs.
[128] Constant (1945), 418.
[129] Constant (1945), 418.
[130] Bailey (2004), 4; 12-14.
[131] This dynamic is at the root of many a scientific or engineering joke.

would decide on whether to place an order for the contraflow unit.[132] But in mid-June (after the DSR had commented on the lack of progress on the ICT), the RAE again raised the matter in a letter to Metrovick, asking whether the company would be able to consider a design. Smith replied that MV would be able to start work on an overview immediately, and that they would be able to start detailed calculations in a fortnight or so.[133] At a progress meeting on 18 July, Smith had worked through and commented on some of Constant's calculations, and was shown a sample double-ring wheel that had been tested at the RAE.[134]

A month later Metrovick had completed calculations on their C.3 design, which was designed for the same conditions as the RAE's reference design, but which had a smaller number of stages. Constant agreed that the design seemed reasonable, noting that his calculations had been done in haste and that the blade angles might well be improved.[135] Metrovick agreed to update their calculations and incorporate an allowance for boundary layer effects, and the collaborators agreed that MV would lay out and start the manufacture of the unit once the development work on scheme D was sufficiently advanced. The main problem with the manufacture of the contraflow unit would be the production of the double-tier blades; Smith had contacted machine tool manufacturers, but none had any suitable special-purpose tools, so he had asked the MV toolroom to consider the possibilities for adapting their existing machines.[136]

During the latter half of September, Smith gave the drawing office notice that the contraflow compressor was likely to be ordered shortly, finally instructing the contracts department that he had received authority to proceed from the Air Ministry on 2 October.[137] The Metrovick team worked on their design, and by the time Smith visited Farnborough on October 13 for a discussion of Metrovick's gas turbine projects he had a basic design sketched out. Smith and Constant had a 'lengthy discussion' about the design, concentrating on the air and blade angles, and on the sonic effects that might be encountered. [138] The proposed blading for the unit was of higher camber and stagger than that used in other compressors, which meant that there were no directly applicable wind tunnel data available. Constant agreed that for the present MV would have to extrapolate from existing tests, but noted that he was making arrangements for wind tunnel testing of blading

[132] DM Smith, 'Visit to Farnborough 23rd May, 1939,' MOSI 1996.3235/1/2. This was perhaps unsurprising, given that Griffith was now on the point of leaving for Rolls-Royce.
[133] Letter WL Taylor to Metropolitan Vickers, 15 June 1939, MOSI 1996.3235/1/2; Letter DM Smith to RAE, 17 June 1939, MOSI 1996.3235/1/1I
[134] DM Smith, 'Discussion with Mr. Constant, 18th July 1939,' 21 Jul 1939, MOSI 1996.3235/1/2
[135] DM Smith, 'Visit from Mr. Constant – 24th August, 1939,' 29 Aug 1939, MOSI 1996.3235/1/2
[136] DM Smith, 'Visit from Mr. Constant – 24th August, 1939,' 29 Aug 1939, MOSI 1996.3235/1/2
[137] DM Smith to Contracts Dept, 2 Oct 1939, MOSI 1996.3235/1/2
[138] DM Smith, 'Visit to Farnborough,' 17 Oct 1939, MOSI 1996.3235/1/2

with high negative stagger.[139] The limiting relative flow speed for compressors seemed to be 70% of the speed of sound, and centrifugal compressors suffered 'a marked drop in efficiency' when operated above that speed. [140] In order to investigate the sonic effects on axial compressors, Smith suggested having one or two stages run at a higher speed. Constant responded that he would prefer to have the design optimised for the lower speed but be capable of running at a 10% overspeed, and he asked Smith to recalculate the design using this constraint. With regard to the losses in the plant from flow leakage and heat conduction in the blades, Constant gave his estimates of their magnitude; Smith agreed to carry out his own calculations, but noted that 'some of the assumptions underlying the calculation [were] very doubtful.' [141] Constant also noted that the RAE's research contraflow unit (manufactured by Armstrong Siddeley) was to be ready in a fortnight or so, and would be tested with a combustion chamber built at the RAE.

By early November, Smith's design had reached the C.6 stage, and he asked the MV drawing office to detail and order up the parts for the compressor, and to put in an order for the stainless steel required. Although he stated that 'delivery of this compressor is very urgent,' he also noted that it should 'not interfere with work already in progress on the Turbocompressors Schemes [*sic.*] B10 and D11'.[142] In order to investigate manufacturing methods for the contraflow compressor, JM Newton, a Metrovick production engineer, and one of his colleagues visited the Armstrong Siddeley works in early December. Initially the Armstrong Siddeley staff were rather suspicious, but once it became clear that the Metrovick men had been working with Constant the staff 'became frankness itself and were most helpful'; the engine department's reputation was clearly enough to open doors across the industry. [143] Newton noted that the Armstrong Siddeley compressor had a very fine finish, and reported on the methods used to grind the blades; though he did not note whether this was to a higher standard that Metrovick's usual manufacture, he was clearly impressed.

In order to test whether the components for the proposed design could be manufactured to the required standard of accuracy, in early December 1939 Smith asked for a two-wheel test unit to be manufactured in ordinary steel.[144] The C.6 itself was to lag badly behind this; in January 1940 the Mechanical Superintendent reported that although the blading tools were almost ready and quantity manufacture might begin with the month, the company had been unable to obtain

[139] DM Smith, 'Visit to Farnborough,' 17 Oct 1939, MOSI 1996.3235/1/2
[140] DM Smith, 'Visit to Farnborough,' 17 Oct 1939, MOSI 1996.3235/1/2
[141] DM Smith, 'Visit to Farnborough,' 17 Oct 1939, MOSI 1996.3235/1/2
[142] Memo DM Smith to MV Mechanical Drawing Office, 9 Nov 1939, MOSI 1996.3235/1/2
[143] JM Newton, 'Visit to Armstrong Siddeley's works re compressor,' 7 Dec 1939, MOSI 1996.3235/1/2
[144] Letter DM Smith to RAE, 11 Dec 1939, MOSI 1996.3235/1/2

supplies of the stainless steel required for blade manufacture.[145] This was still the case in early March; a memo sent to Henry Tizard pointed out that in order to accelerate development, it was 'essential' to have the necessary supplies of materials and specialist tools, though the actual amounts needed were 'relatively very small.'[146] Although the copy in the file is unsigned, a marginal note suggests that it was sent by Henry Guy; as Tizard had no formal responsibility for the Metrovick work, clearly at this stage the company was attempting to use its informal networks of influence to expedite the process.

By late April, the forgings for the contraflow discs had still not been received, but now Constant was unsure about the blade profiles for the outer ring of the contraflow compressor. Recent wind tunnel tests at Farnborough had suggested that the compressor efficiency would be disappointingly low, and Constant suggested that Metrovick try and carry out some of their own tests to verify this.[147] The RAE sent the graphs of their test results to Trafford Park to be copied, and pointed out that the extrapolations from the older data did not match the new experimental results.[148] As a result, the RAE suggested to Metrovick on 2 May that the necessary changes to the blades would require a complete redesign of the unit.[149] In response the drawing office suspended work on the detailing of the outer ring sections, and the manufacture of tooling was held up.

The following week, Smith visited Farnborough in order to discuss the redesign. Constant explained that the tests on the RAE contraflow compressor had shown that its performance was less than expected, which suggested that his reservations about the C.6 blading were accurate.[150] Smith presented an updated set of blade calculations, which both parties deemed satisfactory, and by the end of May the updated design had been passed to the drawing office for manufacture.[151] The C.6 suffered from many of the same production problems that had plagued the B10 and the D.11, with delays in the manufacture of forgings and the delivery of the specialist materials required. By late 1940, however, the wheel forgings had been received and the plant was taking shape. In the bombing raid of 23 December 1940, many of the C.6 parts were damaged beyond repair. As the production machinery require to complete the plant (especially blading)

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[145] DM Smith 'Visit from Mr. Constant,' 10 Jan 1940, MOSI 1996.3235/1/3
[146] 'Memorandum on Internal Combustion Turbine Proposition,' 11 Mar 1940, MOSI 1996.3235/1/3.
[147] DM Smith, 'Turbo Compressor A,' 30 Apr 1940, MOSI 1996.3235/1/3
[148] WL Taylor to MV, 30 Apr 1940, MOSI 1996.3235/1/1II; WL Taylor to MV, 'Contra-flow Compressor,' 2 May 1940, MOSI 1996.3235/1/3.
[149] WL Taylor to MV, 'Contra-flow Compressor,' 2 May 1940, MOSI 1996.3235/1/3
[150] DM Smith, 'Visit to R.A.E.,' 13 May 1940, MOSI 1996.3235/1/3
[151] WL Taylor to MV, 'I.C. Turbine,' 14 May 1940, MOSI 1996.3235/1/3; Memo DM Smith to Mechanical Drawing Office, 31 May 1940, MOSI 1996.3235/1/3

was being used for projects with a higher priority, the Ministry of Aircraft Production ordered that work on the contraflow unit be suspended, and it was never completed.[152]

Conclusion: multiplying schemes

Given the urgency expressed by the Air Ministry at various times, why did the RAE suggest new projects to Metrovick on multiple occasions? The decision to launch new projects was probably the result of a number of factors: Whilst progress on the B.10 was slow, this was due to bottlenecks in production and material delivery rather than due to a shortage of design resources. Given these constraints, there was little danger in Metrovick's design work on the D.11 and contraflow schemes impeding the work in progress. As mentioned previously, work on the gas turbine schemes was as much to examine the mechanical and metallurgical issues that would come up in the development of a unit. MV's involvement in the gas turbine scheme was due in no small part to their experience with the mechanical design of turbine plant; given the contraflow scheme's complexity, this experience would be of some help.

The company's experience with exotic materials and manufacturing methods was also of some use; experience on the B.10 (and to a lesser degree on the D.11) had shown the difficulties in forging and machining the high-temperature alloys used in gas turbine work. Indeed much of the initial work Metrovick carried out on the contraflow schemes was simply to consider the best methods for manufacturing individual blades and blade rings, including casting, welding, and machining from solid.[153] There was little danger of Metrovick's initial design work on the contraflow scheme holding back the development work on the other unit. Certainly the company never indicated that it would have trouble in taking on the extra work, and it does not seem that this was for fear of offending its client; Smith pointed out on a number of occasions that work would not be able to start for a while due to the pressure of other projects. However, on the whole, the work was limited by the resources available for development, rather than by design capacity. Paper schemes are cheap and easy to multiply, especially when flowing from the fertile pens of technically adept staff, and Metrovick's design engineers were certainly more than competent. Materials, machine tools, and skilled workers were far harder to improvise. Given these conditions, it is perhaps unsurprising that the RAE's spreading of effort across multiple projects did not result in an aircraft engine before 1942, especially as many of the projects were treated as speculative research rather than prototype production designs. In contrast, Whittle's monomania in pursuit of a single concept – jet propulsion – linked to a drive to manufacture test

[152] See eg the letter from HL Guy to DR Pye, 24 Feb 1941, MOSI 1996.3235/1/3

[153] Indeed Metrovick's welding expertise had been instrumental in gaining a gas turbine development contract in the first place.

engines (and backed by a certain amount of luck) resulted in a flight-worthy engine by May 1941.[154] Power Jets was growing at break-neck speed, and as a small start-up company with a single goal could concentrate resources in a way that Metrovick perhaps could not.

With regard to the design of a complete gas turbine, the RAE's approach was a strange mix of the radical and the conservative. It was radical in that very different complex new designs were suggested based on limited practical experience; at the same time the designs used quite conservative assumptions with regard to such factors as achievable stage pressure ratios. In order to produce an efficient gas turbine, compression would have to take place at a pressure ratio of at least 4 to 1 with an efficiency of about 80%.[155] Griffith's earlier reports on the gas turbine had concluded that, in order to avoid starting problems, compression would have to take place in mechanically independent compressors of low pressure ratio.[156] When thinking about an actual powerplant design, Griffith's preference for the theoretically elegant solution led to his advocacy of the contra-flow compressor. Yet by December 1937 it must have been clear to the Farnborough staff that the required compressor performance was achievable in a single unit without starting difficulties, as the Brown Boveri industrial gas turbine the establishment had ordered used a single axial compressor to give an output of 2,000 SHP.[157] Although this was an impressive achievement in its own right, it was accomplished by using a 21-stage compressor. The RAE's challenge was then to design a compressor that would achieve this pressure ratio within the size and weight constraints applicable to an aircraft powerplant.[158] There was admittedly a further complication in the case of an aero-engine: unlike an industrial plant, the engine would have to deal with a range of entry pressures and temperatures, and it would need to run smoothly over a greater range of speeds and loads.[159]

As this chapter has shown, the same factor was at the root both of the proliferation of gas turbine schemes investigated by Metrovick and the RAE, and of the relatively slow progress of the schemes undertaken. This was a relative lack of development capacity, and a privileging of design

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[154] The first British jet aircraft, the Gloster E.28/39, first flew on 15 May 1941, powered by a Whittle W.1 engine. For an account of Whittle's uncompromising pursuit of the jet engine, see Nahum (2004). Although Power Jets encountered many development difficulties, later analysis of its engines revealed how the company had avoided serious aerodynamic issues with its compressors more or less through good luck in choosing the layout. See Bailey (2004)

[155] In order to provide useful shaft power; a jet engine could run with lower component efficiencies.

[156] Griffith was worried that in a single compressor the early blade stages would stall; see Armstrong (1976).

[157] Some sources give the date of the order as 1938, but in their initial discussions with Metrovick the RAE staff indicated that the Brown Boveri plant had been ordered; see DM Smith, 'Report on Conference with RAE Engineers,' 16 December 1937, MOSI 1996.3235/1/1. There is a description of the Brown Boveri unit in D.M Smith, 'Vist to R.A.E.,' 10 December 1938, MOSI 1996.3235/1/1

[158] Bailey (2004), 12-13.

[159] Bailey (2004), 13.

over development. One reason that projects were slow was that Metrovick's deliberative style, inherited from their steam turbine and heavy engineering business, laid a premium on careful design; conversely, it lacked the development resources to quickly build prototype designs, but had the design resources to carry out studies for new projects. Yet this same design capacity and turbine expertise was one of the reasons for the RAE choosing MV as a partner. Similarly, the RAE's research focus meant that it had a bias towards coming up with new experiments and designs, in order to help gain data for future work. Apart from the pressures of war reinforcing the Establishment's desire to gather data at any cost, there was perhaps a sense of design freedom that had not existed at the Engine Department in decades; the RAE had gained the ability to design powerplants for the first time since the First World War, albeit in conjunction with a design partner.[160] The following chapter will examine the way in which the RAE began to design a jet propulsion unit, and how Metrovick again came to be involved.

[160] A point which Constant himself made to the RAE's Engine Department in a 1942 memo, Eng/2038.R/HC/21. I am grateful to Bob Pick for a copy of this document.

Chapter 3: Building a jet engine

'A demonstration which does not break down in my presence is a production job.'

-Henry Tizard commenting on the Whittle Unit, January 1940[1]

By the end of the Second World War, the RAE had gained a crucial gatekeeping role in the UK gas turbine field. It was the design approval authority for projects funded by the Ministry of Aircraft Production, and, having been merged with Power Jets, was the central research establishment for gas turbines, dispensing test data and design methods.[2] Metrovick started the war as the RAE's favoured gas turbine development partner; yet despite developing a working jet engine, by the 1945 the company had no production contracts, and was still carrying out relatively small-scale research and development work. By contrast, all of the major aero-engine manufacturers had gas turbine designs at or near the production stage. This chapter will explain how the fortunes of the RAE and Metrovick diverged in this way. First it examines how the former involved the latter in the development of a jet engine. It covers the institutional environment in which the jet engine was developed, then gives a detailed history of the way in which Metrovick's compressor research work and its blade manufacturing expertise led it to the design of a jet engine.

However, continuing doubts in the Ministry of Aircraft Production about the company's ability to produce a practical aero-engine led to collaboration with the aero-engine manufacturer Armstrong Siddeley. I will trace the course of this relationship, and explain why it did not result in a manufacturing agreement. By this point, the Ministry of Aircraft production was funding a variety of gas turbine projects, and the circle of producers had expanded to include manufacturing firms such as Rover and, crucially, aero-engine producers such as Rolls-Royce and de Havilland. By setting the Metrovick jets in the context of the resource allocation decisions made by the Ministry of Aircraft production, I will explain how, despite the technical promise of the F.2 and its variants, they never entered production. In order to set the context, I will now turn to the changes to the organisation of aeronautical research and development made during the Second World War.

The Ministry of Aircraft Production and Gas Turbines

The decisions that resulted in the adoption of the gas turbine as an aircraft powerplant took place against a background of institutional flux. As noted in previous chapters, as a long-term research project, the gas turbine was the responsibility of the Air Ministry's Directorate of Scientific

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[1] Clark (1966), 301-2.

[2] It was renamed the National Gas Turbine Establishment (NGTE) in 1946.

Research, part of the Air Member for Development and Production's (AMDP's) department.[3] The effort of managing rearmament had swelled the size of the Air Ministry's production directorates to the point where they were becoming almost a ministry within a ministry. However, despite this growth, there was public worry about the strength of the RAF, with questions being raised in parliament about the progress of the air rearmament schemes.[4]

On the outbreak of war, the Air Ministry's production directorates were dispersed to Harrogate in Yorkshire.[5] The events of May 1940 were to provide another shock to the system, with the fall of France, the accession of a new Prime Minister, and the formation of the Ministry of Aircraft Production. The Ministry's formation was in part a political move; as a critic of pre-war aircraft production and procurement policy, Churchill wanted to show tangible proof of a new approach. As minister he appointed the businessman and newspaper magnate Lord Beaverbrook, in part because of his proven drive and energy, but also because his media empire meant that he was potentially an influential critic of the government.[6] There were advantages to the creation of a new ministry: it allowed the Air Ministry to concentrate on RAF strategy and operations, now that procurement and production issues were removed from its remit. The creation of MAP was relatively simple; it essentially consisted of the AMDP's departments, which were transferred wholesale to the new Ministry. However, for all his qualities of energy and dash, Beaverbrook was not the ideal Minister to head an organisation essentially concerned with planning; he was infamously contemptuous of formal organisation and hierarchy, which led to confused lines of responsibility and communication, and his empire-building tendencies caused a great deal of friction with the Air Ministry and the RAF.[7]

Beaverbrook's immediate priority was to increase aircraft production for the immediate needs of the RAF. In this he was fortunate that the aircraft industry was beginning to reap the benefits of the capacity expansion and reorganisation that had been carried out in the aviation industry and Air Ministry during the late 1930s; indeed, 1940 second quarter aircraft production was significantly higher than first quarter production, a result of measures taken before the creation

[3] Until August 1938, this post had been known as the Air Member for Research and Development; the change of name indicated the importance of the rearmament effort.
[4] Churchill was one of the more vocal critics. Part of the problem was that the rearmament schemes were intended to be as much instruments of deterrence as actual contributions to a balanced air force; see James (1990), Maiolo (2010), 229-231.
[5] Although the Directorate of Scientific Research remained in London. The bombing threat proved to be less severe than had been anticipated; due to the difficulties and disruptions of moving departments, the only other ministry to disperse (some of) its directorates was the Admiralty, which sent a large number of its technical staff to Bath; see Scott and Hughes (1955), 82-88.
[6] Chisholm and Davie (1992), 374-379.
[7] Furse (2000), 133-146; see also Cairncross (1991), ch.1, and Ritchie (1997), 228ff.

of MAP. [8] Although some of Beaverbrook's measures did have a short-term effect on the output of aircraft and on front-line numbers, these were mostly at the expense of medium- and long-term production and serviceability, by (for instance) concentrating on the production of aircraft over spares, running down stocks of the latter. Even more potentially damaging was a concentration on the 'big five' of aircraft types currently in production: three twin-engined bombers (Whitley, Wellington, and Blenheim) and two single-engined fighters (Hurricane and Spitfire). Although this may have produced an extra two or three hundred aircraft in the short term, the concomitant orders to halt work on other projects, including long-term research, caused delays in other programmes.[9] This dictum was therefore honoured as much in the breach as in the observance, and it was formally dropped after representations from the Air Council in June 1940.[10] Another measure that caused disruption was the setting of hopelessly unrealistic production targets in order to galvanise producers, which made accurate resource allocation very difficult. [11] Beaverbrook's working methods and the lack of clear responsibilities at the top also caused friction with his senior staff; the supremely competent Wilfrid Freeman (who as AMDP had effectively run MAP's constituent parts when they were still part of the Air Ministry) left the Ministry in September 1940, in large part due to disagreements with Beaverbrook.[12] Beaverbrook eventually resigned as Minister of Aircraft Production in April 1941, at least partly due to his political ambitions.[13] In the wake of his departure the responsibilities at the top of the ministry were in a state of flux until September 1942, when Freeman returned as the (civilian) Chief Executive; he was to remain in this post until the end of the war.[14]

The consequences of MAP's creation for the Air Ministry's gas turbine projects were mixed; on the one hand, Harold Roxbee Cox (formerly the RAE's Superintendent of Scientific Research) was appointed as Deputy Director of Scientific Research (DDSR1) at MAP, with a specific responsibility for gas turbine projects.[15] Given the many and varied responsibilities of the DSR, this gave the gas turbine an institutional champion.[16] On the other hand, the MAP's suspension of development

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[8] Furse (2000), 140

[9] Quite apart from the effects of stopping production of trainers and transport aircraft.

[10] Furse (2000), 139

[11] Furse (2000), 141; Devons (1950), 27-30. It should be noted that some of Beaverbrook's reforms were more clearly positive; aircraft repair was centralised and streamlined, giving an improved supply of repaired aircraft back to the squadrons.

[12] Furse (2000), 146-7; 156-7.

[13] Which were put at risk by the discovery that aircraft production could not be willed into increasing. See Chisholm and Davie (1992), 396-402.

[14] Lord Brabazon, Beaverbrook's successor as Minister of Aircraft Production, did formalise the organisation of the ministry, but the directorate heads all had direct access to the minister, and their responsibilities still overlapped to some degree.

[15] This post was later upgraded to Director, Special Projects.

[16] This is not to suggest that the DSR, David Pye, was not a supporter of the gas turbine – he was – but he

projects affected Power Jets' progress on the Whittle engine. Fearing cancellation, MAP staff even concealed the existence of the project from Beaverbrook for a period, with the result that it merely lost its priority status for a few weeks.[17] However, this caused Power Jets' subcontractors to suspend work on engine components, although MAP's Director-General of Research and Development (DGRD – Air Vice-Marshal Arthur Tedder) quickly assured Power Jets and their subcontractors that the work could continue if it did not conflict with priority projects. Whittle later estimated that the disruption caused the equivalent of several months' delay.[18] Whittle was finally called to a meeting with Beaverbrook on 9 July and was quizzed on his invention; the Minister told Whittle that he would support the manufacture of a prototype fighter for the engine. MAP's formation seems to have been less disruptive to Farnborough's gas turbine projects, if only because they were generally proceeding at a more leisurely pace. However, there does appear to have been some delay in the issuing of contracts for the RAE's Jet Propulsion Unit. The RAE staff had to repeatedly ask for permission to issue them, a process which was only formally settled in August 1940. Yet for Metrovick, the whole process of getting to the design of a jet propulsion unit was even more complicated.

From shaft power to jet propulsion

In the late spring of 1939, around the time that Metrovick was finalising its turboprop D.11 design, Frank Whittle's jet experiments were starting to bear fruit. Even the initially sceptical Hayne Constant was 'coming to agree that [Whittle] had, after all, got the basis of a practical aero-engine'.[19] Constant recommended that Power Jets' efforts be intensified in order to produce a workable engine within a reasonable amount of time, and suggested that the company should be developing 'several engines simultaneously'.[20] Whittle's engine was demonstrated to David Pye, the Air Ministry DSR, in late June 1939; as a result of his enthusiastic response, shortly thereafter the Ministry placed an order with Power Jets for a flight version of the engine, and ordered an experimental aircraft from the Gloster Aircraft Company to fly it in.

Although the RAE's engine department was still committed to its existing gas turbine projects, it now began to consider the development of a jet propulsion gas turbine. According to William Hawthorne, who joined the RAE's turbine team in 1940, in September 1939 Constant suggested to Whittle that Power Jets should consider the construction of a gas turbine with an axial flow

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was overworked. See eg. the letter from Henry Tizard to Pye, IWM HTT77, 7 Jun 1939.

[17] Furse (2000), 139. According to Whittle's biographer, the priority suspension lasted from May 20 to June 11; see Golley (1996), 146.

[18] Golley (1996), 146.

[19] Whittle (1953), 87

[20] Whittle (1953), 87

compressor; by December 1939 the engine department had produced an outline design and sent it to Power Jets, with the suggestion that the RAE manufacture its compressor and Power Jets the combustion system and turbine.[21] The choice of Power Jets as a development partner is interesting for a number of reasons. Given the RAE's existing collaboration with Metrovick on axial turbomachinery, one might have thought that the Manchester firm would be the first choice of partner; it also suggests that the relationship between Power Jets and the RAE was closer than has been suggested by Whittle's biographers. In part the choice may have been motivated by Whittle's progress on his own jet engine; apart from his turbine design ability, he already had successfully run his first test 'WU' unit for tens of hours, and so had experience of a running gas turbine and combustion system.[22] Metrovick's slow progress on the B.10 and D.11 may have also been a factor, as both projects were suffering from manufacturing difficulties. Certainly by January 1940 Constant was able to write to Gloster aircraft giving an updated performance curve for an 'R.A.E Jet Propulsion Unit,' and was able to show outline drawings of the projected unit to Smith and the other Metrovick engineers.[23] Shortly thereafter, in February 1940, the Air Ministry began to discuss the development and production of a Whittle-designed jet engine.[24] As Hermione Giffard has pointed out, this made the UK the first nation to commit to the production of a jet engine, and this decision was to shape the course of the British jet programme.[25] Indeed, if one had to pick a caricature for Ministry of Aircraft Production's attitude toward the jet, it would be closer to irrational exuberance than the parsimonious negativity portrayed in the enthusiasts' literature.[26] The decision was motivated by a number of factors, not least the presumed ease of production; the air defence role for which the jet engine was intended had also gained greater importance, certainly after the events of May 1940.

Scheme E

Yet as noted above, Constant was not initially thinking of Metrovick as the RAE's jet development partner; for them he had another task in mind. In late November 1939, he had asked Smith, Baumann, and Guy whether they would be willing to consider the manufacture of another axial research compressor, with a mass flow some 20% greater than that of the D.11.[27] Following up on this in January 1940, Constant explained that this compressor was intended for a proposed 2000HP[*sic.*] jet propulsion plant, and was to be used 'both for ground testing of compressor

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[21] Hawthorne(1991), 98
[22] See the graphs in Whittle (1945).
[23] H Constant to Gloster Aircraft Co., 9 Jan 1940, NA AVIA 13/1403; DM Smith, ''Visit to RAE 20th January, 1940,' 24 Jan 1940, MOSI 1996.3235/1/3
[24] Nahum (2003), 60-63.
[25] Giffard (2011), 59, 64 ff.
[26] And particularly prevalent in biographies of Whittle, eg. Golley (1996)
[27] DM Smith, 'Visit from Mr. Constant. 21 November, 1939,' 24 Nov 1939, MOSI 1996.3235/1/2

characteristics and for flight testing of jet propulsion'.[28] Unfortunately, Farnborough's test rigs did not have enough power to ground test the compressor, even with a throttled air intake, so Constant asked the Metrovick staff to consider the design of a compressor with about ¼ of the original mass flow. They agreed to consider it, although Guy pointed out the problems of scale effect in comparing its performance against the B.10. [29]

A few weeks later Smith and Guy visited the RAE, where Constant showed them the drawings of the proposed RAE jet unit. The research compressor was to be half the linear size of the jet unit's compressor, which would allow it to be tested on the RAE's supercharger test plant; Smith pointed out that given the compressor's requirements, it would not be possible to use the existing tooling developed for the D.11, and that cost and time estimates would require 'a good deal of consideration'.[30] The following month Constant asked for estimates to be made as quickly as possible for the new compressor, which by now had the Metrovick designation of scheme 'E'.[31] By early March, Smith had his estimate; the E.2 was costed at £3,000 for manufacture and development, excluding testing.[32]

Meanwhile, the engine department had continued to work on its jet propulsion design. In early April 1940, referring to a previous discussion with Constant, WL Tweedie, of the Air Ministry's engine research and development branch, informed the engine department staff that the DSR had approved the construction of two axial compressors, one 'for supercharger research' – i.e. the Metrovick E scheme – and 'the other for a jet propulsion unit for flight development'.[33] Rolls-Royce had pointed out that the smaller compressor unit would be suitable as a supercharger for a two-stroke engine they currently had under development; the DSR agreed that the compressor should be built with this end in mind.[34] Tweedie noted that Griffith would be in touch with the engine department directly to discuss his requirements, and asked for updated cost estimates for both compressors.[35] This seems to have been the first formal approval for the scheme that the RAE was aware of; a week or so later Roxbee Cox replied to the Air Ministry, noting that this indicated approval for the construction of the two compressors, and that he presumed this

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[28] DM Smith, 'Visit From Mr Constant,' 10 Jan 1940, MOSI 1996.3235/1/3
[29] DM Smith, 'Visit From Mr Constant,' 10 Jan 1940, MOSI 1996.3235/1/3
[30] DM Smith, ''Visit to RAE 20th January, 1940,' 24 Jan 1940, MOSI 1996.3235/1/3. The RAE had expressed the hope that as the compressor was to be manufactured in the same material as the D.11's, it might be possible to use some of the latter's HP blade tooling.
[31] DM Smith, 'Visit from Mr Constant,' 26 Feb 1940, MOSI 1996.3235/1/3
[32] Letter DM Smith to RAE, 11 Mar 1940, MOSI 1996.3235/1/3
[33] WL Tweedie (on behalf of DSR) to RAE, 12 Apr 1940, NA AVIA 13/1403
[34] This was the Ricardo/Rolls-Royce two-stroke mentioned in chapter 1.
[35] WL Tweedie (on behalf of DSR) to RAE, 12 Apr 1940, NA AVIA 13/1403. As noted in chapter 2, Griffith had left the RAE the previous summer; it is unclear how closely he was kept informed of the engine department's current projects.

approval meant that the Air Ministry would be making arrangements with Power Jets for the manufacture of the jet engine's turbine. Roxbee Cox stated that Metrovick had been asked to submit an updated cost estimate for the supercharger, and that the RAE would shortly submit an estimate for the jet compressor. [36] This discussion about the use of the compressor recalls the ARC Engine Sub-Committee discussions of a few years previously; even while a gas turbine jet engine was a promising technology to be developed, work on its components was seen to have utility for other, piston-engine, applications. Indeed, long after the decision had been taken to embark upon a pure-jet project, MAP continued to monitor the progress of this engine supercharger.[37]

Constant informed Metrovick of the change of role to a supercharger on his next visit to Trafford Park in April 1940.[38] Apart from the changes in design pressure ratio and mass flow, using the test compressor as an engine supercharger entailed another design change; in the interests of weight, the material was changed from steel to an aluminium alloy. Again Constant asked if the company could provide him with an updated cost estimate as soon as possible.[39] By the time the Metrovick staff next visited Farnborough Smith had drawn up a number of preliminary designs. Constant emphasized that he wanted the design to be as light as possible; though the test compressor would only be used for bench testing, it would form the basis of a potential production supercharger with as few changes as necessary.[40] Due to material difficulties and air raid damage, the E.5 was not run until the summer of 1941, and suffered blade fatigue failures of the high pressure stage. By this point, Rolls-Royce's engine design had developed to the point that they were unlikely to use the E.5.[41] The unit was to be repaired as a research compressor for MV, but the work had low priority; it was finally abandoned in November 1942, with the parts being sent back to the RAE.[42]

Meanwhile the RAE's engine department had continued to do work on the jet propulsion plant; at the beginning of May, Constant sent a letter to Power Jets giving updated details of the unit's compressor and turbine conditions, as well as some comments on the proposed assembly

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[36] H Roxbee Cox to RDE.1, Air Ministry, 20 Apr 1940, NA AVIA 13/1403
[37] See eg, the letters between the RAE and Metrovick, 9 and 13 Jan 1941, MOSI 1996.3235/1/4. As late as early 1941 the E.5 had works priority over the F.2 jet scheme.
[38] See DM Smith's report on Constant's visit of 26 Apr, 30 Apr 1940, MOSI 1996.3235/1/3
[39] Although this seems to have taken rather longer than the previous estimate; Smith sent the MV contracts department an estimate of £2,425 on July 25 – see MOSI 1996.3235/1/3
[40] DM Smith, 'Visit to RAE,' 13 May 1940, MOSI 1996.3235/1/3
[41] WL Taylor to Metropolitan Vickers, 12 Jul 1941, MOSI 1996.3235/1/4
[42] DM Smith to WR Hawthorne, 5 Dec 1942, MOSI 1996.3235/1/5.

procedure for the engine.[43] In his reply, Whittle stated that Power Jets expected to gain greater thrust from the turbine, but said that he would discuss the matter further once his calculations were more complete.[44] By now Farnborough's estimate of the manufacturing cost of the jet unit's compressor was £1,600.[45]

Methods of manufacture

One of the axial compressor's drawbacks when compared to the centrifugal was that it required the manufacture of many sets of subtly different blades; as had been discovered in the manufacture of the B.10 and the D.11, this could be a time-consuming and expensive process.[46] Now that they had agreed to the manufacture of a compressor, the engine department staff were interested in alternative manufacturing methods for the compressor blades, in particular extrusion through a die or die stamping. As a result, the department sent enquiries to a number of companies asking for advice on whether the production of blades by extrusion was a possibility. The department must also have put out feelers within the RAE, as they received at least one enquiry via the RAE's chief metallurgist H Sutton, who had discussed the matter with a specialist steel manufacturer.[47] In the event, the RAE decided to work with the Slough-based specialist manufacturer High Duty Alloys (HDA). The company was well known for its aeronautical alloys, and had some familiarity with gas turbine projects, as it had produced some of the forgings for the B.10's compressor. After discussions with Constant in late May, the outcome was that HDA would design dies based on the RAE's blade drawings. The dies would be then manufactured at the RAE and sent to HDA for testing.[48]

On June 5, at one of the RAE's regular engine conferences, the subject of Farnborough's gas turbine work in progress was raised.[49] The Air Ministry representative informed the conference that work that had priority from MAP 'should not be interrupted' by work on the RAE's jet unit.[50] He also noted that work on the Whittle turbine 'had been suspended', at which point the RAE representative asked for copies of 'all A.M. correspondence relating to the future policy concerning this unit.'[51] Metrovick's work on the 'E' compressor was not greatly affected; in early

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[43] Letter WL Taylor (initialled by Constant) to F Whittle, 2 May 1940, AVIA 13/1403
[44] F Whittle to RAE, 9 May 1940, AVIA 13/1403
[45] See the note dated 13 May 1940 in AVIA 13/1403
[46] Hence the interest in, for example, the re-use of D.11 tooling by Metrovick for the 'E' scheme compressor.
[47] See the letter of SJ Nightingale to H Sutton, 30 May 1940, AVIA 13/1403
[48] See the record of the telephone conversation, 22 May 1940, AVIA 13/1403
[49] These were regular conferences held to discuss all the engine work being carried out at Farnborough.
[50] See the excerpt from the minutes of the conference, 5 Jun 1940, AVIA 13/1403.
[51] See the excerpt from the minutes of the conference, 5 Jun 1940, AVIA 13/1403. As mentioned above, It is unclear whether Power Jets ever did suspend work on the unit; Whittle does not mention this in his memoirs, and the biographer of the then Air Member for Development and Production suggests that the

June Smith was able to send calculations for the E.4 to the RAE.[52] When Constant next visited Trafford Park, he informed the Metrovick staff that he had discussed the compressor's design with Rolls-Royce and that they would prefer lighter construction.[53] Constant informed the MV staff that the RAE were now manufacturing a jet propulsion plant, for which they were looking to have the blades produced by extrusion. He noted, however, that if this process was not successful the RAE would probably place outside orders for the manufacture of turbine and compressor blades, and asked whether Metrovick would be prepared to undertake such an order. Baumann indicated that it would be.[54]

Constant's question may well have been occasioned by the news coming from High Duty Alloys, who a few days previously had indicated that they had decided to produce blades by pressing rather than extrusion.[55] When one of the engine department staff enquired why, the HDA representative explained that metal would not flow into the very thin trailing edge of the blade die, but suggested that they might be able to produce a blade with a thicker trailing section.[56] In a letter sent in response, Constant noted that blade pressing would give only a minimal improvement in manufacturing time over machining from the solid, which was the main reason for trying extrusion. He pointed out that if a blade could be extruded with a thicker trailing edge, it might still be possible to thin this with a single machining operation, gaining a significant improvement in manufacturing time, and asked HDA to consider whether this was feasible.[57]

Meanwhile, design work was proceeding on the RAE's jet propulsion unit. Power Jets had requested further design data for its turbine design, which the RAE provided in early July.[58] At the same time WGA Perring, the RAE's new Superintendent of Scientific Research, asked the Ministry of Aircraft Production for clarification of the project's status.[59] Perring noted that the DSR had informed the Engine Executive Committee (a spin-off from the ARC's Engine Sub-Committee) that the axial jet propulsion unit was to be constructed; the DSR had given authority to construct the unit's compressor in April, but no mention of the remainder of the plant had been made.[60] Perring outlined the present position of the unit's design: Power Jets were carrying out detail design of

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Whittle unit merely lost its priority status between 20 May and 11 Jun 1940; See Furse (1999), 139.

52 Letter DM Smith to RAE, 7 Jun 1940, MOSI 1996.3235/1/3

53 See DM Smith's report on Constant's visit, 28 Jun 1940, MOSI 1996.3235/1/3

54 See DM Smith's report on Constant's visit, 28 Jun 1940, MOSI 1996.3235/1/3

55 Letter A McNab to RAE, 20 Jun 1940, AVIA 13/1403

56 See the record of the telephone conversation between AD Baxter and HDA, 26 Jun 1940, AVIA 13/1403.

57 Letter WL Taylor (copy initialled HC) to HDA, 29 Jun 1940, AVIA 13/1403.

58 Letter F Whittle to RAE, 1 Jul 1940, AVIA 13/1403; Letter WL Taylor to Power Jets, 6 Jul 1940, AVIA 13/1403.

59 WGA Perring to H Roxbee Cox, MAP, 7 Jul 1940, AVIA 13/1403

60 Due to the difficulties of travelling in wartime, the ESC's more urgent work was carried out by a smaller Engine Executive Committee, still chaired by Tizard.

the turbine, and the RAE themselves were detailing the compressor, combustion chamber, and the plant auxiliaries. Enclosing a general arrangement drawing of the unit, he repeated the Farnborough estimate for the compressor's cost of £1,600, and asked for the authority to be given to the RAE to arrange for the construction of the complete plant; as he put it, 'it is suggested that the place of manufacture of the different parts of the unit be left to our discretion.'[61]

Yet the RAE's choice of partners was now to be complicated. On July 9 Whittle had a meeting with Lord Beaverbrook at the Ministry of Aircraft Production, at which he was grilled on the prospects for his new engine. As noted above, production of Power Jets engines had been planned during early 1940, and industrial partners had been sought in April 1940, but the creation of the MAP and its priority programmes had caused these to be shelved.[62] However, in June 1940 the Whittle programme had its priority reinstated, and by the time of Whittle's meeting with Beaverbrook, production was again being discussed.[63] Whether as a direct result of this meeting, or more generally because of the pressures of developing the Whittle engines, Power Jets withdrew from the RAE's jet propulsion scheme; though Whittle did complete his analysis of its turbine, the company was to do no further work on the unit.[64] Now the RAE would have to turn to another development partner.

Metrovick and the jet

On July 19, the RAE's Chief Superintendent AH Hall asked the DSR for further authority to continue with the design and construction of the jet plant. He listed the advantages of the axial compressor configuration, and noted that 'it was originally intended that the design of the turbine should be undertaken by Power Jets Ltd., but it is now agreed that the design of the complete unit, i.e. compressor, turbine, combustion chambers, and all auxiliaries should be undertaken at the Royal Aircraft Establishment'.[65] Hall pointed out that much development work might have to be done, giving the example of the extruded compressor blading. He stated that 'it would also be an advantage if after the design is complete, we could arrange for a firm like Metropolitan Vickers to undertake the main constructional work.'[66] He emphasised that firm cost estimates were 'impossible' to make for experimental work, but reassured the DSR that 'it [was] thought that the

[61] WGA Perring to H Roxbee Cox, MAP, 7 Jul 1940, AVIA 13/1403
[62] Postan, Hay, and Scott (1964), 196.
[63] Postan, Hay, and Scott (1964), 196-7.
[64] F Whittle to H Constant, 27 Jul 1940, AVIA 13/1403
[65] AH Hall to DSR, MAP, 19 Jul 1940, AVIA 13/1403
[66] AH Hall to DSR, MAP, 19 Jul 1940, AVIA 13/1403

work, including any development work[…] necessary, should not exceed £10,000'.[67] It was obvious that in order to build an engine, the RAE would need a manufacturing partner, as the Farnborough workshops were not able to handle the amount of work required. For an axial design like the RAE was proposing, using a partner with experience of blading manufacture made sense, but what is interesting is that the RAE appeared to be to trying to design a jet unit without the help of a development partner. It is unclear what the reason for this was; as noted in chapter 2, the DSR had previously expressed reservations about the pace of Metrovick's work on the B.10 and D.11 projects, but Hall was happy to suggest the use of the company to manufacture the unit. Perhaps this was merely increased confidence on the part of the Engine Department, leading them to revert to their traditional approach of asking external contractors to manufacture to their design. By now the department had experimental data from the 'Anne' and B.10 compressors, as well as information on the Power Jets turbines and combustion systems, which would assist in the detail design; as noted previously, the RAE had completed a basic layout for the Jet Propulsion Unit by January 1940.[68]

Perhaps Hall was merely attempting to suggest a greater fixity to the design than actually existed in order to gain support; Hayne Constant clearly envisaged the possibility of a greater role for Metrovick. On the same day as Hall was asking for approval for the jet unit, DM Smith visited Farnborough, where he had a meeting with Constant. After discussing the design of the E.5 compressor, Constant asked Smith whether Metrovick would be 'prepared to manufacture a complete Jet Propulsion Plant,' and explained that this was the unit for which MV had already been asked to consider the manufacture of blading.[69] Constant gave some details of the jet units that had been manufactured by BTH for Power Jets, and stated that although various troubles had been encountered, one of the units was expected to be flight tested shortly. He handed over drawings of the RAE design, and explained that it was designed for flight at 450 mph.[70] Constant explained that extruded blading was being considered, but expressed doubt as to whether it would be successful. After some discussion of the details, he asked Smith whether Metrovick would be willing to start manufacture of the plant immediately, or whether the company would want to recalculate the design themselves.[71] Constant pointed out that 'early completion [of the

[67] AH Hall to DSR, MAP, 19 Jul 1940, AVIA 13/1403
[68] A copy of the layout drawing is among the correspondence for late May 1940 in NA AVIA 13/1403.
[69] DM Smith, 'Visit to Farnborough,' 25 Jul 1940, MOSI 1996.3235/1/3
[70] Or some 100 mph more than the fastest fighters currently in RAF service. Given the reservations mentioned in the ESC about the flight speeds needed for efficient jet propulsion just a few years previously, this was quite a jump (see Chapter 1).
[71] DM Smith, 'Visit to Farnborough,' 25 Jul 1940, MOSI 1996.3235/1/3

unit] was of great importance and would largely determine whether the Contract was placed' with Metrovick. He gave the RAE's cost estimate as £7,000.

Smith returned to Manchester for the weekend, and the following Monday sent a telegram asking for some clarification of the figures given.[72] On Wednesday he telephoned the RAE and told SJ Moyes, an engineer in the Turbine Department, that Metrovick were 'prepared to manufacture the unit from RAE designs and drawings as soon as they [were] available and the contract placed'.[73] However, in the confirming letter sent the same day, Smith noted that 'In the event of our receiving instructions to manufacture the plant we should use your calculations and drawings as our starting point, but we should require to check this information and possibly to discuss with you the introduction of certain modifications before detailing the drawings. We do not anticipate that any such revisions would delay the completion of the plant, as we should be in a position to order the principal items of material immediately the Contract is placed.'[74]

As Metrovick wanted to check the RAE's design assumptions, Moyes visited Trafford Park to lead them through the design. The information he gave the Metrovick staff was that the unit, now given the name of scheme 'F', was to be used for ground testing, but would be the prototype for a flight unit. Moyes noted that the RAE had ordered up some of the compressor's forgings already, which were due for delivery that August.[75] He also reiterated that although the RAE had ordered experimental extruded compressor blading, it was not certain that this method would succeed, and so Metrovick should manufacture its own set of compressor blading. With regard to the unit's turbine, Smith agreed that a two-stage turbine was probably the most practical (as on the RAE's preliminary design) but did not agree with the form of the passages.[76] He said that Metrovick would design the turbine themselves, and would draw up a number of alternatives. The company would submit these designs to the RAE for approval of the centrifugal and thermal stresses, as Farnborough had gained experience of these factors from interwar engine turbocharger experiments.[77]

A few days later AH Hall confirmed with Metrovick that the company were to produce a jet propulsion unit 'substantially in accordance with G.A. [general arrangement] drawings' supplied

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[72] Telegram Smith to Constant, 23 Jul 1940, AVIA 13/1403
[73] SJ Moyes, record of telephone conversation, 25 Jul 1940, AVIA 13/1403
[74] DM Smith to RAE, 25 Jul 1940, AVIA 13/1403
[75] DM Smith, 'Visit from Mr Moyes,' Jul 30 1940, MOSI 1996.3235/1/3.
[76] Interestingly this phrasing would suggest that Metrovick were still thinking in terms of gas passages rather than blade profiles.
[77] DM Smith, 'Visit from Mr Moyes,' Jul 30 1940, MOSI 1996.3235/1/3.

by the RAE.[78] If this was not quite what the company had agreed to, Hall's promise that 'the necessary contract action [would] be taken in due course' was presumably taken in the spirit in which it was intended. In the meantime, Hall asked Metrovick to proceed with the design work and the ordering of material as quickly as possible. With regard to the urgency with which the unit was required, Hall commented that it was 'required for flight development work and should be manufactured on the highest priority. Its manufacture should take precedence over the other turbine work being carried out for this Establishment (B.10, D.11 and C.6) which is regarded as being in the nature of research.'[79] Part of the reason for this sudden urgency may have been the state of jet aircraft production planning at this time; as noted previously, a production Whittle engine had recently been given the go-ahead by the Ministry of Aircraft Production, and a Gloster experimental test-bed aircraft was under construction. In August 1940, Gloster presented their initial designs for a production type, a twin-engined fighter, to the Ministry.[80] Another factor may have been the fact that the German bombing campaign against the UK was on the increase – the RAE itself was bombed on August 13th– which underlined the needs of air defence.[81]

In his letter to Metrovick, Hall suggested that as difficulties might arise in the manufacture of the stainless steel turbine forgings – no doubt informed by bitter experience on the B.10 and D.11 – Metrovick should also consider ordering up forgings in a Ni-Cr alloy from Mond Nickel.[82] He also noted some points of detail, asking whether boundary layer control might be retained on the compressor, unless its inclusion would delay manufacture. Despite Hall's implication that the Metrovick engineers would be working from the RAE's designs, it was not at all clear that these were sufficiently detailed; a couple of days later Guy rang Constant and asked whether the RAE could send Whitehead to Manchester 'to clear up obscure features in [the] design of [the] axial propulsion unit.'[83]Nonetheless, the following week Smith was able to inform the RAE that Metrovick had started detailing the plant, and that manufacture would be undertaken 'with all possible speed'; the company had ordered sets of blading to be machined from bar stock as well as the extrusions. [84] Smith pointed out that boundary layer control would greatly increase the

[78] AH Hall to MV, 4 Aug 1940, MOSI 1996.3235/1/3.
[79] AH Hall to MV, 4 Aug 1940, MOSI 1996.3235/1/3.
[80] A formal specification was to be issued in late 1940, and prototypes and pre-production aircraft were ordered in early 1941.
[81] This attack destroyed the research compressor 'Anne'.
[82] AH Hall to MV, 4 Aug 1940, MOSI 1996.3235/1/3. By March 1941, Mond Nickel had given this alloy the trade name Nimonic; it was the first of a series of alloys that were used widely in gas turbine applications.
[83] Record of telephone conversation, 6 Aug 1940, AVIA 13/1403
[84] DM Smith to RAE, 12 Aug 1940, AVIA 13/1403

unit's complexity and manufacturing time, so that the Metrovick staff would prefer to limit the design to bleed tappings as required for thrust balancing or for cooling air.[85]

Meanwhile, despite the RAE's urgency, the Ministry of Aircraft Production was proceeding at a leisurely pace. At the same time that Smith was confirming his design choices, the Directorate of Scientific Research's H Moss was still noting that the 'design of a jet propulsion engine should be undertaken at the R.A.E. with a view to subsequent manufacture under R.A.E. supervision' as if the decision had not been taken.[86] He noted that contracts should be let under similar terms to those for the previous ICT, and asked the RAE to forward a programme of work once the precise division of work between the establishment and Metrovick had been agreed. A fortnight later, WGA Perring replied that detail designs for 'a considerable part of the unit' had been sent to Metrovick, and that the company had indicated that they would be able to carry out its construction.[87] Perring reiterated that the speedy issue of contracts was now 'essential' to enable the firms involved to obtain the priority materials required. Moss agreed that the blade extrusion development should managed by Metrovick, who would sub-contract the manufacture to High Duty Alloys.[88]

Perhaps in an attempt to clear up the confusion, Perring sent clarifying notes up the chain of command, to both the Director and Deputy Director of Scientific Research, pointing out that the RAE had recommended that Metrovick be given a contract to produce one jet unit, and that the RAE understood that MAP's engine research department would be placing the contract very shortly.[89] Perring also informed the Deputy DSR that the RAE was investigating the possibility of fitting their unit to the planned Gloster Aircraft Company twin-jet aircraft; AD Baxter of the RAE's turbine section had given Gloster's assistant designer, RW Walker, details of the unit's layout, and had asked him to consider whether it would be suitable for installation on the aircraft.[90] This correspondence seems to have crossed with the Air Ministry's contract approval for both the E.5 compressor and the F scheme; on August 27 Metrovick's contracts manager informed the Ministry of Aircraft Production that approval for both items had been received, and that the contracts were expected to follow shortly. Unfortunately, progress on the unit itself was less speedy, which was to lead Metrovick to a troubled collaboration with an aero-engine manufacturer.

[85] DM Smith to RAE, 12 Aug 1940, AVIA 13/1403
[86] H Moss to RAE, 'R.A.E. Jet propulsion Unit,' 12 Aug 1940, AVIA 13/1403
[87] WGA Perring to RDE1, MAP, 23 Aug 1940, AVIA 13/1403
[88] Record of telephone conversation between Constant and H Moss, 24 Aug 1940, NA AVIA 13/1940
[89] WGA Perring to DSR, 24 Aug 1940, NA AVIA 13/1403; WGA Perring to DDSR1, 24 Aug, NA AVIA 13/1403
[90] WGA Perring to DDSR1, 24 Aug, NA AVIA 13/1403; AD Baxter to RW Walker, 26 Aug 1940

Enter Armstrongs

From the time that work was authorised on the F scheme, Metrovick began to work on its design, which it gave the designation of 'F.2', the F.1 being the company designation for the RAE's original layout. Work began on a first batch of three engines; however, many of the material supply difficulties that had affected the previous gas turbine projects continued to dog the F.2 scheme.[91] This was despite the efforts of Guy and Bailey to use their personal contacts to speed up some of the deliveries.[92] The decision to try various methods of blade manufacture proved to be fortuitous, as the machined blades were ready some six months before the pressings, allowing the F.2 first compressor to be manufactured and tested in September 1941.[93] The first engine was assembled in November 1941, and ran on test in December 1941.[94] Though the first batch engines were merely intended for ground running, and not for flight test, the MAP and RAE staff worried about the units' weight.[95] Even as the units were under construction, the RAE staff were comparing the heavy-gauge sheet metal used for components such as the combustion chamber and the tailpipe with the much lighter material used by the Power Jets engines, and were suggesting other ways of reducing the weight of the engines.[96] Again one can see here the influence of Metrovick's technical style; as DM Smith was later to put it: 'The design was not lightened to extreme limits as it was felt more important to obtain reasonably successful mechanical running than to achieve the lightest possible engine at the first attempt.'[97] Lightness of construction was not a core value of steam turbine design, but reliability was; without staff who had internalised the values of aeronautical practice (as noted in the previous chapter, the company had not been able to hire any aeronautical draughtsmen) it did not have the same salience as 'mechanical running'.

In response, staff at MAP began searching for a development partner who would be able to help the company lighten the unit, as well as adapting it to aircraft practice. The Deputy Director of Engine Research pointed out to Roxbee Cox that Metrovick did not have suitable manufacturing

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[91] Apart from lack of supplies, the forging of turbine drum components encountered difficulties similar to those encountered with the D.11; see eg. the memo from the MV Research Department, 22 Oct 1940, MOSI 1996.3235/1/3.

[92] For an example of Guy's efforts, see the mention in DM Smith, 'Discussions with Mr Constant, 15th & 20th inst.', 27 Nov 1940, MOSI 1996.3235/1/3. Bailey's links with research metallurgists at a number of firms led to various suggestions for replacement materials, some of which found their way into later batches of engines.

[93] Smith (1947), 473.

[94] Whyte (1978), 10.

[95] See eg the report 'Modifications for Aircraft Service,' 29 Sep 1941, MOSI 1996.3235/1/4, and letter H Constant for Director RAE to DM Smith, 25 Nov 1941, MOSI 1996.3235/1/4.

[96] On the sheet metal thickness, see DM Smith, 'Visit from Mr Ricardo', 21 May 1941, MOSI 1996.3235/1/4; more general weight comments are eg. in DM Smith, 'Visit from Mr Constant and Mr Hawthorne', 15 Jul 1941, MOSI 1996.3235/1/4

[97] Smith (1947), 473.

facilities if the decision were made to put the F.2 into production.[98] Constant had made informal queries about what kind of manufacturing facilities might be required for mass production of F.2s in May 1941; when the production issue was raised again in September, MV's Baumann pointed out that large-scale manufacture would require either the provision of shadow factory capacity or collaboration with an aero-engine manufacturer.[99] MAP's choice of partner was the Armstrong Siddeley Company, not least because though it was one of the big four 'ring' aero-engine manufacturers,[100] its piston engine projects were well behind schedule, and, in the opinion of the MAP's engine development expert, unlikely ever to produce production engines.[101] Another factor may have been that, like Gloster, Armstrong Siddeley was a subsidiary of the Hawker Siddeley group. As Gloster were the manufacturers of the F.9/40 fighter that was intended to be the Metrovick engine's testbed, it made sense to pick a development partner that had an existing relationship with the company.

The following week Roxbee Cox visited Manchester and put the possibility of collaboration to Smith, Baumann, and the Metrovick director HC Pierson. Their reaction was not exactly effusive, but they agreed to consider the issue. With regard to the design, however, they indicated their desire to 'keep control over the rotating parts, the design of which was their particular province'.[102] With regard to production, the MV staff indicated that they hoped to have free capacity in their factory in early 1942, and that if a programme of work were decided upon quickly, they would be able to earmark this space for jet propulsion.[103] Given Smith and Baumann's previous discussions and apparent willingness to cooperate with a production partner, the reluctance may mainly have been Pierson's, driven by protectiveness over Metrovick's commercial rights – he was Metrovick's home sales manager.[104] By late October, both MV and Armstrong Siddeley had indicated that they would be willing to collaborate, but there was still confusion about what role each company would play. According to the Armstrong representative, their role was to assist in lightening the engine, whereas Metrovick saw Armstrong's role as assisting with aircraft installation and engine auxiliaries.[105] A major point of contention seemed to be the commercial basis for collaboration; Pierson was quite insistent on settling the issue, as he

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98 Memo DDRE to DDSR1, 18 Sep 1941, NA AVIA 15/1509
99 Memo DM Smith to K Baumann, 10 May 1941, MOSI 1996.3235/1/4; DM Smith, 'Visit from Dr Hawthorne and Mr Moyes', 16 Sep 1941, MOSI 1996.3235/1/4. The initial query was for an output of 50 engines per week, which would have been a very high production rate.
100 See chapter 1.
101 'Notes of a Meeting held in C.R.D.'s Office, on 3/10/41,' n.d., NA AVIA 15/1509.
102 'Policy for Development of Metropolitan Vickers Jet Propulsion Unit,' 10 Oct 1941, NA AVIA 15/1509
103 'Policy for Development of Metropolitan Vickers Jet Propulsion Unit,' 10 Oct 1941, NA AVIA 15/1509
104 In 1944 he was to be appointed the company's general sales manager.
105 'Note on discussion between representatives of Metropolitan Vickers and this Ministry,' 12 Nov 1941, NA AVIA 15/1509

argued that technical collaboration could never be uninhibited without agreement on the commercial points. [106] After the meeting, George Bulman, Director of Engine Development, wrote to Hawker Siddeley's managing director to say that where possible the liaison would be left to the two companies themselves. He also suggested that Metrovick were rather touchy about their 'rotating parts,' and that if there were suggestions for improvement that became apparent during the course of 'aero-enginising' the unit, they should be put forward as 'constructive suggestions without any inference' that Armstrong were attempting to redesign these components.[107]

This seems to have helped somewhat; though over the next few months Pierson sent a number of prickly letters seeking to precisely define the commercial and technical divisions of the collaboration, some agreement seemed to have been reached.[108] Bulman noted wryly in a minute that though all the parties recognised the Metrovick experience in 'what they term the "rotating parts,"' the company did not realise 'how much they do not know about aero engines.'[109] Metrovick clearly had some comprehension of the issue, as they were happy for Armstrong Siddeley to advise on installation design and engine auxiliaries. However, they seem to have treated the engine itself as a turbine not that different to the industrial units that formed the company's core expertise, which perhaps led them to discount non-turbine aero-engine expertise.[110] Armstrong Siddeley was happy to offer the latter; in a preliminary meeting in January 1942, Armstrong's chief designer, Stewart Tresilian, discussed with DM Smith various methods that the company were using 'to lighten and cheapen some of their existing designs'.[111] As Armstrong Siddeley had not yet manufactured any gas turbines (beyond the RAE's experimental contraflow unit), this production engineering expertise would have come solely from piston engine practice.

The need to bring in an aero-engine partner suggests that the RAE's oversight over the F.2 was not as effective as it had intended, or even that the Establishment's aero-engine design experience was perhaps not as relevant as it had hoped. As noted previously, the RAE had not designed complete engines since the First World War, and had been limited to the design of engine accessories. As the Establishment's engine designers had moved to industry, Farnborough

[106] 'Note on discussion between representatives of Metropolitan Vickers and this Ministry,' 12 Nov 1941, NA AVIA 15/1509
[107] DED to Sir Frank Spriggs, 12 November 1941, NA AVIA 15/1509
[108] See the letters for the period in NA AVIA 15/1509
[109] Memo DED to DDSR1, 8 Dec 1941, NA AVIA 15/1509
[110] Interestingly, this dynamic was mirrored in the relations between Rover and Power Jets, and to a lesser degree between Rolls-Royce and Power Jets; as newcomers to the field, the engine companies could see the gas turbine experts' contributions, but the latter did not appreciate the perhaps seemingly more pedestrian production and development expertise of the engine companies. See eg. Giffard (2011), 123-4.
[111] R Eldred, Report on visit to A-S, n.d. (but early Jan 1942), MOSI 1996.3235/1/5

had lost tacit knowledge of everyday engine design and development, even though the Engine Department saw and tested many engines. Though it could pass on detail design suggestions to MV, these were at one remove from industry practice. Yet with regard to the wider gas turbine field, Farnborough's importance was expanding.

The RAE gains in importance

This was the result of the growth in the number of jet development and production projects supported by MAP. The RAE had formed a gas turbine section in the summer of 1941, with Hayne Constant being promoted to head of the Engine Department, and William Hawthorne (previously on secondment to Power Jets) succeeding him as head of the gas turbine section. This was part of a more general expansion of the RAE under its new Director, WS Farren. Along with the change in title (from Chief Superintendent) came a new institutional position; the Director was now formally on equal terms with the MAP's Director of Scientific Research.[112] MAP's Airworthiness Department – which was responsible for administering aircraft design compliance with airworthiness regulations, and was based at Farnborough – had been merged with the RAE. Farren argued that as a technology amenable to theoretical analysis, jet engines should be subject to the same kind of design oversight as jet airframes, which greatly increased the gas turbine section's influence.[113] The Engine Department began to act as a standards agency and clearing house for gas turbine information, including the drawing up of such mundane but important documents as standard glossaries of gas turbine terminology and symbology.[114] Another MAP innovation that increased the interaction between companies was the August 1941 creation of the Gas Turbine Collaboration Committee (GTCC). Composed of all the engine and auxiliary equipment companies working on gas turbine projects, it met bimonthly at the various firms involved, with members presenting progress reports and discussing their development problems. Any recurring technical issues were referred to sub-committees, where the companies could attempt to pool information and solutions. All issues of patents and proprietary information were deferred until after the war; the committee proved to be remarkably successful, and continued up until the early 1970s. This was in contrast to the US experience, where NACA's charter prevented it from passing information obtained from one private firm along to another. There were very few

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112 DM Smith, 'Visit from Dr Hawthorne', 2 Sep 1941, MOSI 1996.3235/1/4

113 I owe this point to Giffard (2011), 215-8. As she points out, this decision was not universally popular within MAP; some of the existing engine development staff saw this as an unwarranted disruption to the relationship between the Ministry's technical staff and the engine companies.

114 See eg. the copy of a later version in MOSI 1996.3235/1/7, dated November 1944

patent issues that had to be solved by the GTCC, suggesting that tacit knowledge and technical know-how were more important in gas turbine development than patentable innovations. [115]

Yet the RAE's increased influence was not solely for these bureaucratic reasons; the Establishment's theoretical and experimental research programmes were also beginning to bear fruit. Apart from the assistance the gas turbine section was giving to firms such as Power Jets and Metrovick, data was coming in from cascade and axial compressor testing. For axial compressors and turbines, the gas turbine section was attempting to come up with methods that gave flow deviation (and thus stage performance) in terms of camber, stagger, and chord ratio.[116] As the major partner working on axial compressors, and with its own cascade testing programme, Metrovick was an important source of information and experimental verification, especially as until about 1943 the company was the only place outside the RAE with a large-scale programme of axial compressor testing.[117] However, it was not limited to experimental work, as it developed its own methods of compressor design and analysis, which were fed back into the RAE's efforts, culminating in the publication by the Engine Department of complete design methods for axial compressors.[118] By the middle of the War, the Metrovick design staff could consider themselves part of a maturing community of axial turbomachinery aerodynamicists and gas turbine engineers.[119]

Other jet projects

The growth of a community of gas turbine engineers was also due to a rise in the number of jet projects being funded by the Ministry of Aircraft Production; in 1941, it gave the de Havilland Engine Company a contract for the development of a 3,000 lb. thrust design. This was the H.1, designed by the consulting engineer (and existing piston-aero-engine designer) Frank Halford. The H.1 had a remarkably swift genesis, being tested in April 1942, and it first flew in March 1943 (indeed the first Gloster F.9/40 to fly was fitted with H.1 engines). Frank Whittle's W.2 engine was also being put into production at Rover, but during 1942 both engines ran into trouble. What saved the W.2 engine was the intervention of Rolls-Royce, who took over the design from Rover

[115] The US experience with regard to patenting and collaboration is described in Dawson (1991); Scranton (2011).
[116] DM Smith, 'Visit from Dr Hawthorne', 2 Sep 1941, MOSI 1996.3235/1/4; see also W Merchant's report on his visit to RAE, 11 Sep 1941, MOSI 1996.3235/1/4
[117] Indeed, it may have had a larger programme, as most of the axial compressors at the RAE seem to have been manufactured by MV for the F.2 programme.
[118] Much of the RAE's theoretical work was done by AR Howell; his work was initially published as Engine Department reports, then (in 1942) as ARC R&M 2095; postwar the work was published in the open literature as Howell (1945a,b)
[119] Indeed, post-war Metrovick's KW Todd published a standard paper on cascade testing; see Todd (1947). As will be discussed in chapter 4, the design assumptions of Metrovick's later gas turbines differed from those used by the RAE/NGTE.

in early 1943; with their huge development resources they were able to produce a reliable engine, and had soon begun a complete redesign of the engine to give greater power.[120] Even for as revolutionary a technology as the jet engine, familiarity with aero-engine practice counted.[121] Meanwhile the RAE's role continued to expand, as the turbine section moved to its own site at Pyestock. As the resources devoted to gas turbines continued to increase, MAP had also reorganised; it created a separate gas turbine deputy directorate in December 1942, with Harold Roxbee Cox appointed as its head. The following year this was upgraded to a full directorate.

International links were also on the increase; among the wider US-UK scientific-technical collaboration, gas turbine technologies formed an important strand. Information about Whittle's jet engine had formed part of information sent on the 1940 'Tizard Mission' to the US.[122] This was followed by the April 1941 visit of the head of the US Army Air Corps, in order to gain more information. In follow-up meetings with MAP in July 1941 US officers obtained more information, including the plans for the Whittle W.2 unit, and negotiated an agreement for license production of the Power Jets W.2 engine by GE.[123] These exchanges continued throughout the war; Whittle was sent to the US in 1942 to assist GE in their development, and men and machines continued to cross the Atlantic in both directions for the rest of the war. Metrovick also took part in these exchanges; though information about the general design had presumably been passed to the US as part of the early exchanges, in February 1943 Roxbee Cox asked the company to provide drawings for the F.2 to be sent to the US; the company agreed, with the proviso that the only manufacturing firm to be given the information should be General Electric (with which the company had patent agreements).[124] Later that year, Metrovick received details about the US axial designs the Westinghouse W19B and the General Electric TG-100; unusually, the company seems to have received information about GE's TG-180 jet through its contacts at the company, as Smith was able to forward a report on the engine to the RAE.[125] The following March, Smith received a letter from OA Saunders, MAP's Deputy Director of Turbine Research, informing him that a number of US jet units were due to be sent to the UK, and asking whether Metrovick would

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[120] Rover's role in this is sometimes overlooked, due to the company's fractious relationship with Whittle; Rover's staff had been redesigning Whittle's engines for production, and the fact that Rover's Adrian Lombard moved to Rolls-Royce with the jets and became Rolls's chief engineer suggests that they had the talent.
[121] This is the argument of Nahum (2004) and is elaborated upon in Giffard (2011)
[122] For more on the Tizard Mission, see Zimmerman (1996).
[123] Pavelec (2007), 75.
[124] Memo K Baumann to HC Pierson, 8 Feb 1943, MOSI 1996.3235/1/6
[125] RAE to MV, 28 Sep 1943; DM Smith to RAE, 29 Nov 1943; RAE to DM Smith, 9 Dec 1943; all MOSI 1996.3235/1/6

like to have any on loan for test purposes.[126] Smith asked to see a number of the axial units, but it is unclear if the company were loaned any or for how long. In either case, Smith was soon able to view US turbine practice more closely; in the spring of 1944 he was a member of the MAP 'Special Projects Mission' to the US, where he was able to view American compressor practice, which was to inform his future design work.[127]

Yet to some degree from 1942 there was no longer quite the same urgency in UK jet production, as the aerial threat which had driven the development of gas turbines receded, and continuing development troubles made it clear that the gas turbine offered no quick and easy path to production. The German campaign against Russia meant a transfer of offensive airpower to the Eastern Front; though the offensive against the UK continued in fits and starts, conventional air defences were able to deal with the *Luftwaffe*. As the RAF's centre of gravity moved to the bomber offensive, thoughts turned to the development of the more fuel-efficient engines that would be needed for bombers that could attack Germany.[128] These would be longer-term projects, as the candidate engines had not yet been flight tested. As the established engine companies moved into jet production, the role of Power Jets became ever more tenuous. As a company that was mostly state-owned, and entirely state-funded it could not compete against the aero-engine companies without causing friction. The Gordian knot was cut by Stafford Cripps, the Minister of Aircraft Production (and former patent lawyer), in March 1944 when he nationalised the company. Power Jets was merged with the RAE's turbine section and, as Power Jets (R&D) Ltd, turned into a pure research and development organisation, with no production plans. Unhappy at this, Whittle and many of his staff left, and in 1946 the company was turned back into a national research establishment, the National Gas Turbine Establishment (NGTE).

The breakdown of collaboration

By March 1942, technical collaboration between A-S and MV was underway, and at the first progress meeting DM Smith gave the current state of the F.2 programme. The first two engines were being tested, and the third was in the process of final assembly; MAP had recently ordered a second batch of three engines. The units' principle of operation had been proven, but a number of issues had arisen that would require development work, principally relating to the turbine bearing. He hoped to have two first batch engines modified and ready to be fitted to an F.9/40 airframe by July 1942, as flight tests of the units were urgently desired. Smith said that though

[126] OA Saunders to DM Smith, 13 Mar 1944, MOSI 1996.3235/1/7.
[127] Hayne Constant's report on the mission is in NA AVIA 10/101. 'Special Projects' was MAP's euphemism for gas turbines; as noted previously, Roxbee Cox was 'Director, Special Projects'.
[128] See Henry Tizard's discussion with the CRD in May 1942, IWM HTT 383, and his note to the Minister of Aircraft Production, 6 May 1942, IWM HTT 263.

these flight units would be lightened as much as possible whilst they were fitted with flight auxiliaries, no extra lightening work would be done that might delay their availability.[129] When the formal meetings got underway the following day, a division of labour seemed to have been agreed upon, with A-S manufacturing a number of sub-components, and having responsibility for arranging engine installation; a wooden engine mock-up was to be sent to A-S, who would liaise with Gloster.[130]

Yet this apparently amicable collaboration soon hit trouble at the executive level again. In July 1942, with the flight engines nowhere near complete, Pierson was again complaining to MAP that Metrovick's prerogatives were being infringed upon. The Ministry had placed contracts directly with Armstrong Siddeley for F.2 components; Pierson insisted that in order to maintain technical control over the engine, all work should be issued by Metrovick as sub-contracts.[131] According to the Director of Engine Development, however, this mode of working had been agreed on by both parties, and he noted that Pierson did not seem to realise how close the collaboration between his technical colleagues and Armstrong Siddeley was.[132] Clearly Pierson did not, as the correspondence rumbled on for another month or so. Bulman, whose sympathies on the whole lay with the aero-engine companies, with whom he had been closely professionally involved for over a decade, was unimpressed. His whole job consisted of making judgements on the development capability of aero-engine companies, and he did not think much of Metrovick's unassisted capability.[133] In an exasperated minute, he made this point to Roxbee Cox, arguing that the F.2 was a 'very long way from practical aero engine standard,' and that by themselves Metrovick would never achieve that standard.[134] As he put it: 'The only hope I see for that project is to get them to realise that fact, and to welcome without any inhibition every kind of help and guidance from Armstrong Siddeleys, which they are ready to offer.'[135] Unfortunately, though Pierson's contractual issues were settled by late summer 1942, Metrovick never availed themselves of Armstrong Siddeley's help in the fashion that Bulman had suggested; whether it was pride in their technical ability, or simply an inability to see 'how little they knew about aero engines,' the collaboration never went beyond looking at the installation of the F.2 in the F.9/40.

Part of the reason may have been due to the internal politics of Armstrong Siddeley; mere days after Smith's January meeting at Armstrong Siddeley, Tresilian had been sacked as chief

[129] 'Preliminary meeting,' 17 Mar 1942, NA AVIA 15/1509
[130] 'Minutes of Meeting no. 1,' 18 Mar 1942, NA AVIA 15/1509
[131] HC Pierson to H Roxbee Cox, 2 Jul 1942, NA AVIA 15/1509
[132] Minute DED to DDSR1, 6 Jul 1942, NA AVIA 15/1509
[133] The importance of expert judgement in the engine procurement process is made in Nahum (2004)
[134] Minute DED to DDSR1, 30 Jul 1942, NA AVIA 15/1509
[135] Minute DED to DDSR1, 30 Jul 1942, NA AVIA 15/1509

designer.[136] Tresilian was a proponent of gas turbines; he had been in favour of manufacturing the Whittle design, and had started design studies for a ducted fan design in 1941.[137] However, he had a difficult relationship with A-S's general manager HS Rowell, who had hoped to be appointed chief designer before Tresilian was brought in from outside the company. Tresilian had urged close collaboration with Metrovick, whereas Rowell and the Hawker Siddeley Group management backed the work of Fritz Heppner, a gas turbine designer who had been hired by the A-S board to develop his own designs. Tresilian considered these complex contraflow units to be impractical, and seems to have been fired after setting out his views in a full and frank discussion with some of the board members.[138]

In the autumn of 1942, after the RAE had rejected Heppner's designs, Armstrong Siddeley began its own collaboration with the RAE. This was an experimental axial jet called the ASX, which drew on the RAE's work on the F.2's aerodynamics. The compressor (known to the RAE as 'Sarah') was based on the F.2's compressor with added low-pressure stages, but the rather unusual reverse-flow engine layout was Armstrong's.[139] The company received a contract for the engine in October 1942, and the ASX first ran in late April 1943; compared to the poor performance and progress of their piston designs, clearly Armstrong Siddeley could develop an engine if they put their minds to it.[140] Perhaps crucially, by the time A-S embarked on the design of the ASX, a wider ecology of gas turbine engineers had begun to form which the company could draw on, including such institutions as the GTCC; as Hermione Giffard has noted, if the lack of collaboration with MV meant that the F.2's development was retarded, it also meant that Armstrong Siddeley was unable to gain much gas turbine engineering knowledge.[141] In the last years of the war and the early post-war period, A-S concentrated on the development of turboprop engines based on their jet designs, in which they were reasonably successful.[142]

The F.2 takes to the skies

In contrast to some of the other UK jet development projects, Metrovick's progress with the F.2 was painfully slow. By 1941, the company had begun to follow a more aero-engine-like

[136] The details of Tresilian's career in this section are taken from Richard Hodgson's biographical website at http://www.designchambers.com/wolfhound/TresilianCV.htm (accessed 23 Aug 2012).
[137] He hired TP de Paravincini, a Rolls-Royce engineer, who worked on A-S's gas turbine projects. See Lawson (2008), 68-70.
[138] Giffard (2011), 136-140 covers A-S's gas turbine work.
[139] The manufacture of this compressor does not ever seem to have been discussed with Metrovick; presumably the RAE considered the company to have its hands full with F.2 development.
[140] Though the ASX only ever flew in the bomb bay of an Avro Lancaster airborne testbed, and was by no means trouble-free in running; see the memo by W Merchant, 9 Sep 1943, MOSI 1996.3235/1/6.
[141] Giffard (2011), 137-8
[142] Lawson (2008), 70-71; Giffard (2011), 139-140.

development process, especially with regard to the F.2's combustion chamber, and had formed a 'development section' within the Mechanical Engineering Department to concentrate on this aspect of the work.[143] The RAE had urged the expansion of Metrovick's testing facilities, and in April the company received MAP approval for the construction of an engine test house in Wincham, Cheshire. Apart from the lack of space at Trafford Park, compressor testing had suffered because deposits from the Manchester smog built up on the compressor blades. Built in the grounds of the New Cheshire Salt Works, the new test house was remote enough for safe testing and for security; somewhat ironically, it was found that the air intake of the test house required filtering because of smoke drifting from nearby Northwich and the salt deposits in the atmosphere.[144] As it became clear that some of the D.11's compressor problems were caused by compressibility effects, Metrovick sought to gain approval for the construction of a high-speed cascade tunnel, which it received in October 1941.[145] This would be of importance for building a flight engine, as the lower temperatures at altitude would make compressibility effects more important. By January 1942 the RAE was able to inform MAP that the early tests on the F.2 had been positive, and asked that the Ministry place an order for a preliminary batch of up to twelve production engines, to incorporate minor improvements on the basis of the testing.[146]

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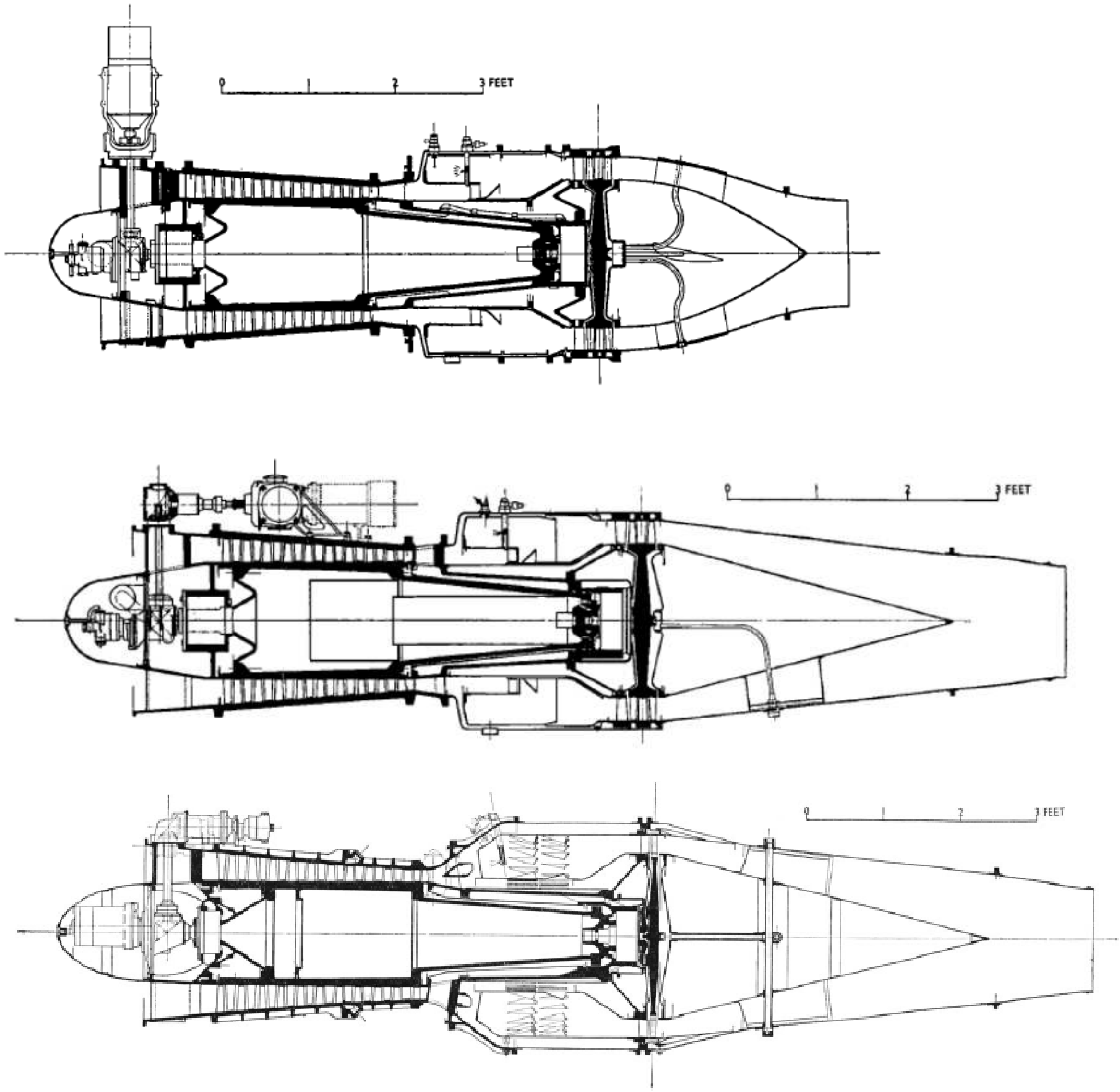
[143] See DM Smith's memo of 13 Jan 1941, MOSI 1996.3235/1/4, which suggests it had been formed some time before this date. An organisation chart dated September 1943 is in MOSI 1996.3235/1/6. The section was headed by Smith, and had roughly 40 members of staff by 1943.
[144] DM Smith, 'Monograph on Gas Turbine Research and Development', 23 Aug 1946, NA AVIA 44/570, 26.
[145] See the notes on the letter from DM Smith to RDE1, MAP, 26 Sep 1941, MOSI 1996.3235/1/4.
[146] H Constant for Director RAE to DDSR1, 15 Jan 1942, NA AVIA 15/1509

Figure 3.1 – F.2 development (Top to bottom: initial version; flight test version, F.2/4)[147]



However, despite the F.2's bench running in December 1941, modifications to the first batch engines to make them flight-worthy were not completed until November 1942.[148] This seems to have been partly due to continuing material difficulties, now made more acute because the expanding number of jet projects at other manufacturers was making demands on the limited supplies of high-temperature metals.[149] Other problems were encountered with overheating bearings, necessitating redesign, and with the combustion chamber designs. The RAE's combustion research programme was more extensive than Metrovick's, so Farnborough was able

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[147] Images from Smith (1947).
[148] Kay (2007) suggests that these were known as F.2/2s
[149] See eg. Karl Baumann to Harold Roxbee Cox, 3 Sep 1942, MOSI 1996.3235/1/5. In November 1942 the F.2 was third in materials priority behind the Power Jets/Rover and de Havilland engines; see the report on the materials conference dated 11 Nov 1942, MOSI 1996.3235/1/5. Armstrong Siddeley's ASX had the lowest priority.

to provide much advice, and temporarily seconded the engine department's AD Baxter to the firm.[150] The delays to the F.2 did nothing to help the engine's production prospects; given the ongoing problems with the development and production of the Power Jets W.2B, the Ministry of Aircraft Production had no desire to tie up further productive capacity by launching another under-developed engine.[151] In an attempt to increase the number of engines available for development, Metrovick tried to build up the sets of spares ordered with the initial engines into complete units, but this took time, due to the inadequate facilities for building and stripping engines.[152] There was also the problem that Gloster made changes to the layout of the engine installation, necessitating redesign of the flight units to move auxiliary equipment.

The modified flight units passed their acceptance tests and were sent to Glosters in February 1943, but no F.9/40 airframe was available until the summer; the aircraft undercarriage had to be modified in order to ensure the underslung engines had enough ground clearance.[153] The third flight engine had been fitted to a Lancaster testbed, with modification work starting on the aircraft in early 1943, and it first flew in June of that year.[154] The aircraft used was fairly elderly – it had been the Lancaster's prototype – and suffered from frequent problems with its piston engines, which meant that the flight testing suffered from delays.[155] It was soon decided that the aircraft would be replaced by a more modern specimen, and the engine was installed in a Lancaster Mk II.[156] The F.2-powered F.9/40 began its ground trials in August 1943, but the test pilots considered the F.2's idling thrust of 350 lbs. dangerously high.[157] After modifications to the controls and the nozzle, the idling thrust was lowered to 220 lbs., and the first flights with the F.2-powered F.9/40 took place in November.[158] Again, progress was slow, as a British winter provided less than ideal weather conditions for flight testing. Unfortunately, on a test flight in April 1944, one of the engine compressor rotors burst in mid-air, killing the pilot in the subsequent crash. Though the cause was traced to metallurgical faults in the rotor forgings, the investigation and

[150] Hayne Constant to Metropolitan-Vickers, 22 Aug 1942, MOSI 1996.3235/1/5.
[151] See eg. the note to the Minister by the Controller of Research and Development, 'Jet Propulsion Engines in Bombers', 9 May 1942, IWM HTT 383.
[152] See Baxter's criticisms mentioned in the memo by JM Newton, Superintendent MV Mech Eng Dept, 3 Sep 1942, MOSI 1996.3235/1/5
[153] 'F.2 Engine Development and Compressor Research,' 6 Apr 1943, MOSI 1996.3235/1/6. The Whittle and de Havilland engines fitted to the F.9/40 were set into the wing rather than underslung.
[154] W Merchant, 'Report on Visit to RAE on 27/1/43', MOSI 1996.3235/1/6; Note AD Baxter to DM Smith, 29 Jul 1943, MOSI 1996.3235/1/6. The modification work was carried out by Armstrong Whitworth Aircraft.
[155] Note AD Baxter to DM Smith, 29 Jul 1943, MOSI 1996.3235/1/6; Smith (1947); See also the correspondence between Roxbee Cox and Smith, Jul 1943, MOSI 1996.3235/1/7
[156] H Roxbee Cox to K Baumann, 27 Jul 1943, MOSI 1996.3235/1/7. A Lancaster II was presumably chosen because Armstrong Whitworth were building that mark at the time.
[157] Smith (1947), 475.
[158] Memo by W Merchant on F.2 progress, 9 Sep 1943, MOSI 1996.3235/1/6; Smith (1947), 475.

additional manufacturing and design precautions 'seriously retarded progress' on the engines during 1944.[159] By now it had become clear that the F.2 was very unlikely to enter service any time soon, as there were no production facilities for the engine, and no potential user aircraft.[160]

Yet this was not necessarily a foregone conclusion; as late as September 1943 MAP was requesting details of the production space and tooling that would be required for the manufacture of 50 or 100 F.2s at the rate of 2 units per week.[161] Based on its cascade tunnel testing, Metrovick was also planning a radically improved fourth batch design, which it called the F.2/4.[162] This was practically a new engine; though it shared the basic mechanical design as the F.2, it had a new 10-stage compressor and used a single-stage turbine, producing almost twice the thrust of the early F.2 models.[163] It was expected to be ready for bench testing in late 1944; crucially, MAP was considering potential aircraft designs that would use it as a powerplant.[164] Metrovick was expanding its testing capacity for the engine, building a new works and test facility at Barton Dock in Trafford Park, and the development section was moved there in early 1944; as the F.2/4 compressor required too much power to be tested at Trafford Park, an 8,000 hp test rig was installed at Wigan Power Station.[165] Initially, one of the pre-production Gloster Meteors (serial DG210) was earmarked for the engine as a testbed; though the airframe was later redirected as the first production Meteor Mark I, the company was considering other jet designs using the F.2, as were others.[166] In October 1943, Roxbee Cox asked Smith to send details of the F.2 to WEW Petter, Westland aircraft's chief designer, who was considering a jet-powered fighter-bomber; Roxbee Cox suggested that the fourth batch units would be most suitable.[167] The aviation historian Tony Buttler has suggested that the Westlands board were not particularly

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[159] DM Smith, 'Monograph on Gas Turbine Research and Development', 23 Aug 1946, NA AVIA 44/570, 7.
[160] The Gloster Meteor was to go into production with Rolls-Royce Welland engines in the Summer of 1944, switching to the more powerful Rolls-Royce Derwent engines in early 1945. The F.2 had been proposed as a speed augmentor for the Bristol Beaufighter, but by October 1943 MAP had decided this project had no operational use; see RH Schlotel to DSP representative, MV, 30 Oct 1943, MOSI 1996.3235/1/7.
[161] MV Contracts Dept to MAP, 16 Sep 1943, MOSI 1996.3235/1/7
[162] DM Smith, 'The Aerodynamic Development and Axial Flow Compressor Blading for M.V. Jet Engines,' n.d. (but c. 1970). I am grateful to Frank Armstrong for a copy of this report.
[163] Though later versions appear to have had 11 stages; I have been unable to discover precisely when this change was made.
[164] See eg AH Travis (MAP Visiting Technical Officer, MV), 'Discussion on Metro Vickers Design Proposals for 3rd and 4th batch units, 11 May 1943, MOSI 1996.3235/1/7; DMS to RDE(T)1, MAP, 27 Oct 1943, MOSI 1996.3235/1/7
[165] DM Smith, 'Monograph on Gas Turbine Research and Development', 23 Aug 1946, NA AVIA 44/570, 11;27.
[166] Roxbee Cox to K Baumann, 16 Nov 1943, MOSI 1996.3235/1/7; DG Tobin to DM Smith, 18 Nov 1943, MOSI 1996.3235/1/7.
[167] Roxbee Cox to DM Smith, 4 Oct 1943, MOSI 1996.3235/1/7

supportive of the project, and in September 1944 Petter moved to English Electric.[168] Though he continued to work on jet projects there, they did not incorporate the F.2/4.

However, by the spring of 1944 another aircraft project was considering the use of the Metrovick engines. This was a Saunders-Roe jet flying boat fighter to MAP specification E.6/44.[169] Ordered in March 1944, the twin-engined SRA.1 was intended for the island-hopping campaigns of the Pacific War, and the F.2/4's good specific fuel consumption would be an asset for the long ranges needed.[170] The F.2/4 was also considered for the E.9/44 Armstrong Whitworth tailless research aircraft.[171] However, at this point changes in MAP's production programme began to affect the project. The F.2/4 was now expected to be bench tested in early 1945, and the Ministry's production programme was based on a production rate of some two engines per month through 1945. As the Deputy Director responsible for the programme put it, this would necessitate adjustment of the aircraft programmes using the engine, and he was worried that even if the F.2/4 were successfully ground tested it might not 'have a fair trial in the air' because of the cancellation of the aircraft projects using it.[172]

This prediction turned out to be prescient; though the F.2/4 was bench-tested in January 1945, and passed a 100-hour type test later that year, the only type designed around the engine was the SRA.1 flying boat.[173] The end of the Pacific war meant that the operational need for the type was much reduced, and though three prototypes were completed, first flying in 1947, the type was not to be put into production. It was clear that though the F.2/4 was powerful – test-bed aircraft using it set a number of climb and time-to-height records – and had the lowest specific fuel consumption of any existing British jet engine, it was unlikely to gain any more orders. Metrovick had no mass production facilities for the engine; indeed it had no engines in production. In contrast, the aero-engine companies had both development and production capacity, and the designs then under development and on the drawing board were likely to be more powerful than the F.2, especially as the design was reaching the end of its development potential. The F.2/4 reached a maximum thrust of some 4,000 lbs; in 1945, Rolls-Royce had the Nene under test and de Havilland the Ghost, both of which were developing over 4,500 lbs and would go on to

[168] Buttler (2003), 7-8.
[169] See RH Schlotel's invitation to the E.6/44 'Advising Design Conference,' 26 May 1944, MOSI 1996.3235/1/7.
[170] Saunders-Roe had begun the design in 1943 after a 1942 Admiralty proposal, and had had advice from the Marine Aircraft Experimental Establishment; see Tagg and Wheeler (1989), 77.
[171] DDTE to DM Smith, 1 Jul 1944, MOSI 1996.3235/1/7.
[172] DDTE to DM Smith, 1 Jul 1944, MOSI 1996.3235/1/7.
[173] The Armstrong Whitworth flying wing being fitted with Rolls-Royce engines.

produce over 5,000 lbs thrust. If Metrovick wanted to gain production contracts, it would have to try this with another design.

Apart from the more routine development work carried out on the basic F.2 design, Metrovick also carried out a more radical research programme in parallel with the F.2's flight development work. This was the F.3 'thrust augmentor', an F.2 gas generator fitted with a turbine-driven aft-mounted ducted fan. A fan moves a greater amount of air more slowly than a pure jet, and is thus more efficient at intermediate flight speeds. Though Frank Whittle had suggested the use of a fan in his early jet patents, Metrovick seem to have come across the idea independently when examining ways of improving the propulsive efficiency of pure jets in 1941. According to Smith's post-war report to MAP, the company started design work on the augmentor as a private venture, but by 1942 MAP had issued a development contract for the design. [174] Discussion of the unit with the RAE was certainly taking place by February 1942, and by early 1943 it had been decided to build two units.[175]

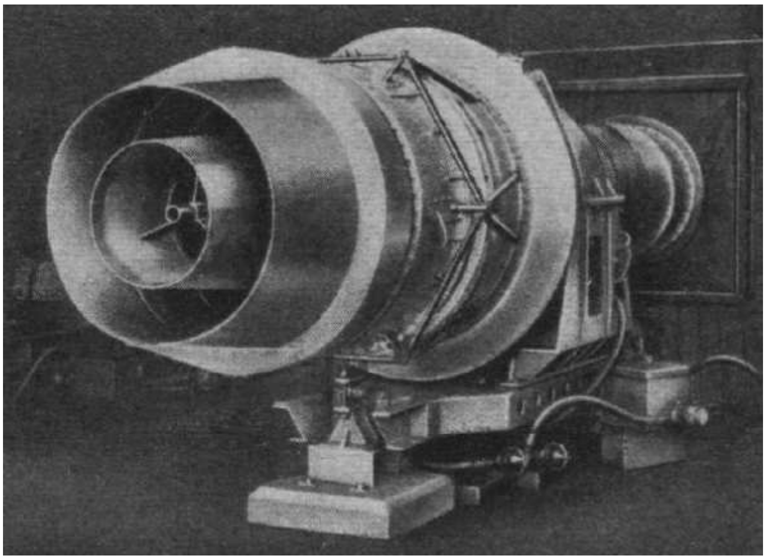

Figure 3.2- F.3 Thrust Augmentor[176]

Testing commenced in August 1943 on one of the second batch engines, and given the augmentor's complex design, development seems to have been remarkably trouble-free. The F.3 gave roughly 65% more thrust than the base F.2 jet for a 25% weight increase; the specific fuel consumption was also about 35% lower than the next best jet available.[177] The improvement in

[174] DM Smith, 'Monograph on Gas Turbine Research and Development', 23 Aug 1946, NA AVIA 44/570, 9-10.
[175] W Merchant, 'Visit of Mr Howell, RAE', 24 Feb 1942, MOSI 1996.3235/1/5; MV Contracts Manager to DDRDE, MAP, 12 Mar 1943, MOSI 1996.3235/1/6.
[176] *Flight,* 25 Apr 1946.
[177] See the technical profile of the F.3, *Flight,* Apr 25 1946, 420-423.

thrust and fuel consumption made the F.3 attractive for a jet-propelled bomber design; at the Ministry of Aircraft Production, Henry Tizard was a great supporter of the design, pointing out that though the engine was heavier than other jet units, for a long-range aircraft what mattered was the combined weight of engine and fuel.[178] Despite this support, the F.3 suffered from a lack of testbed aircraft and projects designed to use it; though at one point an F.9/40 was earmarked for flight testing, it was never fitted with the augmentors; as with the F.2, its lack of production facilities and aircraft projects reinforced one another in a vicious spiral. The F.3 ended up as a research unit at Power Jets (later the National Gas Turbine Establishment), where it seems to have been left unused.[179] Metrovick also designed the F.5, an 'open-fan' thrust augmentor, which was intended to be lighter than the F.3, giving slightly more thrust; it is unclear how extensive testing was before Metrovick closed its jet propulsion projects. [180]

Conclusion

What were the achievements and failings of Metrovick's jet programme, and how did it compare to its competitors? On the plus side, it had contributed greatly to the development of axial compressors and axial compressor theory and had produced the only workable British axial engine of the Second World War. This expertise meant that it had been, and would continue to be, supported by the Ministry of Aircraft Production to develop axial engines; by the end of the war, it was the only non-aeronautical manufacturer with an active jet development programme. Yet a more critical view would suggest that the company never really committed to jets as a new business area, being content to rely on MAP funding rather than aggressively commit its own resources to the development of the F.2 units. In terms of Braun's taxonomy of failure, this was a failure of timely development.[181] Though Metrovick adjusted its working methods, forming a development section in 1941, and constructed new test and development facilities, the work was on a small scale compared to the resources available at other companies. Even though some manufacturing was carried out by MV's general workshops, the development section itself does not ever seem to have been more than 50 strong; by contrast, in 1941 Power Jets had over 300 staff, which rose to almost 1,000 by 1943, and once Rolls-Royce became involved its development efforts dwarfed other gas turbine projects.[182] Indeed, as far back as the initial work on the B.10, Metrovick's projects had always been limited by development rather than by design resources.

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[178] See Tizard's notes on the (MAP) Controller of R&D's minute to the Minister, 13 May 1942, IWM HTT 383
[179] Personal Communication, Nick Forder. The F.3 is now on display at the Manchester Museum of Science and Industry.
[180] See the images and description in *Flight*, 28 Nov 1946,593, and 2 Jan 1947, 18.
[181] See the discussion in the introduction.
[182] See the chart in Giffard (2011), 239. Giffard (2011), 124, cites a Rolls-Royce figure of a total of 14,000 hours of gas turbine test running by October 1944, vs. 12,000 hours for the rest of the industry combined.

Though this approach was to some degree conditioned by Metrovick's deliberative technical style, stemming from steam turbine development, conscious decisions were taken not to closely collaborate with engine manufacturers such as Armstrong Siddeley; if, as seems likely, these decisions were motivated by a sense of technical possessiveness and a desire for commercial control on the part of Metrovick's management, then in the long run this approach was counter-productive.

In terms of business strategy, MV never committed itself to jet production. Given the actual numbers of jet engines produced during the war – far fewer than some of the early predictions – this was perhaps a fortuitous choice.[183] For the aero-engine manufacturers, once it became clear that the gas turbine was a viable technology, their core business demanded that they make the switch to gas turbines. Aero-engine manufacturers already had large development and production resources (whose expansion in the past few years had been mainly state-funded), which they could switch to gas turbine development once a basic familiarity with the technology had been achieved. But for Metrovick, a large company with a diversified product portfolio, the pool of development resources to be switched to gas turbines was limited; any major investment would have to come from the company itself, or from the state. Yet from early 1940 onwards it seems that MV was becoming a back-up partner for the RAE, as evidenced by the fact that the Establishment initially sought to collaborate with Power Jets on a jet design. Despite the Engine Department's preference for the axial design, the building momentum of Whittle's engine meant that the RAE committed the bulk of its gas turbine design and analytical resources to the latter project. Though it is debatable whether this slowed the F.2 – Metrovick had sufficient design resources and support that the bottleneck was in development – it is suggestive of a project being run as a second string. By the time the F.2 began to look like a viable project, the Ministry of Aircraft Production had had its fingers burned by the development problems of the W.2 and the H.1, and was unwilling to provide the necessary resources for F.2 production. As a result, Metrovick's policy seems to have been to continue the development at their best possible pace, which was all funded on a cost-plus basis.

At various points MAP clearly considered production of F.2 variants, but the company's slow development progress and lack of committed production facilities meant that the Metrovick engine was always at a disadvantage to the Ministry; though it had good fuel consumption, its increases in power and reductions in weight were slower than for other engine designs, putting it

[183] Giffard (2011), 63 gives the total number of production jet engines during the war as 745; over 250,000 piston engines were produced in the UK in the same period.

at a production disadvantage.[184] Given these factors, the Ministry clearly decided to treat the company essentially as a large experimental and research partner. The difficulties of this approach were to come to a head in the immediate post-war period; the ways in which the company negotiated this is the subject of the following chapter.

[184] See eg. the note to the Minister by the Controller of Research and Development, 'Jet Propulsion Engines in Bombers', 9 May 1942, IWM HTT 383.

Chapter 4: Jets and ships

Introduction

As shown in the previous chapter, though it carried out large amounts of gas turbine development work during the Second World War, Metrovick did not manage to gain a production contract. In the post-war period the company was initially successful in gaining further jet engine development contracts, but it was ultimately forced to divest itself of its jet engine business. Yet in the same period, another strand of its wartime gas turbine work was more successful, namely its naval business. The firm's naval engines fell into two categories: light-weight high-powered engines for fast attack craft, and as part of a larger integrated propulsion system for large warships. This chapter will compare the Admiralty and MAP's procurement, place it in the context of national defence policy, and will show how Metrovick's greater success in the naval arena was the result of the Admiralty's technical and production requirements better matching Metrovick's style; more specifically, its requirements for power and durability, as well as the production numbers required, meant that the Navy's gas turbines were closer to industrial units than to aviation engines. I will also show how the Navy's embrace of the gas turbine was in part due to perceived failings in its pre-war propulsion equipment, and was part of the development of a wider portfolio of propulsion technologies that it hoped would allow it to regain a position of technical leadership.

The structure of this chapter is as follows: I will first of all examine the UK's post-war military-industrial situation. I will then give an overview of the Admiralty's engineering research establishment, and will show how it partnered with MV to develop a naval gas turbine for small craft; I will then briefly describe some of the other technologies funded by the Admiralty for this purpose, including diesel and other gas turbine designs. I will then compare the company's experience with the Ministries of Aircraft Production and Supply in the same period, and will describe how Metrovick came to divest themselves of their jet business. I will show how the Admiralty's procurement process for warship propulsion systems was changed in response to perceived equipment failings uncovered during the Second World War; by giving a brief sociological overview of the Navy's Engineering Officer corps, I will show how changes in its makeup enabled the assessment of new technologies, including combined steam and gas turbine plants. Finally, I will describe Metrovick's involvement in the procurement of these systems from the 1950s to the 1960s, and how the company left the field.

Defence-industrial Policy

British military-industrial policy in the immediate post-war period was guided by four principles, set out in the 1946 Statement Relating to Defence: concentration on research; limited introduction of modern equipment (chiefly jet aircraft and armoured vehicles); maximum use of accumulated stocks; and the maintenance of 'a reasonable war potential.'[1] This war potential was to be maintained by the letting of repair contracts for existing equipment, as well as through R&D contracts. Maintaining this capacity was somewhat problematic, in that a balance had to be struck between the total amount of capacity, and the health of individual firms thus supported. This was especially true in an environment where the civilian economy required many of the same skills and resources that the arms industry consumed. The overheads of military production meant that combining both types of work in a factory was generally inefficient, and firms were reluctant to do so unless compensated. (Thus, for instance, the Ministry of Supply had trouble in giving radio and radar research contracts to the electrical industry; in a booming civilian market they were concentrating on consumer radios and the like.)[2] Multiple defence firms were necessary, but at the same time the UK's global military commitments and its domestic economy required severe reductions in procurement budget; as a result, the UK defence industry was under-employed until Korean War rearmament.[3]

The military-industrial strategy also privileged the maintenance of industrial capacity for a long war over the procurement of capital-intensive sophisticated systems, despite the ostensible commitment to research.[4] The concentration on war potential was also in tension with a desire to rationalise the aircraft industry; in 1946, there were twenty-seven airframe and eight engine companies in the UK. Between 1945 and 1950, the Ministry of Supply (MoS - the Ministry of Aircraft Production had been merged with this Ministry in 1946) supported 19 aviation companies with development contracts, repair work, and limited re-equipment contracts.[5] Although the MoS was aware that this was a large number of companies to support, it was relatively unwilling to force mergers, and preferred to let the industry form larger groups organically (some of the weakest companies did indeed fail, such as Miles Aircraft, which was taken over by Handley Page.)

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[1] Cmd. 6743.
[2] Geiger (2004), 126.
[3] Geiger (2004), 298; though the 1949 Defence White Paper did call for an increase in expenditure to modernise and re-equip the Army and the RAF; see Lider (1985), 512.
[4] Geiger (2004), 128. The latter strategy would have suggested the maintenance of fewer but larger companies. There were exceptions, such as the Defence Research Policy Committee's 1947 suggestion that guided missile projects should be funded; see Agar and Ballmer (1998), 233.
[5] Geiger (2004), 124-5; combined with the post-war shrinkage of the RAF, this limited reequipment was sufficient to have replaced most of the RAF's front-line fighters with jet types by 1950; see Edgerton(1992), 98-99.

In 1950 the Treasury suggested a plan to reduce the number of companies to 13, but this was thwarted by the onset of the Korean War.[6]

Naval R&D and the gas turbine

The main institution responsible for the Admiralty's gas turbine research was the Admiralty Engineering Laboratory (AEL). It had been set up in 1917 in response to perceived shortcomings in British marine engineering, especially when compared with German practice.[7] The AEL's propulsion work concentrated on the internal combustion engine, particularly on diesels for submarines and small craft. Research and development work on internal combustion engines continued throughout the interwar period, with the AEL keeping abreast of work elsewhere through its liaison officers. The AEL provided the Admiralty representative on the Aeronautical Research Committee's Engine Sub-Committee, and so was kept fully informed of the Air Ministry's gas turbine research work.[8] The AEL was clearly aware of Metrovick's work; its Superintendent visited Manchester to view the B.10 on test in late 1940.[9] Whether directly influenced through the Engine Sub-Committee or through other contacts, in 1940 the AEL formed its own Gas Turbine Section.[10] Its initial work on gas turbines appears to have been on power turbines coupled to a free-piston gas generator, the so-called 'Fratric' project, but this had been abandoned by late 1943, by which time the AEL was also providing liaison officers to the MAP's Gas Turbine Collaboration Committee.[11]

With few exceptions (mainly submarines and small craft), the Royal Navy's warships were powered by steam turbines; there was therefore a large pool of engineering officers that understood the theoretical advantages of the gas turbine, especially its potential for light weight and compact size; it would also require fewer sailors to operate it, as the boilers used to produce

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[6] Geiger (2004), 124-5.

[7] A (very) brief history of the AEL is 'Our Half Century: A Brief History of the Admiralty Engineering Laboratory,' NA ADM 227/2922. After the First World War the AEL was also given the responsibility for the development of electrical plant for warships.

[8] As mentioned in Chapter 1, the AEL representative, WG Cowland, was initially somewhat sceptical about the merits of the gas turbine for aircraft (and indeed for naval) use. He later rose to head the AEL, and retired as a rear-Admiral and deputy Engineer-in-Chief of the Fleet; he was also a director of Power Jets(R&D) Ltd. After its nationalisation, Power Jets was intended to carry out research into the applications of gas turbines to all sectors, hence the presence of a senior naval engineer – even if he was a somewhat sceptical one.

[9] See the letter by DM Smith to Capt. Maxwell RN, AEL, 29 Nov 1940, MOSI 1996.3235/1/3.

[10] 'Our Half Century: A Brief History of the Admiralty Engineering Laboratory,' NA ADM 227/2922, 2. Given the dates, it is likely that this took place before the AEL's representatives had visited MV to view the B.10.

[11] Le Bailly (1991), 83. During the late 1930s the ARC's Engine Sub-Committee had discussed the use of free-piston gas generators for aircraft gas turbines, but had dismissed the idea after negative evaluations from the RAE.

steam required large teams to tend to them.[12] Faced with a growing number of gas turbine projects in the aeronautical arena, the Admiralty decided to investigate the development of gas turbine plant for naval propulsion. However, the gas turbine's high fuel consumption meant that its use would have to be restricted to short-range craft. The Admiralty decided to fund two lines of enquiry: a powerplant for fast coastal craft, and a boost turbine for larger warships, possibly in conjunction with next-generation steam plant.[13] As warships spend most of their time cruising at low speeds, the gas turbine's high fuel consumption was not considered to be a serious drawback for a boost unit, which by its nature was used only infrequently.

Metrovick goes to sea

For the small-craft engine, the Admiralty decided to take advantage of the work done by Metropolitan Vickers. There were a number of reasons for this: firstly, Metrovick were a company with naval propulsion turbine experience. Apart from their pre-war marine turbine and gearing business, Metrovick had some experience of marine engineering for light craft, having designed and built the steam plant for the Royal Navy's Steam Gun Boats (SGBs) in 1940.[14] The SGBs were large coastal craft intended to combat German torpedo boats; due to a shortage of high-powered diesel engines they were designed to use a light-weight steam turbine, and the company worked closely with the turbine engineers of the Engineer-in-Chief's department. Secondly, the AEL would have been familiar with the company's gas turbine work; as noted above, its staff had seen the B.10 on test. The Metrovick gas turbines had started out as shaft power designs, which meant that the company had experience of designs more suitable for naval propulsion than jet engines. Perhaps most crucially, the costs of adapting an existing gas turbine design would be far lower than designing an engine from scratch, and MV was not committed to aeronautical production.

The first discussions on using a Metrovick gas turbine in naval craft took place between the Admiralty and Metrovick in July 1942, and the Engineer-in-Chief's department investigated the design of gas-turbine-powered fast craft during 1943, but it was not until August 1943 that concrete design proposals were made.[15] The AEL Superintendent met with Baumann and Smith for a detailed technical discussion; later that month a contract was placed for 3 G.1 or 'Gatric' units based on the current third batch F.2s then being designed, permission being obtained from MAP to use three of the units currently under construction at Metrovick.[16] The Gatric units were

[12] Friedman (1993)
[13] Rippon (1994), 167.
[14] Lay and Baker (1948)
[15] *The Engineer*, 25 Jun 1948, 621; See the discussion of the E-in-C about using Metrovick gas turbines in high speed craft, Jun-Aug 1943, NA ADM 1/15319
[16] 'Discussion with Metropolitan Vickers re Gatric,' 13 Aug 1943, NA ADM 227/506; Whyte (1978), 27; *The Engineer*, 25 Jun 1948, 621. It seems that MAP were expected to meet the base cost of the F.2 gas

to be fairly simple; because of the F.2 gas generator's characteristics, they were not designed for efficient part-load operation, but were to be used as full-speed boost units.[17] Given Metrovick's resource constraints on development and manufacture, this was presumably to do with the third-batch units' position in the production programme; the materials were there for them, but they units themselves were not committed to any particular experimental programme. The first third-batch engines were due to be bench tested in May 1944, but the units earmarked for the Admiralty were the last of the batch, numbers seven through nine.[18] As mentioned above, being able to use existing jet designs as gas generators was a bonus for the Admiralty, as the Ministry of Aircraft Production had already shouldered a large part of the development costs; as naval powerplants were built in far smaller numbers than aero-engines, it was impossible for manufacturers to amortise development expenses across production, leading to large up-front costs. However, by the summer of 1944 the Gatric gas generators had a lower production priority than the F.2/4 jet engines under contract to the Admiralty, presumably because the latter were intended for the E6/44 project designed with the continuing Pacific war in mind.[19] In the meanwhile, the Admiralty asked Metrovick to test the response of the F.2 to diesel oil, which was the planned fuel for the gas-turbine-powered boat (rather than aviation kerosene).[20]

The Admiralty had also been thinking more widely about its future fast craft propulsion requirements. In 1943 it set up a committee of engineers, chaired by the distinguished aero-engine designer Sir Roy Fedden (among its members was Harry Ricardo), to investigate future powerplant developments.[21] One of the UK's pre-eminent piston aero-engine designers, Fedden had left the Bristol Engine Company in 1942 after disagreements with the board, and spent the rest of the war heading a number of committees and technical missions dealing with engine and aeronautical matters.[22] At the time the UK's coastal forces were mostly powered by petrol engines (unlike the diesel-powered German *Schnellboote*), and the volatile fuel was considered to

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generators; see the note by E-in-C, 28 Jun 1943, NA ADM 1/15319.

[17] 'Discussion with Metropolitan Vickers re Gatric,' 13 Aug 1943, NA ADM 227/506.

[18] DM Smith to RDE(T), MAP, 27 Oct 1943, MOSI 1996.3235/1/7. Because of the way engines were rebuilt with different compressors, F.2 production is very confusing, but it appears that only three first batch engines were built before the Admiralty units; I am grateful to Bob Pick for this information, taken from RR Whyte's production charts.

[19] DM Smith to Group Captain Watt, DDTE, MAP, 12 Jul 1944, MOSI 1996.3235/1/7; see also chapter 3.

[20] RH Schlotel, MAP, to DDTE representative, Metrovick, 14 Jul 1944, MOSI 1996.3235/1/7

[21] Reynolds (2008), 222.

[22] I have been unable to locate the records of the Fedden committee; it is mentioned in passing in a number of secondary sources, eg Rippon (1994); Le Bailly (1991), and occasionally in post-war Admiralty correspondence. Among Fedden's technical missions were vists to the US and (in 1945) to occupied Germany. He was also instrumental in the founding of the postgraduate College of Aeronautics at Cranfield.

be a fire hazard in combat. The committee recommended the development of two technologies to give a leap in performance: both gas turbines and the Deltic diesel engine.

Like the Gatric, the Deltic was also inspired by aeronautical practice, and was associated with the Admiralty Engineering Laboratory. Developed by the Napier company, the Deltic was an opposed-piston diesel engine with its cylinder banks in a novel triangular configuration. This had been suggested by Herbert Penwarden, a draughtsman at the AEL. The naval Engineering Officer, Louis Le Bailly, has suggested that the design was inspired by the receipt of a Junkers Jumo engine captured in North Africa, but this seems fanciful: the AEL would have been aware of the existence of opposed diesels, as Napier had been building the Jumo designs under license since the 1930s.[23] Throughout the interwar years, the RAE had had a heavy-oil aero-engine research programme, and the ARC's engine sub-committee (on which the AEL was represented) had discussed the diesel's possibilities during the same period. However, the AEL's new Superintendent, Capt (E) C M Hall, had been a submariner, and so was more familiar with diesel engines than most RN Engineering Officers; the AEL was also the Navy's institutional home for diesel engine engineering and design, which made it the obvious place to come up with the Deltic.[24] Indeed, the AEL's initial assessments of the gas turbine suggested that the high-speed diesel might be superior, but that much would depend on the relative development of both technologies.[25] Development of the Deltic began after the Second World War, and the Admiralty spent large amounts on the engine and on a turbocharged derivative.[26] Faced with rising costs and changing operational needs the turbocharged version was cancelled in the mid-1950s, though variants of the Deltic were used in a variety of naval small craft, such as the *Dark*-class fast patrol boats (which could reach some 40 knots) and the *Ton*-class minesweepers.[27]

With regard to the gas turbine, the Gatric gas generators were finished in 1945 and were coupled to a four-stage power turbine. Testing and development of the complete units continued for the next year or so, by which time the rated power was 2,500SHP. Shore trials of the first unit were completed in August 1946, with the other two following in the coming months. In February of that year the Admiralty had commissioned the boatbuilders Camper and Nicholson to modify their motor gun boat MGB 509 (soon renamed MGB 2009) to accept the Gatric unit, using 'guidance

[23] Le Bailly (1991), 80. Napier built the Jumo 204 under license as the Culverin.
[24] The main use for diesels in the pre-war RN was as submarine powerplants; the AEL had carried out most of the Navy's research on the subject.
[25] WJ Robinson, 'Gas Turbines for Marine Propulsion', Jul 1943, NA ADM 227/452.
[26] Complaints about the cost can be found in NA T225/1412.
[27] The Deltic and a smaller derivate engine were both also used in railway locomotives.

drawings' provided by the Director of Naval Construction.[28] According to a later account published in the trade journal *The Engineer*, the end of the war and subsequent decommissioning caused some delays, but a formal contract was placed for the conversion by May 1946.[29] The conversion consisted of replacing one of the boat's three petrol engines with the Gatric, as well as adding extra air intakes (the gas turbine would require far more air than the previous piston engines) and rearranging some of the internal machinery.

Figure 4 – Gatric unit preserved in the Science Museum London. The power turbine and gearbox are on the left.[30]

Once the work had been completed, the Admiralty wasted no time in commissioning the boat, and it began its sea trials on 14 July 1947. These trials made MGB 2009 the first gas-turbine-powered naval vessel, and took place almost exactly 50 years after Charles Parsons had demonstrated *Turbinia* at the 1897 Diamond Jubilee Review.[31] The trials passed remarkably smoothly, with no major faults being revealed; the most serious issues encountered were that the engine would lose power due to salt spray buildup on the compressor; this required spraying distilled water through the running engine every 20 hours or so.[32] By October 1948, the Admiralty had spent some £145,000 on the Gatric programme; writing to the Treasury to justify these costs, the Admiralty representative stated that the original cost of £100,000 had risen to £130,000 due

[28] Presumably because the variation in hand-built boats meant that fixed blueprints were inappropriate.
[29] *The Engineer*, 25 Jun 1948, 621
[30] Picture from Wikimedia Commons, user geni, http://commons.wikimedia.org/wiki/File:Gas_turbine_from_MGB_2009.jpg, accessed 24 Sep 2012.
[31] After the end of the Gatric programme, one of the units was donated to the Science Museum in recognition of its historic status.
[32] See the power graph in Harris (1965), 117.

to modifications to the unit after its initial trials (the original Gatric unit fitted to the MGB had been replaced with another unit in 1948).[33] The remaining £15,000 had been the result of extending the test programme to cover the effects of 'degraded' and contaminated fuels on the engine.[34] The trials confirmed the Admiralty's faith in the gas turbine, and provided cautious support for further gas turbine development. At the same time, it was becoming clear that some of the earlier enthusiastic predictions that the gas turbines might supersede piston engines had been rather premature – not least because of the gas turbine's high fuel consumption – and that the Admiralty would have to continue supporting research into both types for the next few years.[35] Their continuing support for the Deltic was informed by these considerations.

With the end of the Second World War, possibly influenced by the bench-running of the Gatric units, the Admiralty began to consider the use of pure gas-turbine propulsion. In September 1946 it placed contracts for two naval gas turbine sets: one with English Electric (EE) for a set based on steam practice, and one with Rolls-Royce designed on more light-weight lines.[36] The English Electric EL60 plant was intended to provide experience of gas turbine running at sea in a warship engine room. The Admiralty intended to use the Lend-Lease frigate *HMS Hotham* as a test-bed; the US Navy (USN) had agreed to the Admiralty's retention of the ship, in exchange for information on the testing.[37] The *Hotham* had twin turbo-electric drive; this would mean that the EL60 could be used to directly replace one of the steam plants fitted, driving the electric alternator. As a result the unit was a simple-cycle design with a heat exchanger, intended to fit the existing machinery spaces. However, both EE and the Admiralty had underestimated the difficulties of manufacturing gas turbine parts, even ones based on steam practice, and the EL60 was not ready for shore testing until September 1951. The unit's performance was disappointing (though many of its issues could have been fixed with further development), and as a result it was decided not to proceed with sea trials.[38]

By contrast, the Rolls-Royce RM60 design proceeded more smoothly. The RM60 was intended to be a main vessel powerplant; in order to provide reasonable efficiency for cruising as well as good peak power, Rolls-Royce chose to build a multi-stage gas turbine with compressor intercooling.

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[33] *Metropolitan Vickers Gazette*, Jul-Aug 1951, 10-11.
[34] RC Dinnie, GF Branch, Admiralty, to HJ Oram, Treasury, 5 Oct 1948, T225/1412
[35] J Montgomery, MoD, to HJ Oram, Treasury, 25 Nov 1948, NA T225/1412. The Deputy Engineer-in-Chief, WG Cowland, was still unconvinced that Gas Turbines would supersede piston engines within the next few years; see his note of 30 Oct 1948, NA T225/1412
[36] Trewby (1955). Trewby (at this time the officer in charge of the Engineer-in-Chief's gas turbine section) suggested that Rolls-Royce had made the approach to the Admiralty with a naval gas turbine proposal.
[37] Trewby (1955), 567; the US Navy had no major naval gas turbine programme at this time. Some discussion of the logistics of the *Hotham*'s retention is in NA T225/1412.
[38] Trewby (1955); Trewby (1962).

Though the unit was far more complex than an aircraft gas turbine, the construction techniques used were similar to those used in R-R's aero engines; as a result, manufacture of the unit proceeded relatively quickly, and it first ran on test in the summer of 1951.[39] Sea trials started in 1953; the Steam Gun Boat *Grey Goose* had had its Metrovick steam plant replaced by two RM60s, making it the world's first vessel to be powered solely by gas turbines. Though the plant was reasonably successful, running for 1,500 hours without major problems, fuel consumption was still too high for service use. Losses between components lowered the efficiency, and the costs of complex gas turbines were much higher than for comparable steam plant.[40]

Even before the conversion of MGB 2009 was complete, the Engineer-in-Chief's turbine section was thinking about commissioning Metrovick to build a larger unit than the Gatric. This would also be a boost unit for coastal craft, and would be based on the F.2/4 aero-engine to give some 4,000SHP. The Admiralty estimated that the cost of the unit would be some £150,000, and requested funds for a research programme for the next three years.[41] However, no contract was placed with Metrovick until late 1948, at which point the company began work on the G.2 gas turbines.[42] It is unclear whether the delay was due to the Admiralty or Metropolitan Vickers, but the Manchester firm's work schedule may have been a factor; for in parallel with the development of the naval boost engines, Metrovick had embarked upon the design of another jet engine, the F.9 or Sapphire.

Building and losing the Sapphire

As noted in the previous chapter, by 1945 it was clear that the F.2 was not going to enter service on a large scale, even in its ultimate F.2/4 version; the only proposed application (apart from test-bed aircraft) was the Saunders-Roe SRA.1 jet flying boat fighter. Nonetheless, Smith and Baumann were undeterred, and had begun to sketch out the design of a new engine of much greater thrust. The question of how great a pressure ratio could be achieved across a single compressor spool had been an issue at every stage of the MV-RAE collaboration; now the Metrovick engineers set out to design an engine that would push the boundaries of what was achievable. After discussion with the MAP's engine development staff, the company was given a design contract (i.e. for a paper design, as opposed to a development contract) for an engine with a pressure ratio of 6.5,

[39] Trewby (1955), 569-571.
[40] Trewby (1962), 354. Trewby also pointed out the problem of amortising development costs across a small number of units, in contrast to aero-engine practice.
[41] HP(L) to HJ Oram, Treasury, 29 Aug 1946, NA T225/1412. The 4,000SHP unit seems later to have been conflated with the Gatric unit in some of the Admiralty correspondence with the Treasury; see the report of 26 Nov 1947, NA T225/1412 and the accompanying tables.
[42] Rippon (1994), 169.

giving 7,000 lbs. of thrust. Metrovick called the project the F.9, later renamed the Sapphire.[43] In his memoirs, MAP's Director of Engine Research and Development (DERD) Rod Banks claimed that at first MV tried to convince the Ministry to support an uprated F.2/4, but that he and his staff told them to design an engine to be competitive with the new Rolls-Royce AJ65 axial design instead.[44] The engine was to share certain design features with the F.2 engines, notably the twin-bearing layout and annular combustion chamber, but was to use a compressor of new design, departing from the RAE's practice. As noted previously, Smith had been part of the 1944 MAP 'Special Projects Mission' to the United States, where he had viewed US compressor design practice. He had come to the conclusion that the low-camber high-stagger blading used there was 'less liable to stalling trouble' than British intermediate-camber blading.[45] Project studies during the latter part of the war had suggested that at higher blade speeds, MV's compressor designs should be changed from drum to steel disc construction.[46] Evaluations of the design made by the Ministry of Supply's technical staff were uniformly positive at the technical level, although they were less positive about the firm's ability to develop and manufacture a production-standard aero-engine on a reasonable timescale.[47] Given Metrovick's performance during the Second World War, this seemed a reasonable assumption to make; the company had probably the most sophisticated understanding of axial compressors in UK industry, but it had proven to be slow in development, and had no production facilities. Yet the company displayed signs of continued interest in the jet engine market, displaying its F.2/4, F.3, and F.5 units at the 1946 Paris Air Show, as well as at the Society of British Aircraft Constructors show the following year.[48]

One factor in the development of the F.9 was that it was seen within the Ministry as a form of backup to Rolls-Royce's first axial engine. Rolls had been given a contract to build an axial jet in the Autumn of 1945; as its 'AJ65' company designation suggested, it was designed to give a thrust of 6,500 lb. Banks's deputy for turbine engines (the DDTE) noted that the Metrovick engine promised to be 'somewhat better [...] in the important aspects of fuel consumption and low frontal area.' He also pointed out the F.9's advanced features, and noted that although the F.9 was heavier than the Rolls-Royce engine, the latter's weight had already risen from 1,650 lb. to

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[43] Whyte (1978), 23. The MoS also asked the Metrovick team to choose a naming scheme for their jet engines; they chose precious stones, and the F.9 was named the Sapphire. The F.2/4 was retrospectively named the Beryl. In both cases the names were not commonly used before 1947; within the MoS the designation F.9 remained more common until the engine was transferred to Armstrong Siddeley.
[44] Banks (1978), 158-9.
[45] DM Smith, 'The Aerodynamic Development and Axial Flow Compressor Blading for M.V. Jet Engines,' n.d. (but c. 1970), 3-4. I am grateful to Frank Armstrong for providing me with a copy of this report.
[46] DM Smith, 'The Aerodynamic Development and Axial Flow Compressor Blading for M.V. Jet Engines,' n.d. (but c. 1970), 3.
[47] See the memo by Hayne Constant, 25 Apr 1946, NA AVIA 54/1352
[48] See *Flight*, Nov 28 1946, 597.

1,900 lb.[49] It was presumably the MoS's reservations about Metrovick's development and production capacity that meant the F.9 was not seen as a first-line powerplant and the Rolls-Royce engine as a backup. The DDTE suggested that Metrovick be given a contract for a number of experimental engines by the MoS, partly as a backup for the AJ65, and partly to obtain 'valuable information for the benefit of the industry as a whole'. [50] The development of the annular combustion chamber was of particular interest, but other engine programmes were too tightly linked to aircraft programmes to risk developing this and other design features in an engine committed to aircraft production programmes. He gave the costs for a preliminary contract as £12,000 for an experimental compressor, plus about £125,000 for three engines, though he recommended ordering six engines at a cost of some £170,000.[51]

In response, Banks agreed that the MoS should support the Metrovick designs and order at least four engines to enable flight tests to be carried out, but disagreed on the value of the F.9 as 'insurance against the failure of the Rolls AJ.65.'[52] Banks argued that the Rolls engine 'must be made to work because of the aircraft commitments [the Ministry] have against it.' Even if the engine were to be delayed, he doubted whether MV could be depended upon to give '[as] speedy results as aircraft engine builders.' [53] Shortly after this, the MoS and Metrovick staff met to discuss their ideas. The MoS's Director-General of Scientific Research (Air), Ben Lockspeiser, reported to Alec Coryton, the Controller of Supplies (Air) [CS(A)] that Smith and Baumann did not think it worthwhile to attempt to develop the compressor and combustion chamber separately from a complete engine. Lockspeiser conceded that the decision had been taken to 'taper off' Metrovicks' aircraft engine activities, but argued that it was worth making a 'big effort' to get four F.9 engines built 'before the tapering off [was] completed'. [54] This tapering off was presumably in reference to the F.2/4; from 1945 onwards, this was the only engine MV was manufacturing, and the company had only received orders for 21 engines, of which it had completed roughly half; the production programme for the rest was due to finish in the summer of 1947.[55] As the company had no follow-on orders, this would be the last chance to keep the jet engine design team together. As Lockspeiser pointed out, the MV team were 'the most advanced and expert in the field of axial compressor design,' and it would be a mistake to lose their expertise 'in a field in

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[49] DDTE to DERD, 5 Apr 1946, AVIA 54/1352
[50] DDTE to DERD, 5 Apr 1946, NA AVIA 54/1352
[51] DDTE to DERD, 5 Apr 1946, NA AVIA 54/1352
[52] DERD to CS(Air), 6 Apr 1946, NA AVIA 54/1352
[53] DERD to CS(Air), 6 Apr 1946, NA AVIA 54/1352
[54] DGSR(A) to CS(A) through DERD, 26 Apr 1946, NA AVIA 54/1352
[55] With the exception of three F.2 units being adapted as naval gas turbines. This information is taken from RR Whyte's F.2 production chart, which was kindly provided by Bob Pick.

which it is admitted on all sides we have so much to learn.'[56] Though there was a view that jets with centrifugal compressors were still competitive – and indeed the last generation of UK centrifugals was currently under design – the majority technical opinion was that the future belonged to axial jets.[57] In light of the proven axial design expertise of Smith and his team, giving a design contract for the F.9 was a relatively cheap way to expand the UK's axial design knowledge. This was all the more so the case because Smith's approach was a novel one within the UK. As noted above, the compressor design for the F.9 was influenced by US practice; though the NGTE's axial design methods were broadly applicable, building on the RAE's wartime work, Smith's design would allow the evaluation of an approach different to that prevailing in existing axial design projects.[58] Interestingly, the Ministry's staff do not seem to have thought about harnessing the expertise of the Metrovick design team by encouraging them to move to an aero-engine company wholesale; the move would not have been without precedent, and would perhaps have allowed an aero-engine company to ameliorate the weaker aspects of MV's design and development.[59] In offering MV a contract there may have been an element of trying to recoup sunk costs; MAP had funded large amounts of research facilities at Metrovick such as wind tunnels and testing beds, as well as providing machine tools for blade production.

By early May, Coryton agreed that in view of the 'unanimous recommendation' in favour of the F.9, the Ministry should place an order for four engines plus an experimental compressor with Metrovick. However, he stressed that the order did not mean admitting Metrovick to the circle of the Ministry's recognised aero-engine firms; in future the MoS would 'have difficulty in maintaining our existing five main engine manufacturers.'[60] Coryton also pointed out that as the MoS financial estimates had already been submitted, the extra funds for F.9 development would have to be arranged with the Assistant Secretary or found through adjustment of the current research programme. In response Maurice Luby, the new DERD, reported that a number of engine research programmes had either been cancelled or delayed, and so the unspent funds for these

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[56] DGSR(A) to CS(A) through DERD, 26 Apr 1946, NA AVIA 54/1352

[57] Nichelson (1988), 162-208; for a more contemporary assessment, see Baxter (1952)

[58] Armstrong Siddeley's post-war gas turbines drew heavily on the RAE's work, and AA Griffith was responsible for the aerodynamic design of Rolls-Royce's AJ65 compressor.

[59] Apart from the pre-war moves from institutions such as the RAE into industry, Rolls-Royce had gained the services of the gas turbine designer Adrian Lombard when they took over manufacture of the Whittle gas turbines from Rover.

[60] CS(A) to DERD, 1 May 1946, NA AVIA 54/1352. The main manufacturers were Rolls-Royce, Bristol, Armstrong Siddeley, Napier, and de Havilland Engines; the pre-war 'ring' engine companies plus de Havilland, which had gained gas turbine contracts during the War.

would more than cover any F.9 costs.[61] By late May a contract had been placed to cover four engines and a research compressor, with costs not to exceed £160,000.[62]

Seeking partners

As Coryton had made clear, the MoS was not to support Metrovick as another aero-engine manufacturer, and so the Ministry began to consider possible manufacturing partners for the company. Among the contenders were the de Havilland engine company (DH), whose designer Frank Halford had suggested to the CS(A) that his company would be interested in manufacture of the F.9. [63] DH's gas turbines had all been centrifugal designs, so manufacture of the Metrovick unit would give them experience of a modern axial jet. Coryton asked his Under-Secretary to consider the implications, so that the Ministry would be prepared to give the scheme their blessings if necessary. In response to a query on the matter by the Under-Secretary, the Director-General of Aircraft Supplies noted that the advantages of the collaboration; apart from DH's knowledge of engines and aircraft installations, he stressed again the difficulties of supporting production at 'still another aero engine firm'; having DH manufacture the design under license would solve this problem.[64] However, the issue was – temporarily – suspended when de Havilland and MV were unable to come to a commercial agreement.

The sensitive issue of production was not raised with MV by Ministry staff; indeed, in some respects they wanted the issue to remain unvoiced, so as not to dissuade the company from continuing with work that would probably never see a production contract. Conversely, some in the Ministry felt that Metrovicks' sedate pace was in part due to a feeling on the company's part that the F.9 engine 'had no future,' and would never enter production.[65] Responding to this issue, the Director-General of Aircraft Supplies suggested to the CS(A) that he discuss the issue with the Metrovick chairman George Bailey, and explain 'that if [the F.9 proved] to be a winner, there would be a future for it.' This would have the effect 'of encouraging the firm to push forward their research work.' [66] At the meeting with Bailey, Coryton suggested that Metrovick should try and ally itself with an aircraft manufacturer to undertake flight development work.[67] The Ministry had suggested that the firm might be able to form an agreement with one of the Vickers Aviation

[61] Banks had left the MoS to return to his pre-war position with the Ethyl Fuel Company.
[62] DERD to CS(A), 8 May 1946, NA AVIA 54/352; DDTE to TE/G.3, 14 May 1946, NA AVIA 54/1352.
[63] CS(A) to US.Air, 29 Jul 1946, NA AVIA 55/78
[64] Minute DGAS to US.Air, 14 Aug 1946, NA AVIA 55/78
[65] Minute DGAS to CS(A), 23 Sep 1946, NA AVIA 55/78
[66] Minute DGAS to CS(A), 23 Sep 1946, NA AVIA 55/78
[67] Although no explicit record of the meeting exists, this is inferred from para 6 in the memo from DERD to CS(A), 6 Mar 1947, NA AVIA 55/78.

companies, but this came to nothing.[68] This may have been an attempt to support more integration within the aeronautical industry, as the Vickers aviation group had no engine assets. According to a later account by one of the MV engineers, Vickers told Metrovick that no airframe manufacturer would choose an engine supplier unless the supplier could produce 30 engines a month and had adequate flight test facilities. Unfortunately for Metrovick, it met neither of these requirements.[69]

Faced with this rebuff, and perhaps now realising that it would never gain a significant aero-engine contract, the company decided to divest itself of its aero-engine projects, and again approached de Havilland.[70] The latter company approached the Ministry of Supply in March 1947, indicating that they had been in discussion with Metrovick, and that the Manchester firm was willing to pass over 'all information and rights in their aero business, including their F2, F4, and F9 units.'[71] In return Metrovick had asked for a lump sum payment, as well as royalties on any F.9 production. As de Havilland was unsure as to whether and how these sums would be chargeable to future MoS contracts, they approached the DERD to ask for advice. Internally the DERD noted that there might be 'serious objections' to letting DH charge any lump sum payment against a future development contract; this was unsurprising, as it would essentially entail the MoS paying for the same work twice. Indeed, the DERD noted that under the terms of the development contract, the MoS could transfer the designs 'to any firm they choose for production purposes without any question of Royalty payment,' although he did suggest that this would cause some friction, and recommended that 'some sort of payment should be allowed' in order to facilitate a smooth transferral of the design, subject to the Director of Contracts' approval.[72]

As a result, EL Pickles, the MoS's Director of Contracts, set out the department's position to Bailey in late June 1947.[73] Pickles noted that Metrovick's lack of flight test facilities would cause 'considerable difficulty' for the development of a production engine. The development and air testing of the F.9 still remained 'a major programme' which would be 'largely, if not wholly, […] at

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[68] Memo DERD to CS(A), 6 Mar 1947, NA AVIA 55/78.
[69] Whyte (1978), 25. Unfortunately, working too closely with an airframe manufacturer could also be detrimental to an engine manufacturer, as other aircraft suppliers could become suspicious of the amount of support they might receive.
[70] It is unclear how much of a matchmaking role the MoS had in this contact; Luby (the new DERD) had apparently been attempting to bring the two companies together, but no official record of this exists before DH formally approached the MoS. See the comments in MG Ash to M. Luby, 5 Mar 1947, NA AVIA 55/78
[71] MG Ash (secretary DH Engine Co) to M. Luby RN, DERD, 5 Mar 1947, NA AVIA 55/78. 'F.4' was presumably a mistake for the F.2/4.
[72] Memo DERD to CS(A), 6 Mar 1947, NA AVIA 55/78
[73] Pickles had been the MAP's Director of Contracts, but in the MoS his formal title at the time was Under-Secretary(C); other sources describe him as the the MoS's Patents and Awards Officer – it is unclear as to whether this was a formal title, or an additional role attached to his position.

the expense of the department'; the government also maintained 'free user' (i.e. royalty-free) rights for the production of engines developed at its expense. He conceded, however, that MV had built up technical expertise beyond the design of the F.9, and suggested that the Ministry would consider offering a payment of £20,000 for the transfer of this know-how to any other company nominated by the department.[74] Bailey's reply on behalf of Metrovick was less than effusive. He stated that there was a 'wide divergence' between the sum envisaged by MV for their technical data and that offered by the Ministry; argued that the company's technical staff would have no difficulty in successfully bringing the F.9 to production if flight test facilities were provided; questioned the Ministry's indication that it might transfer F.9 information to companies other than de Havilland; and pointed out that the free user rights 'had been settled as applying to aircraft for war purposes only'.[75] He ended by expressing the view that 'it would be to the interests of all concerned to bring this negotiation to an early and amicable conclusion, so that the M.V. gas turbine team is attracted to supply information in a helpful spirit and with the utmost goodwill behind the effort'.[76]

There was some pressure on the Ministry of Supply for the transfer to occur smoothly; a fortnight after Bailey's letter, the Director of Military Aircraft Research and Development asked Coryton about the F.9's status. The Air Ministry's Director of Operational Requirements (DOR) had asked for assurances that the development of the engine was not being delayed due to problems with the transfer to DH. The DOR pointed out that the F.9 was envisaged as the preferred engine for a number of new aircraft tenders, due to its higher thrust than the Rolls-Royce Avon.[77] In response, Coryton tried to find out what stage the negotiations were at.[78] By mid-August, one of the MoS's Assistant Secretaries informed the Treasury that agreement had been reached with Metropolitan Vickers over the terms of the handover agreement, and asked for confirmation of payment authority.[79] Metrovick and the MoS had agreed on a payment of £32,000 for the transfer of Metrovick's gas turbine know-how, but the Treasury baulked at this cost. They argued that settling the original £160,000 contract would cover any such claims, and did not see what any additional payments were for.[80] In addition, the Treasury pointed out that MV had received over

[74] Letter EL Pickles to Sir George Bailey, 24 Jun 1947, NA AVIA 55/78
[75] Letter GE Bailey to EL Pickles, 2 Jul 1947, NA AVIA 55/78
[76] Letter GE Bailey to EL Pickles, 2 Jul 1947, NA AVIA 55/78
[77] DMARD to CS(A), 15 Jul 1947, NA AVIA 55/78
[78] Minute CS(A) to US(C), 19 Jul 1947, NA AVIA 55/78
[79] WG Downey to L Peteh, Treasury, 20 Aug 1947, NA AVIA 55/78
[80] L Peteh to WG Downey, 27 Aug 1947, NA AVIA 55/78

£220,000 of government-funded plant, and asked the MoS to ensure that it would not 'lie idle,' whether transferred to MV's successor firm or elsewhere.[81]

In the meanwhile, it was not now certain that de Havilland would be the Ministry's first choice to develop the F.9. Even as the MoS staff were trying to reach agreement with MV on a contract settlement, Luby (the DERD) was writing to the Under-Secretary to seek alternatives. He requested that the department consider whether other firms might be able to develop the F.9 more cheaply and quicker than de Havilland.[82] The DERD argued that the negotiations with de Havilland had been started in late 1945 because the company had had no new engine in development, as well as a lack of axial experience, and that an F.9 order would have helped them remedy both these defects. Since then, however, Armstrong Siddeley had lost a tender for a new gas turbine design (TE.2/46) to Napiers, and so also had no follow-on engines in sight.[83] Luby argued that A-S had five years' experience of axial jet design, and might therefore be quicker at developing the F.9 than DH. Although the latter company might take exception to what it could perceive as a reversal of policy, the rights to the F.9 had been acquired by the state when DH had been unable to reach agreement with MV. The Ministry should be able to transfer the rights to the company best able to handle the development; Luby argued that as a result of the Hawker Siddeley Group's recent reorganisation Armstrong Siddeley were likely to be the 'more powerful engine industrial unit', not as solely reliant on research and development.[84] At the time of his assessment, Armstrong Siddeley had a number of turboprop designs under development, as well as a small turbojet; it was also producing a radial piston engines for military trainer aircraft.[85] By contrast, de Havilland was manufacturing two centrifugal jet designs, and light piston engines for sport aircraft.[86] As noted previously, de Havilland had only entered the 'ring' of aero-engine companies through its production of gas turbines from 1941 onwards, and so it was the relative newcomer in this dispute.

Luby's arguments clearly carried the day; a month later he had on his desk a report by two of his Assistant Directors comparing the engineering and production capabilities of de Havilland Engines

[81] L Peteh to WG Downey, 27 Aug 1947, NA AVIA 55/78
[82] DERD to US(A), 29 Jul 1947, NA AVIA 55/78
[83] DERD to US(A), 29 Jul 1947, NA AVIA 55/78
[84] DERD to US(A), 29 Jul 1947, NA AVIA 55/78. It is unclear from the surviving correspondence as to precisely which rights were acquired by the MoS at what time; later correspondence suggests that by now the Ministry could transfer the F.9 design to whomever they pleased, albeit with a payment to MV for the transfer of their development know-how (production technique was covered by the original contract.)
[85] The turboprop designs were the Python and Mamba, soon to be followed by the Double Mamba; the turbojet was the Adder.
[86] Though some of these were fitted to military trainers and communications aircraft.

and Armstrong Siddeley.[87] Although they were careful to state that due to the short timescale much of their analysis was conditioned by the companies' past performance, they were unanimous in recommending that unless DH's team was strengthened generally and with respect to development specifically, the F.9 design should be handed to Armstrong Siddeley.[88] The Directorate of Engine Production's opinion was formally conveyed the following week, and expressed a lack of confidence in DH's production capability, based on their past performance on jet engine production programmes and the limited floor space they could command for production.[89]

At a meeting of all the MoS senior aviation staff in late September to discuss the transfer of the F.9 from Metrovick, all present agreed that the engine should go to Armstrong Siddeley; apart from being better suited to the development and production of the engine, the company 'were prepared to provide their own capital facilities for research and development.'[90] Luby expected that an amicable relationship would be established between A-S and MV, stating that the difficult relationship between the companies during the War had been due to 'a clash of particular personalities.' He was presumably referring to HC Pierson's combative approach to defining the spheres of influence for the F.2 collaboration; Pierson had retired in 1945. The meeting also noted that although de Havilland expected to be nominated for the transfer of the F.9, they could not argue that the MoS was 'in any way morally committed'; the DERD had explained to the DH representative that after the Ministry had obtained the rights to the F.9 it must review the field.[91] By now the MoS's commitment to the F.9 had reached £450,000, which included the cost of 10 test engines, with an expected total cost of £1M (i.e. a further £550,000) to get the design through a full programme of bench and flight testing.[92] The contracts secretary noted that the MoS was committed to MV 'to the tune of about £2m in respect of the whole of their jet work,' but noted that most of this was 'water over the dam.'[93] The Treasury was also reconciled to making a payment for MV's 'development know-how'; having looked into the matter they had

[87] The two ADs were RH Weir (RDE.1) and HP Baker (RDE.2), responsible for engine tenders and projects, and gas turbines, respectively.
[88] Report to DERD from RDE.1 and RDE.2, 29 Aug 1947, NA AVIA 55/78
[89] DEP to AS/Air.1, 5 Sep 1947, NA AVIA 55/78
[90] 'Transfer of development and production of F.9 from Metro-Vickers,' 25 Sep 1947, AVIA 55/78
[91] 'Transfer of development and production of F.9 from Metro-Vickers,' 25 Sep 1947, AVIA 55/78
[92] US(C) to CS(A), 22 Sep 1947, NA AVIA 55/78
[93] US(C) to CS(A), 22 Sep 1947, NA AVIA 55/78. It is not clear whether this includes the B.10 and other shaft power projects; in either case, it was a not insignificant sum.

decided that the original contract only covered 'manufacturing know-how', and agreed with the £32,000 sum suggested previously.[94]

The day after the meeting, the Under-Secretary wrote to Armstrong Siddeley to invite the company to take over Metrovicks' aircraft gas turbines, and to MV to inform them of this decision.[95] The draft Memorandum of Agreement provided for Metrovick to pass all ten F.9 engines under construction to Armstrong Siddeley, for A-S to provide information on their work on the F.9 design to MV for a further five years, and allowed A-S to produce civil versions of the engine without payment to Metrovick, though in this case the Ministry of Supply would receive a 5% royalty on orders.[96] Both firms were happy with the decision, though Armstrong Siddeley's managing director asked for some time for his engineering staff to view the proposals. [97] By early November A-S and Metrovick staff were meeting to discuss the details of the handover at a meeting chaired by the DERD. He pointed out that the Ministry's priority was to put the Sapphire into production for aircraft use 'at the earliest possible date,' and that all other considerations were secondary to this objective.[98] High-powered axial engines were crucially important for defence needs; as well as giving fighter aircraft high speed and climb rates, the only way to build a bomber with the ability to carry a nuclear weapon across intercontinental distances was with the axial jet's combination of high power and good fuel consumption.[99] In order to ensure to shorten the development time of the engine, the meeting decided that instead of handing over all the engines under construction at MV over, the Manchester firm would complete the four 'Series I' development engines and their test programme, but that the six 'Series II' engines, which were intended to be flight-testable, would be constructed by Armstrong Siddeley.[100] The DERD estimated that Armstrong Siddeley would be ready to start manufacture of their first engine in July 1948, and noted that the company had decided to keep the name 'Sapphire' as a token of all the work that Metrovick had done on the design.[101]

In the event, the estimates for the Armstrong Sapphire's timetable proved to be somewhat optimistic; the first Armstrong Siddeley engine began bench running in October 1948, the same

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[94] L Peteh to WG Downey, 24 Sep 1947, NA AVIA 55/78
[95] EL Pickles to HT Chapman (Managing Director, Armstrong Siddeley), 26 Sep 1947, NA AVIA 54/1352; EL Pickles to GE Bailey, 26 Sep 1947, NA AVIA 54/1352
[96] Memorandum of Understanding (Encl. 17), n.d. (but probably Sep 1947), AVIA 54/1352
[97] See letters HT Chapman, Armstrong Siddeley, to EL Pickles, 29 Sep 1947, NA AVIA 55/78, and GE Bailey to EL Pickles, 1 Oct 1947, NA AVIA 55/78.
[98] Minutes of Meeting – 7 November 1947, n.d., AVIA 54/1352
[99] A fact that led the US to spend billions of dollars on crash programmes to develop designs; see eg. Scranton (2006). US fears about the Soviet Union's ability to acquire axial technology led to conflict with the UK over plans to export civilian axial engines; see Engel (2007), 139-158.
[100] Minute DERD to D.of C(A), 10 Nov 1947, AVIA 54/1352
[101] Minute DERD to D.of C(A), 10 Nov 1947, AVIA 54/1352

month in which the Metrovick Series I engines passed their MoS acceptance tests.[102] Progress on the Armstrong engines was delayed – somewhat ironically in view of the wartime disputes about design responsibility for the F.2's 'rotating parts' – by mechanical redesign of the engine's compressor rotor and the bearing arrangements, though the F.9's excellent basic aerodynamics were retained.[103] Indeed, details of the Sapphire's compressor design were passed to Rolls-Royce in 1950 in order to help solve the AJ65's compressor surge issues; the improvements were incorporated in the R.A.14 200-series Avons.[104] The various changes made to the Metrovick design suggest that by the late 1940s Smith and his design team were excellent gas turbine aerodynamicists, yet that their mechanical design and development choices were perhaps less suited to a production aero-engine. It was an ironic reversal of the firm's role in the original collaboration with the RAE, where the latter institution had provided the aerodynamic expertise; Metrovick were chosen mainly for their mechanical and material expertise.

Sapphires entered service with the RAF in 1953 on Gloster Javelins, and in their final ASSa.7 version powered the Victor B.Mk. 1 nuclear bombers of the V-Force. Armstrong Siddeley's design was also manufactured under license in the US as the Curtis-Wright J65, of which over 10,000 were built.[105] Yet Metrovick were not yet finished with the gas turbine; they were to continue with the development of their jet engine designs into naval units.

The naval gas turbine

As noted above, Metrovick did not start work on the naval G.2 design until 1948, possibly because of the disruption of the Sapphire's disposal, by which time the Admiralty was planning a building programme to replace the Navy's wartime-vintage fast attack craft.[106] The Admiralty ordered two experimental fast patrol boats designed by the Director of Naval Construction, *Bold Pathfinder* and *Bold Pioneer*.[107] They were intended to test a wide range of technologies: their main engines were to be Deltic diesel engines, which were currently under development by English Electric (Napier's parent company) for the Admiralty; they were to be fitted with gas turbine boost

[102] See *Flight*, 6 Jan 1956, 18.
[103] *Flight*, 6 Jan 1956, 19-20. The redesign added a bearing, which allowed removal of the complete 'hot end', making maintenance and servicing of the engine easier; my thanks to Bob Pick for pointing out the implications of the change. Metrovick's design and casing was more similar to an industrial turbine; clearly the company's technical style still had an influence.
[104] Whyte (1978), 25; Kay (2007), 96. The Avon's original compressor design had incorporated features against the NGTE's advice.
[105] For more on the chequered story of the US development, see Scranton (2011); in large part due to US-UK differences in development and production procedures, the J65 program suffered from delays and large cost overruns.
[106] Preston (1982), 13.
[107] Somewhat of a departure for small craft; the wartime MTBs and MGBs had been built to the designs of private yards.

engines; and the boats were to use two different hull forms, to see which was superior at high speeds.[108] The boost unit chosen for the new boats was the G.2; it began its bench tests at Barton in 1951, and sea trials started later that year. Although the Royal Navy's *Bold* boats had good seakeeping qualities, the G.2 engines proved more troublesome than the Gatrics in service. They suffered from a compressor instability known as 'rotating stall', which was made worse by salt buildup on the compressors.[109] The combined effects of salt corrosion and vibration caused by the flow instabilities on the aluminium blading led to fatigue failures, which tended to give the whole compressor a 'haircut'; limited numbers of spares then meant that it took a long time before the engine could be repaired. There were also vibration problems with the bearings, the ball and roller types fitted being less suited to the marine than the air environment.[110] However, some of the aerodynamic failings were cured by redesign of the inlet blading, and when the engines worked they produced up to 4,500SHP.[111] Part of the problem seems to have been that after the relatively smooth progress of the Gatric, the RN accepted comparatively short shore trials on the G.2s before fitting them for sea trials.[112]

At about the same time, the US Navy ordered two G.2s of an updated design, with a modified compressor and turbines, to be fitted to the experimental torpedo boat PT812.[113] The USN had disbanded its torpedo boat forces after the Second World War, as they had mainly been used in southwest Pacific; the Navy planned to use carrier air power in this arena in future conflicts. However, it authorised the construction of four experimental torpedo boat prototypes for possible future production. [114] The USN had no major gas turbine propulsion programme – with no fast patrol craft, one of the major applications did not exist – and acquiring the G.2s was presumably a good way to keep abreast of the field.[115]

Back in the UK, based on the experience of the sea trials, in 1954 the Admiralty commissioned the shipbuilders Vospers to carry out design studies for a fast attack craft, including variants powered solely by gas turbines; Metrovick had already begun the design of an improved naval gas

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[108] Whyte (1978), 31; Rippon (1994), 169. In the event neither the Deltics nor the G.2s were ready in time, and initially the boats were launched with Mercedes-Benz diesels, the other engines being installed later.
[109] Harris (1965), 117-8.
[110] Trewby (1955)
[111] Preston (1982), 13-14; Harris (1965), 117.
[112] Trewby (1955)
[113] See the *MV Gazette*, Jan 1953, 313. Friedman (1986) mentions the US boats in passing; Preston (1982), 15 provides diagrams of both the original and modified variants, and stated the modified designs were known as G.2/IIs, though he gives a date of 1955 for the first run of this type.
[114] Friedman (1986), 202.
[115] The first US naval gas turbine was fitted to the cargo ship *John Sergeant* in 1956;it was the best part of another decade before gas turbines were introduced into USN warships.

turbine.[116] This was the G.4, and its design was changed in response to the mechanical difficulties encountered with the Gatric and G.2 units. Based on Metrovick's experience of designing an industrial gas turbine for use in a locomotive (discussed in more detail in the following chapter), the G.4's design used heavier frames than the earlier aeroderivative units, and journal and thrust bearings were used instead of the aeronautical ball and roller bearings.[117] As noted above, the earlier designs' aluminium compressor blades were not strong enough to withstand the impacts of a broken blade, so a single blade failure could destroy the whole compressor. As a result, the G.4's compressor blading was made from tougher stainless steel. Vosper produced a number of fast craft design studies in response to the Admiralty's request; one version was fitted with two Metrovick G.4 engines of 5,000SHP each, but the eventual design selected used three Bristol Proteus turboshaft engines.[118] These were built as the *Brave* class fast patrol boats, and the first was laid down for the Royal Navy in 1958. Although the RN only ordered two due to the run-down of its coastal forces, Vospers were very successful in selling the design abroad.[119] As for the G.4, the Admiralty seems to have bought two units for testing, which would suggest the engine was covered by a development contract; the only buyer to fit G.4s to vessels was the Italian navy, which bought two to fit to their fast attack craft MC-491 *Lampo* and MC-492 *Baleno* as boost engines.[120] Metrovick do not seem to have attempted to sell their G.2s and G.4s in any great number; as the success of the Proteus and the Vospers fast craft showed, there was a market available. This was possibly because the company again did not have the manufacturing facilities to build large numbers of gas turbines; given the post-war boom in power station building, they were probably marginal from a commercial point of view.[121] It seems unlikely that sales were limited from a security point of view, as Italy had previously been considered a security risk for axial jet engines; if gas turbines could be sold to the Italian navy, they could presumably be sold anywhere in the West.[122]

By now, however, Metrovick had become involved in the design of a combined steam and gas turbine propulsion system for the Royal Navy's large warships. The company's involvement with the system was in part due to changes made to the Admiralty's procurement system for warship power plants made during the Second World War. In order to understand these changes, we must

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[116] Du Cane (1960); Preston (1982), 14.
[117] Though captioned as a G.2/II, from the evidence available it is possible that the diagram in Preston (1982), 15, is in fact a G.4.
[118] Du Cane (1960). The Proteus was originally built as a turboprop, but was adapted for use as a marine and industrial gas turbine.
[119] Friedman (1986), 207.
[120] Harris (1965), 118; Friedman (1993), 207.
[121] I will consider Metrovick's wider post-war business in more detail in the following chapter
[122] See Engel (2007) for more on the security issue.

examine the perceived failings of the previous system, and look at one possible reason for these failings. This has to do with the structure and institutional status of engineering officers in the pre-war Royal Navy.

Powerplant engineering and the Royal Navy

As the Royal Navy began operating alongside the US Navy in the run-up to US entry to the Second World War, the Royal Navy discovered – to its dismay – that the performance of its warships' powerplants lagged far behind that of the USN's in maintainability and fuel efficiency.[123] One of the major differences was that by comparison with US practice, the RN's steam plant used lower temperatures and pressures. This is usually ascribed to the fact that the Admiralty gave shipbuilders (who adopted conservative designs under license from Parsons) contracts to build warship turbines, whereas the US Navy placed contracts with specialist turbine manufacturers; these could draw on recent developments in land and power station practice.[124] British specialist turbine manufacturers were not noticeably inferior to US companies (indeed, in many cases had cross-licensing agreements), and also in many cases manufactured turbines and gearing for naval propulsion.[125] If one accepts the point that the RN's steam plant was technically inferior to the USN's, this was therefore not due to some generalised British industrial backwardness, but rather the result of Admiralty decisions.[126] Yet this account simply relocates blame to a reactionary Engineer-in-Chief's department within a reactionary Admiralty; if one wants to understand why the department was technically conservative, a brief analysis of the Navy's engineering corps provides a more satisfactory explanation.

The problem was essentially one of status; within the Royal Navy, engineers were not 'executive' officers, which meant that not only could they not command a warship, they could not issue orders to non-engine-room crew, and had no power to award punishments. In some sense this specialisation was similar to other (civilian) 'guilds' within the Admiralty; the Corps of Naval Constructors, the scientific staff of the Directorate of Research, and the Royal Dockyards. All were acknowledged as important to the smooth functioning of the Navy, and they were separate –but not quite equal – from the RN, each with their own promotion paths.[127] Unlike these, however, the Engineering Officers were embarked on warships, and there was a definite social divide

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[123] Friedman (1993), 200.
[124] See eg. Rippon (1994); Lyon (1977)
[125] Certainly both Metrovick and BTH did.
[126] Barnett (1991) is typically scathing about both the Admiralty and British Industry; Roskill (1968, 1976) and Ranft (1978) are still critical but more sympathetic to the Admiralty's constraints and dilemmas. Sumida (2001) surveys the historiography on the Admiralty and technological innovation, but gives the above sources credit for setting the basic contours of the debate.
[127] Scott and Hughes (1955), 134-6.

between the Engineering and Executive branches of the Navy, which could be traced back to the Victorian Navy's oppositional relationship between the 'gentlemen' and the 'tradesmen'.[128] When combined with an elite naval staff composed entirely of executive officers, these tensions led to a somewhat insular Engineering Branch, which had limited influence on staff requirements, and whose officers had as much in common with their counterparts in the civilian sector as they did with the rest of the Navy. [129]

After initial attempts in the 1920s were beset with development troubles, efforts to develop high-pressure steam plant were dropped.[130] The interwar period also saw a severe slump in the British shipbuilding industry, which had problems in maintaining skilled labour and building capacity; together with reduced warship production and limited funds, this militated against further steam plant development.[131] Perhaps as a result, the Engineer-in-Chief's department's major concern was with reliability, which encouraged an evolutionary approach to machinery development, and a certain amount of groupthink between the department and shipbuilders.[132] Thus the stage was set for the somewhat disappointing performance of the RN's ships' machinery during the Second World War.

Yet from the early 1930s the Engineering Branch began to change and attract higher-quality candidates. In part this was due to engineering's increased attractiveness to naval entrants. The depression caused applicants to think than an engineering qualification would be useful in civilian life, and applications to the Engineering Branch from public schools and from the Royal Naval College began to increase.[133] Finally, in the late 1930s the Engineer-in-Chief's department created specialist sections under Engineering Officers with postgraduate technical qualifications to investigate boiler design and steam turbine efficiency respectively, which led to new assessments of naval propulsion technologies. During the Second World, despite the urgent need for engineering officers to keep the Navy's warships running, the Admiralty attempted to ensure that

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[128] See Penn (1955), though the debates had mostly settled by the end of the Victorian era.

[129] Le Bailly (1991), 40; 52-4. Gunnery and Torpedo specialists were executive officers, which meant that the naval staff paid more notice to weapons developments than to powerplant engineering.

[130] The steam plant had been installed in a destroyer rather than first being tested on shore, which was responsible for many of the teething troubles; see the discussion in Kingcome (1949)

[131] Sumida (2001), 136. It should be noted that the lack of funds was in some sense only relative to the hugely inflated sums spent in the pre-WWI naval arms race, and to a degree when measured against the RN's unavoidable strategic commitments.

[132] Le Bailly (1991), 54; see also Lyon (1977). In his memoirs, Harold Brown (appointed Engineer-in-Chief 1932) noted that 'progress possibly was not spectacular but I think it was steady and continuous and reliability was maintained and improved'; in a later addition to the typescript, he regretted that the use of high-pressure steam installations had not been pursued after the initial 1926 trials. See Brown Memoirs, pp 104; 114.

[133] Le Bailly (1991), 60-61. Le Bailley (1990) also noted that changes to the Dartmouth curriculum pushed students to the (E) track.

they were rotated through ship and shore appointments, so that experience was spread throughout the Engineer-in-Chief's department and the Fleet.[134] Spurred on by what they had seen of their own and other nations' machinery, the Engineering Officers ascending through the hierarchy brought with them a sense that change was needed in the RN's propulsive design. By the war's end the Navy had taken on board a number of innovations in propulsion machinery – not least the gas turbine – and had begun the design process for a new generation of steam powerplants. A new generation of Engineering Officers was now in senior positions within the Navy's Engineering hierarchy, which led to a more adventurous Engineer-in-Chief's department. The wider post-war Royal Navy was also more receptive to the idea that fleet mobility should be a priority, with many of its senior officers having fought alongside the US Navy in the Pacific; the long distances of this campaign had emphasized the poor endurance of the British Pacific Fleet when compared to the USN.

New approaches to powerplant procurement

As noted previously, up until this point the RN's warships had been fitted with steam turbines licensed by shipbuilders from the Parsons company, albeit with Admiralty pattern boilers. The first change in the RN's steam plant procurement came in 1943, with the ordering of the 'Daring'-class destroyers. These were intended to operate in the Pacific; conscious of its existing steam installations' poor fuel consumption (and thus endurance), as revealed by joint operations with the US Navy, the Admiralty formed a Propulsion Committee to come up with better designs. This was composed of representatives from the major shipbuilders and the Engineer-in-Chief's department; the US Navy also supplied representatives, who gave accounts of the USN's development problems with high steam conditions.[135] A Turbine Sub-Committee, chaired by Commander (E) I G Maclean, head of the Gearing and Turbines section in the Engineer-in-Chief's department, brought together marine engineering and industrial turbine companies, and selected two promising designs submitted by English Electric for further development; a joint BTH-PAMETRADA design was later added.[136] PAMETRADA was the Parsons and Marine Engineers Turbine Research and Development Association, which was formed by the shipbuilders in 1943 under pressure from the Admiralty in order to improve their turbine designs.[137] Although the Admiralty were members of the association, finance came mainly from the shipbuilding and

[134] Le Bailly (1991), 69.
[135] Cowlin and Veitch (1956)
[136] Cowlin and Veitch (1956), 497-8;see also Le Bailly (1991), 71-75. The industrial companies involved were English Electric, BTH, and Metrovick.
[137] Le Bailly (1991) suggests that this was in part a defensive move to prevent the Admiralty from simply choosing industrial turbine manufacturers for future warship powerplants.

turbine companies; the DSIR also made a 'considerable' financial contribution.[138] The designs chosen by the Turbine Sub-Committee were to be developed by PAMETRADA and English Electric respectively, and to be tested at PAMETRADA's new shore test facility.[139]

By 1944, the Admiralty had issued the requirements for the *Daring*-class destroyers' machinery, and Sir Harold Yarrow picked the English Electric turbines to power those *Darings* built by the Yarrow shipyards, as he considered these to be the best turbine design available. As a result of this collaboration, in 1947 the Admiralty asked Yarrows and English Electric to work on a survey of world naval steam plant practice.[140] A team of engineers from both companies worked with the E-i-C's department, and this 'YE47A' team acted as engineering consultants to the Admiralty. The results of the YE47A investigation were presented to the Admiralty in 1948, and concluded that 'British Naval machinery has, for the first time in history, become inferior in many vital aspects to that of the United States Navy.'[141] The report noted that the *Daring*-class machinery currently under test was comparable to current US plants, but that in order to bridge the gap in future, the research and development capabilities of both the naval and the commercial organisations should be reviewed. By 1950 English Electric had withdrawn its staff from the team, possibly because the company was concentrating its efforts on the booming land power turbine industry.[142] As a result, the team adopted the name Yarrow-Admiralty Research Department (YARD) in 1952. Effectively independent from Yarrow shipbuilders, YARD acted as engineering consultants and project managers to the Admiralty.

From steam to joint steam and gas

As part of the YE47A study, YARD had been asked to design a steam plant installation including boilers, gearing, and turbines, as designing a plant for optimum performance required careful selection and matching of the various components; previous practice had been to pick components in more-or-less standard sizes, but then to adapt them to the desired rating. The first integrated design built by YARD was the YEAD-1 plant (Yarrow-English Electric Advanced Design), which was a shore test plant. YEAD-1 was shortly followed by the design of the Y.100 plant, which

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[138] Rippon (1994), 24. PAMETRADA acted as an industry research association, providing shore test facilities for turbine designs. The association was wound up in the late 1960s as the costs of providing test equipment became too great.

[139] The third design was developed by John Brown; see Cowlin and Veitch(1956)

[140] Le Bailly (1991), 75-76, suggests that this arrangement led to Yarrow's relinquishing the right to tender for warship powerplant designs, but it is unclear whether this is true; the company did continue to manufacture powerplant components.

[141] 'Yarrow – English Electric Advanced Steam Investigation – Volume I,' Feb 1948, NA ADM 317/1, 3.

[142] The obituary of the EE turbine engineer James L Gray suggests that the company's chief turbine engineer at the time insisted there was 'no future in naval engineering'. See http://remember.snp.org/tributes/view/jim_gray/ , accessed 15 Aug 2012. The failure of the EL60 to be selected for sea trials may also have been a factor.

was a production design fitted to anti-submarine frigates. Given the success of these designs, in 1952 the RN issued a staff requirement for a next-generation plant, Y.102, which would use high-pressure steam for cruising, but would have gas turbines for boost purposes in a 'combined steam and gas' (COSAG) layout. The plant was intended for use in the proposed type 81 'Tribal' class general purpose frigates, and the 'County' class guided missile destroyers. The COSAG arrangement allowed the gas turbine to be used either as a boost unit, or as the sole powerplant when its lower startup time gave it the advantage over the steam plant (such as leaving port in a hurry; a serious consideration for warships in a nuclear conflict, where it might take at least 30 minutes for a conventional plant to raise steam.)[143] For the study, YARD would partner up with Metropolitan Vickers; the former responsible for boiler and overall design, and the latter responsible for steam and gas turbine design and gearing.

The choice of Metrovick as a partner made good sense; as English Electric had withdrawn from the collaboration in 1950, YARD was looking for another turbine manufacturer to work with. MV had experience with both steam and gas turbine designs, and had supplied both to the RN in the past. The company had recent experience of high-pressure steam installations, having designed the plant for the Blue Funnel Line's recent liners *Nestor* and *Neleus* that used higher temperatures and pressures than any other contemporary installation.[144] Crucially, Metrovick also had extensive gearing expertise from their power and naval business, and were to be called in to assist on problems with the Y.100 plants' cruising turbines. As a boost installation would require high-speed gearing able to withstand loads of thousands of horsepower, the company was an obvious choice to assist on the Y.102.

The feasibility report on the powerplants was presented to the Admiralty in 1954, and recommended two related designs for the frigates and the destroyers respectively.[145] Y.102A consisted of HP and LP steam turbines giving 15,000SHP, and two 7,500 HP G.6 gas turbines connected to a gearbox; Y.111A consisted of a single 12,500SHP steam turbine and one 7,500 SHP G.6 boost unit connected to a gearbox.[146] The design of these components brought the Metrovick engineers back onto their home turf of large industrial-scale units designed for very high reliability. In addition, the units had to be able to withstand shock loadings such as might be encountered on a warship. The Metrovick engineers had been moving in this direction already in

[143] Dunlop and Good (1963).
[144] Baker and Falconer (1955)
[145] A copy is in NA ADM 317/76
[146] Metrovick initially proposed a 15,000 shp 'G.5' gas turbine for the destroyer powerplant, but analysis of the machinery spaces made it preferable to use two smaller units, which also had the advantage of greater commonality with the frigate powerplant. See NA ADM 317/76.

the design of the G.4; similarly, the G.6's mechanical design was based on industrial rather than aeronautical practice. Although the G.6's aerodynamics were based on that of the Sapphire, no Sapphire components were used.[147] In some sense this must have suited Metrovick's design team; they had had no experience of aero-engine design since the sale of the Sapphire to Armstrong Siddeley, but they had continued to work on the aerodynamics of the various naval gas turbines; as will be seen in the following chapter, their other gas turbine designs in this period had all been for industrial use. Comparing the details of the G.6 to MV's earlier naval units suggests that it was a relatively conservative design with regard to weight and performance, but this was to be a unit designed for long service in warships rather than a research or short-life unit for fast craft. The result was – after overcoming initial teething troubles[148] – an outstandingly reliable unit for naval use; eventually overhauls were only carried out during the ships' dockyard refits.[149] This was again due in part to the problems encountered with the G.2 units; in order to gain as much shore running experience as possible, MV created a Y.102A test installation at their Barton test works with two G.6 units to carry out development on the gas turbines and the gearing, which allowed the company to overcome vibration troubles with the compressor.[150] Metrovick also created full mock-ups of the machinery spaces of a County-class destroyer and of a Tribal-class frigate in order to best arrange the engine rooms.[151] The other major issues encountered were with poor combustion causing heavy smoke production, which was solved after collaboration with the NGTE, and the need for safeties to prevent turbine over-heating.[152]

Table 4.1 - Metrovick Naval Gas Turbines[153]

	G.1	G.2	G.2/II	G.4	G.6
Year of Test	1946	1951	1955	1956	1958
Max Power (shp)	2,500	4,800	4,800	5,000	7,500
SFC (lbf/lb-hr)	1.06	0.82	0.82	0.68	0.77
Pressure ratio	3.5	4	4	6.3	6.3
Turbine inlet temperature, °K	1022	1072	1072	1089	1066
Weight, lbs.	4030	6950	6950	8160	41,440

147 Whyte (1978), 32.
148 Which included the catastrophic failure of one of the type 81's G.6 units.
149 Rippon (1994), 170-1.
150 Trewby (1962), 351.
151 Dunlop and Good (1963)
152 Trewby (1962), 350.
153 Preston (1982), 55.

Given the company's mixed previous experience with aero-engines and aero-derivative naval engines, this would provide more evidence for the importance of technical community and familiarity with particular ways of doing things. Metrovick's basic aerodynamic and engineering competence were not in doubt; but clearly the company was more successful in designs that were closer to its industrial and steam core business. Metrovick produced more G.6s than all of their other military engines combined, with fifty-three units being manufactured in total. [154] The engine was also a minor export success, with the Italian Navy buying a number which were fitted to a training cruiser and two frigates.[155]

The only institution unhappy with the Y.102 sets was the Treasury, as the cost overruns on the project were around 100 per cent. As one of the Metrovick engineers put it, it was the 'humbling experience' of comparing the predicted cost with the actual cost that led him to formulate a law of development overspend, which he later presented to the IMechE.[156] In July 1957 the Admiralty representative asked the Treasury to increase the amount spent on Y.102 to £950,000; by February 1958 he estimated that the total project cost would be £1,105,000, but that this overspend could be mostly covered by making cuts in other research programmes.[157] He attributed this to difficulties in manufacture, informing the Treasury that the G.6 compressor had failed on test and had required redesign, and that new blading had been required to reach the design performance.[158] As the Treasury representative rather wearily informed his superiors in a memo, the Admiralty 'have not been slow to point out that Y.102 is based on a radically new design'; he concluded that under the circumstances, all the Treasury could do was try and make sure that the overspend was not due to 'faults in the Admiralty's financial machine'.[159] Yet worse was to come; in September 1958 the Admiralty representative again wrote to the Treasury that the probable cost of the Y.102's development was now estimated as £1.6m. Though enquiries were being carried out into the cause of the cost overruns, he wrote, the work was 'vital to our New Construction programme and cannot be stopped.'[160] It was not until June of the following year that the Admiralty had completed its review; although it put the majority of the cost increases down to problems in development, it also pointed to inadequate organisation at Y-ARD

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[154] Though some of the units were built by shipyards; presumably this was a case of assembling the turbines from parts provided by MV, as precision manufacturing single units would have been incredibly expensive.
[155] The ships were the *San* Giorgio, the *Alpino*, and the *Carabiniere*; each had two G.6s alongside a number of diesel engines. The local partner was the steam turbine manufacturer Franco Tosi, who presumably played a similar role to the UK shipbuilders in assembling the powerplants.
[156] Whyte (1978), 32; 4-7 discusses his laws of overspend.
[157] WJ Hanman to JC Leeming, 12 Feb 1958, NA T225/1414
[158] WJ Hanman to JC Leeming, 12 Feb 1958, NA T225/1414
[159] 'Y.102 – as of 12 Feb,' JC Leeming, 20 Feb 1958, NA T225/1414
[160] WJ Hanman to M Lynch, 10 Sep 1958, NA T225/1414

and at Metrovicks for cost estimation and financial control. In his letter, the Admiralty representative stated that new systems had been put in place at the contractors, and that the lessons learned would 'be taken to heart'.[161] Somewhat forlornly, he concluded that in light of the 'considerable advantages' of the Y.102 with regard to fuel consumption, space, and machinery weight, 'in our opinion at £1.6M. the project is still very good value for money'.[162] The Treasury appeared distinctly unimpressed, but the damage was done; the first 'Tribal' class ship had been launched in March 1959, and the first 'County' class was launched in June 1960. In practice, the costs of the COSAG installations was higher than that of comparable steam units, but there were savings in manpower and potential savings in maintenance costs, apart from the size advantages of the plant.[163]

The Tribals and Counties proved that the gas turbine could be reliable in naval service; indeed, because of the ease of startup, and because running on gas turbines required fewer crew than steaming, in service the boost units were used as the ship's sole source of propulsion far more than had been anticipated.[164] As a result, the Engineer-in-Chief's department began to investigate the possibilities for all-gas-turbine propulsion. The logistics of this decision were helped by the RN's 1960s switch from heavy oil to distillate fuel for its steam boilers, due to the lower maintenance requirement and better reliability this gave; this meant that gas turbines could burn the same fuel.[165] After the previous disappointing experience with the EL60 and RM60 powerplants' off-peak performance, and having proved the high-powered gearing required in the G.6-powered ships, the Admiralty decided to use combined gas propulsion. This meant using multiple gas turbines, sized so that the base-load turbines running at peak efficiency could maintain a normal cruising speed, with boost turbines clutched in for high speed. This required gas turbines providing on the order of 25,000-30,000shp for a large warship; roughly twice the power of any gas turbine design considered by MV.[166]

However, by the early 1960s, the reliability of jet engines had improved rapidly, especially as the entry of jet engines into airline service had provided millions of hours of total running time, allowing faults to be ironed out. Combined with the ability to take advantage of the huge amounts being spent on jet engine development by air forces (and the ability to spread those costs over

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[161] WJ Hanman to M Lynch, 5 Jun 1959, NA T225/1414
[162] WJ Hanman to M Lynch, 5 Jun 1959, NA T225/1414
[163] Trewby (1962), 369. I have been unable to find any cost data from the plants in service to confirm or deny whether the savings were realised in service; Preston (1982) suggests the plants were not significantly cheaper overall.
[164] Preston (1982), 49-50.
[165] Preston (1982), 48
[166] As noted previously, Metrovick had proposed a 15,000 shp G.5 design for the initial Y.102 powerplant.

larger numbers of engines), the Royal Navy's Assistant Director of Marine Engineering decided to adapt aeronautical designs for future use.[167] The latest twin-spool gas turbines could reach cycle pressure ratios of 9:1, giving reasonable efficiency, and by the late 1960s 'navalised' gas turbines were capable of generating over 25,000SHP per unit. With no jet development programme of its own, once MV had completed its G.6 production, it could not hope to compete in this market, as it would have had to develop designs from scratch. Mergers in the aero-engine industry, driven in no small measure by the ever-expanding costs of developing a new engine type, meant that there was only one company left with the capability to develop new high-powered aero gas turbines; since the early 1970s, Rolls-Royce has been the sole supplier of propulsion gas turbines to the Royal Navy.

Conclusions

In the end, the difference between Metrovick's jet and naval gas turbine fortunes was a question of procurement. The company's technical ability was well-regarded, but it had neither the development nor the production facilities required to produce a service jet engine. Given the reservations expressed by the Ministry of Supply's technical staff, one must conclude that they viewed the F.9 as essentially a research project for an advanced compressor design. Indeed, it is hard to shake the feeling that though the Metrovick technical staff were developing designs for a state-of-the art engine, they were doing so without any thought being given as to whether it would ever reach production. As noted previously, Metrovick's bottleneck was in development resources; even if it had been provided with unlimited funds by the Ministry of Supply, it is unlikely the programme would have been much hastened. Such support was never likely to be forthcoming, given AVM Coryton's headaches about keeping the MoS's aero-engine manufacturers in business with his limited resources. Though Metrovick directors such as Bailey were touchy about the intellectual property rights vested in the Sapphire, they were unwilling or unable to invest in the kind of development and production facilities that would have been required to make Sapphire production viable. Given the RAF's operational need for high-powered jet engines, the transfer of the F.9 design to an aero-engine company became almost inevitable, especially given the MoS's desire to see some return on its investment of some £500,000 in the engine. Whether this constituted a 'failure' for MV depends on one's point of view; given the fact that Metrovick was not committed to engine manufacturing at the business level, the profits made on the F.9 development contracts and the payments for the transfer to Armstrong Siddeley were as good an outcome as could be expected. As a result the company had gained a great deal

[167] Trewby (1962); see also his memoirs held at the LHCMA, GB 0099 KCLMA Trewby.

of advanced compressor design experience at government expense, which it was able to use for its other gas turbine projects.

In comparison, the Admiralty's interest in the gas turbine was more as one of a portfolio of technologies: for fast craft, it competed with high-speed diesels such as the Deltic; for large warship plants, it was compared to more advanced steam installations. Moreover, Metrovick's steam-turbine-derived development style was well-suited to the development of naval gas turbines. They were ordered in small numbers, making development costs difficult to amortise across production runs, so a more deliberative process suited this environment; the low production numbers and rates required by the Admiralty also meant that MV could meet them with its existing production capacity.[168] How successful was Metrovick as a naval gas turbine builder? In one sense, very; the company's development costs were covered by the RN, and in service its units seem to have been successful and well-liked. Yet in another, the project was dogged by Metrovick's problems of cost control, and the numbers of units built (and thus the company's profit) was relatively small, especially as some of the powerplants were built by shipbuilders.[169] As the Royal Navy turned towards aeroderivative units, MV's lack of an aero-engine business meant that it was unlikely to gain further orders, and the company concentrated on its core business of industrial plant; the sector that is the subject of the next chapter.

[168] Though of course the state had paid for most of this development and production capacity; recall the £220,000 of jet engine tooling the Treasury hoped to reallocate after the Sapphire disposal.
[169] Though as previously noted, this was presumably through assembly of parts provided by MV. As shown by the EL60 (and to a degree the RM60), cost and schedule overruns were by no means exclusive to MV.

Chapter 5 – The civil gas turbine

MORE POWER… *means prosperity*

-Metropolitan Vickers advertising slogan[1]

'Only a few years ago the gas turbine was to the British engineer a new kind of aircraft engine, to the Swiss a new kind of power station plant, and the American a new form of supercharger. To-day, to engineers everywhere, it is all these things and a marine engine, a locomotive engine, and a useful auxiliary engine into the bargain. This list is not exhaustive: indeed, the gas turbine bids fair to be the Proteus of power generation.'[2]

As this 1955 assessment suggested, in the decade after the Second World War the gas turbine's role had greatly expanded. This chapter sets out to explore how and why the gas turbine was adapted by the civilian realm, in particular examining the roles played by the civilian institutions of the British state. Some of these institutions – ministries and nationalised industries – took a far more interventionist stance with regard to the development of new technologies than had previously been the case. Staff who had wartime experience of economic and R&D planning returned to civilian life with a desire to apply these ideas to their postwar responsibilities.

Though Metrovick was brought into the gas turbine field by the military, in the post-war period the company would apply its expertise to industrial applications. Yet state intervention was crucial to the industrial context of gas turbine development, whether indirectly through the post-war regime of controls and the nationalisation of large parts of the economy, or directly through the gas turbine research and development programmes of such organisations as the Ministry of Fuel and Power (MFP). These latter policies in particular can be viewed as aspects of what Robert Bud has called 'Defiant Modernism.' In Bud's view, new technologies developed by the state (especially through military research) were refashioned and used for peacetime (if not always peaceful) purposes, in order to maintain the UK's international standing at a time of economic and geopolitical challenges.[3] The case of the gas turbine is especially interesting in this context, as the technology was almost entirely the creation of the state, funded through government development contracts when not being directly developed by state institutions.[4] In post-war Britain, the gas turbine's potential as an industrial power source led to enthusiastic support for

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[1] *Metropolitan-Vickers Gazette*, Nov-Dec 1951.

[2] Roxbee Cox (1955), v.

[3] For which, see Bud (1998). Defiant Modernism in this sense is distinct from the (earlier, artistic) modernist movement; in Bud's usage it is meant to suggest the use of technoscience for state goals.

[4] Though, as noted in chapter 3, industrial expertise was crucial in making the gas turbine a viable aircraft powerplant.

civil development from both civilian, and (more indirectly) from service ministries. The stress on the gas turbine's efficiency suggests that staff at the ministries saw it as a tool to improve the efficiency of the national industrial infrastructure; the turbine's potential to use indigenous fuels such as coal or peat made it doubly attractive at a period where it was imperative to reduce imports that would require scarce foreign currency. The degree of support for these civil applications makes the gas turbine unique; though the British television and radio industry built on government support for wartime radio and radar technology, it was not directly supported by the state in the same way as the industrial gas turbine was. Though often motivated by fears about the supply of military materiel, arguments about control of non-aeronautical and civilian gas turbines are suggestive of the importance of the gas turbine and the hopes for its peaceful application. Though other historians have highlighted the UK's support for military science and technology in industry, consideration of the gas turbine gives a picture of a British state that is far more interventionist and supportive of *civilian* technologies than is conventional.[5]

In this chapter I will first discuss the political-economic context of the postwar period, and will then discuss how this affected Metropolitan-Vickers' business strategy. I will review Metrovick's first post-war civilian gas turbine order, a contract for a gas turbine railway locomotive. I will then examine the formation of the Ministry of Fuel and Power, and explain how the Ministry came to support gas turbine research; I will show how arguments about who should control gas turbine research meant that the funding of civil application did not get underway until the late 1940s. I will situate Metrovick's products in the wider context of the various gas turbine projects that were being launched in the decade from 1945, and will review how the Ministry of Fuel and Power funded gas turbine research in the hope of developing indigenous power resources. Finally, I will show how Metrovick's lack of a clear business strategy for the gas turbine meant that the company's business did not outlast the end of government support for civilian gas turbines.

Nationalisation and the post-war industrial context

The Labour Party had long had a commitment to, in the words of the party's 1918 constitution, 'secure for the workers by hand or by brain the full fruits of their industry'; this was to be achieved by 'the common ownership of the means of production, distribution and exchange.' In Labour's 1945 general election manifesto this was expressed as a policy of 'public ownership.' With the party's overwhelming electoral victory, the Labour government set out to implement a programme of nationalisation.[6] This aim was reinforced by wartime experience; the record of

[5] I am referring here in particular to David Edgerton's work on the 'Warfare State'; see eg. Edgerton (2006).
[6] For a general overview of the period, see eg. Morgan (2001)

British war production seemed to show that the country could produce large amounts of goods efficiently under a planned economy.[7]

The government planned to seize control of the 'commanding heights' of the economy, in order to better direct the economy for the benefit of all. The major industries nationalised were: coal (1947); inland transport, including the railways (1948); electricity generation and distribution (1948); gas (1949); and iron and steel (1951).[8] In addition, a state welfare system was created, building on a pre-war patchwork of national, municipal, and charitable provision. Healthcare was nationalised through the creation of the National Health Service (1948), though resistance from the medical profession led to some services being provided by self-employed doctors contracted to the NHS. The nationalised industries made up some 20% of the British economy, with the largest dwarfing the private sector's manufacturing companies;[9] yet some of the areas controlled were at best foothills, and some of the towering peaks of the economy were omitted, such as the chemical industry. Arguably this was due to the influence of trade unions on the Labour party; worries about industrial relations in particular sectors were as influential on Labour nationalisation policy as any strategic plan for the development of the economy.[10] This meant that there was an emphasis on older over newer industries; for instance, nationalisation of the large and economically important chemical industry was never seriously considered. [11]

Nationalisation did not give the government that much more influence than had previously the case, as most of the industries nationalised had historically been subject to a degree of state control. As either natural monopolies or crucial pieces of economic infrastructure, they had long attracted pro-nationalisation arguments, such as 'technological efficiency, the avoidance of wasteful competition, targeted capital, investment, and the need to improve industrial relations.'[12]The organisational forms adopted for the nationalised industries also made direct government control more difficult; following the technocratic ideals of Labour moderates such as Herbert Morrison, the model adopted was that of the public corporation, with a board of experts appointed by government, but run at arms' length. The nationalised industries therefore had a somewhat ambiguous status: they were to be run for the public benefit, yet were also to be

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[7] Though the planners themselves were often less sanguine about their achievements; see eg. Devons (1950); Cairncross (1991).
[8] Smaller nationalisations included airlines, the Bank of England, and Cable and Wireless.
[9] Gourvish (1991), 113. Even the mid-size nationalised industries such as gas and electricity were each the size of ICI in manpower and turnover.
[10] A point made by Ceadel (1991), 266-7.
[11] Ibid. The fact that the giant of the chemical industry, ICI, was well-run and had been close to government since its creation must have helped its case. See eg. Reader (1975), 252.
[12] Gourvish (1991), 118.

financially self-supporting, expressed as a requirement to balance costs and revenues over multiple years. Many of the managers in the public sector industries had a public service ethos (especially in those industries, such as the railways and electricity, that had been quasi-governmental for many years), but were not sure how this ethos was to inform their business strategy.[13] The nationalised industries' most important role was as suppliers of inputs (fuel, power, transport, and steel) to the economy. In the post-war economic climate of excess demand (and in an environment where industrial plant had deteriorated after heavy wartime use), government pressure on the nationalised industries was to provide more of everything, regardless of efficiency.[14] This was complicated by raw material shortages, as well as by the need to produce export goods in order to gain foreign currency. High-technology goods such as gas turbines were ideal for this task, as they had high added value.[15]

Despite the need for maximum output, government also sought to improve Britain's general economic performance alongside particular nationalisations. After 1947, as the economy approached full employment, and with limits on capital investment, improvements in productivity were the only ways to boost economic output.[16] As economic historians such as Tiratsoo and Tomlinson have shown, Labour was as concerned with industrial efficiency and production as much as with redistribution, even if they were less successful in influencing reluctant business and union leaders.[17] Alongside the physical infrastructural regeneration of nationalisation, Labour also sought to renew the human capital of the economy. Stafford Cripps (President of the Board of Trade and later Chancellor of the Exchequer) was a technocrat and an enthusiast for scientific management, and presided over the creation of such organisations as the Anglo-American Council for Productivity and the British Institute of Management.[18]

Yet apart from those industries affected by nationalisation, at the business level the government's post-war industrial strategy was mostly limited to trying to encourage business to pursue more efficient production methods.[19] Unfortunately for the government, the methods that promised the greatest improvements to productivity were those that required the most capital investment and would take the longest to implement, and implied a regime of specialised, standardised

[13] Ibid., 119-20.
[14] Tomlinson (1997), 100-1.
[15] This economic advantage could outweigh security concerns; for the specific case of jet engines, see Engel (2007)
[16] Zeitin (2000), 126-7.
[17] See eg. Tiratsoo and Tomlinson (1993), Tomlinson (1997). Cairncross (1985) also notes the Labour government's emphasis on productivity.
[18] Burgess (1999), 190-192; 197; 203ff.
[19] The regime of material and investment controls were mostly an attempt to allocate limited resources; see eg. Chick (1996).

production that did not necessarily fit the long-established working styles of British industry. As a result, much of the immediate response was to try and improve existing tooling along with wider use of work-study methods.[20]

Metropolitan Vickers's post-war business

In contrast, Metropolitan Vickers' post-war position was a happy one: the company had made healthy wartime profits, and the need for industrial reconstruction meant that the future demand for electrical equipment was high. As noted previously, government policy was to increase production as much as possible, and MV's heavy electrical plant manufacture was constrained by material rationing rather than by a lack of demand; production for the UK electricity industry was also limited by the need to export plant to help the economy.[21] Indeed, profits for MV's parent company, Associated Electrical Industries, were to rise almost ten-fold in the decade after the war.[22] The company expected this state of affairs to continue; as Lord Chandos, AEI's chairman, noted in a speech to shareholders in April 1956, electricity usage had doubled every decade from 1900, and he was confident that this pattern would continue for the next twenty to thirty years. Calling for the expansion of the company, he gave three main reasons for this prediction: the development of nuclear power and the associated electrical gear; a growing demand for electric traction on the railways; and a growing demand for automation.[23] Combined with the guaranteed income from government gas turbine development contracts, Metrovick had the cash to fund speculative gas turbine projects such as their railway locomotive and industrial designs.

Born Oliver Lyttelton, Lord Chandos had replaced AEI's elderly chairman Sir Felix Pole in 1945 due to the latter's poor health. Scion of an aristocratic family, with the trappings attendant thereupon (a captaincy in the Grenadier Guards; a marriage to a duke's daughter), Lyttelton had turned to a career in the City between the wars.[24] He had become the general manager of the British Metal Corporation, an organisation with close ties to the British state.[25] As a result, on the outbreak of war Lyttelton became the Controller of Non-Ferrous Metals, and was quickly promoted to President of the Board of Trade (1940), before being sent to the Middle East as Minister of State (1941), and succeeding Lord Beaverbrook as Minister of Production (1942).[26] However, with the

[20] Zeitlin (2000), 129-30
[21] In 1949, nearly half of the heavy plant manufactured by MV was for export; see the *MV Gazette* for Jan 1949, 4.
[22] Jones and Marriott (1970), 227.
[23] Jones and Marriott (1970), 228
[24] For more on Lyttelton's milieu, see Ball (2004)
[25] Though privately owned, the corporation was given the task by the Government of making the British Empire self-sufficient in non-ferrous metals; see Ball (2004), 78-9; 137-141.
[26] Ball (2004)

Labour general election victory of 1945, he lost his cabinet posts and reverted to being a backbench MP, which gave the directors of AEI the chance to approach him and secure his services.

Though Lyttelton managed to overhaul the organisation of AEI's constituent companies (Metrovick and British Thomson-Houston) to some extent, he was unable to effect any significant merger between the two. This was partly due to the ingrained rivalry between the subsidiary companies, but there was also no immediate financial incentive to merge in the face of the large profits being earned by Metropolitan Vickers and BTH. Lyttelton's tenure as AEI chairman was interrupted by the return to power of the Conservatives in October 1951; temporarily handing over the reins to Sir George Bailey, Lyttelton was appointed Secretary of State for the Colonies. Bailey was an engineer who had been chairman of Metropolitan-Vickers, and though he had a reputation for toughness (and, it should be noted, good labour relations) he did little to rationalise the subsidiaries' operations, as he was wary of being seen to be too partial to Metrovick in inter-subsidiary disputes. He he was also aware that Lyttelton would eventually return as chairman, which may have affected his decision-making.

When returned in 1954, Lyttelton (now Viscount Chandos) attempted to reorganise AEI, but his first reorganisation consisted mainly of renaming the old operating companies.[27] An expansionist by temperament, he concentrated his energies on raising capital in the City for new factories and plant. As one BTH executive put it: 'Chandos had effectively said to us: "I know nothing about engineering but I can raise any money you want."'[28] The results were dramatic: AEI's capital commitments expanded almost seven-fold, from £2.9M in 1953 to £20.2M in 1956. Yet even as the new capacity was brought into service, the company's profits began to decline sharply; 1955 was AEI's year of peak profits. The company's weaknesses of duplication and poor cost control were still present, and the electrical supply boom was coming to an end. AEI (and Metrovick's) wider business strategy was still heavily influenced by the prestigious heavy plant market, with an emphasis on designing and building to order.[29] The heavy plant engineering approach carried across to the light electrical and consumer electrical divisions; Metrovick's domestic appliances, though beautifully engineered, had production costs that were too high for the company to compete in the consumer sector.[30]

[27] Jones and Marriott (1970), 242.
[28] Quoted in Jones and Marriott (1970), 229.
[29] 'Megawatt mania' to those less committed to heavy plant; see Jones and Marriott (1970), 229
[30] Duplicating the problems the Metrovick Supplies subsidiary had suffered from in the 1920s.

Partly in response to the worsening financial outlook, in 1957 Lyttleton started a second round of reorganisation. AEI's products were split into three groups: Generation and distribution (turbo-generators, transformers, and switchgear, based in Manchester); Application of electricity (heavy electrical plant, motors, electronic devices, based in Rugby); Telecommunications and radio components (based at Woolwich.) Equally controversial within the subsidiaries was the removal of the traditional company names, made official in 1960; instead of Metropolitan Vickers and British Thomson-Houston, they were now known as AEI(Manchester) and AEI(Rugby).[31] Through the 1960s the group's profits continued to decline, despite further reorganisations and management changes. In 1967 AEI was taken over in a hostile bid by their competitors GEC.[32] In the period covered by this chapter, then, Metrovick maintained its heavy plant orientation, with all the advantages and disadvantages of the attendant technical style. Until the late 1950s, the company's profits were high enough (and its systems of cost control were loose enough) that it could take on speculative projects without financial restraint. After this point, as profits fell and AEI group control became tighter, it became ever harder for the company to undertake speculative work. I will now examine one of these speculative projects, which was the first major civilian gas turbine project Metrovick undertook: the construction of a gas-turbine-powered railway locomotive.

Metrovick and the railways

Despite their financial difficulties, and the fact that they operated a natural monopoly, the UK's railways had avoided nationalisation after the First World War. Instead 123 competing companies were amalgamated into four regional monopolies: the Great Western, London and North Eastern, London Midland and Scottish, and Southern Railways. As monopolies the 'big four' were regulated by government, but the hoped-for economies of scale were not achieved, and increasing competition from road transport (and the effects of the economic depression) meant that the railways' profits fell throughout the 1930s. The effect of the Second World War was to massively increase traffic on the railways and to reduce maintenance; although the Treasury had set up a fund to pay for future repair and reconstruction funded from wartime excess charges, post-war

[31] Jones and Marriott (1970), 243. Arguably the renaming was a mistake. It did nothing to reduce the subsidiaries' resentment against the changes, and it lost the companies' not inconsiderable brand name recognition.
[32] Jones and Marriott (1970). Insult was added to injury in the eyes of the heavy electrical engineers by the fact that GEC's growth had come from its consumer electricals business. For more on GEC and its chairman see Brummer and Cowe (1998).

shortages meant that even the most optimistic estimates put the time to repair the wartime backlog at the best part of a decade.[33]

Metrovick's involvement with the railway gas turbine came in 1946, as the result of a collaboration with the Great Western Railway (GWR). From the time of the tenure of Isambard Kingdom Brunel, the GWR had considered itself the *primus inter pares* of the railway engineering fraternity. However, the Second World War had meant the cessation of design work on new locomotives, especially on the prestige types intended for express passenger services. The War's reduced maintenance schedules had also been responsible for the deterioration of much of the railway's rolling stock; as a result, the GWR began to consider the acquisition of new locomotives for the post-war period.[34] Although the GWR appears to have briefly considered the use of diesel engines for mainline locomotives, with a report being presented to its Locomotive Committee in January 1946, no further action seems to have been taken; the high-powered diesel engine was still somewhat of a novelty, and the best form of power transmission was still unclear.[35] At about the same time, the GWR was considering the use of a gas turbine for locomotive power, for which they wished to engage Metrovick.

The first evidence for this relationship is in a letter of 11 February 1946 from the GWR's general manager, Sir James Milne, to Sir George Bailey, Metrovick chairman.[36] Referring to earlier discussions, the letter sought to confirm the financial terms agreed verbally, namely that the construction costs of the engine would be split equally between the two companies. This arrangement suggests that Metrovick's management had enough faith in their gas turbine experience to embark upon a commercial venture; up until now, their wartime and military contracts had been on a cost-plus basis with little financial risk. Metrovick clearly saw a market for railway equipment; the company was a long-standing manufacturer of electric traction equipment, having supplied locomotives to countries around the world. The company had support for its estimates of post-war business: for instance, in 1938 it had received a contract for 74 electric locomotives for the Manchester-Sheffield line, and in 1944, it received orders for the supply of electric locomotives to South African railways. [37] Metrovick had no locomotive manufacturing facilities itself, subcontracting out chassis production, so in 1949 it formed the joint company Metropolitan-Vickers-Beyer, Peacock, Ltd. The company's aim was to manufacture

[33] Gourvish (1986), 4-5.
[34] Robertson(1989), 3-6.
[35] Robertson(1989), 5; See also Clough(2011)
[36] The correspondence is quoted in Robertson(1989), Appendix A.
[37] Dummelow (1949), 229-30; the work was interrupted by the outbreak of war; work restarted in the late 1940s.

mechanical parts for 'electric, gas-turbo-electric, and diesel-electric locomotives.'[38] The variety of traction types is interesting; as noted below, from late 1948 the nationalised Railway Executive was examining the alternatives for railway modernisation, and the optimum mix was as yet uncertain; Metrovick was positioning itself to be able to supply equipment whatever the outcome.

Meanwhile, at the GWR's March 1946 AGM, its Chairman, Lord Portal, announced that the company was investigating the use of gas turbines for railway use. However, the Metrovick machine was not to be the GWR's only gas turbine locomotive; the company was also to take advantage of overseas expertise. In the summer of 1946, the International Railway Congress (the major conference for railway engineering) was held in Switzerland, and Sir James Milne and the GWR's chief mechanical engineer, FW Hawksworth, attended as delegates. Whilst they were there, they visited the Brown Boveri works and inspected the gas turbine locomotive that had been built for the Swiss railways in 1939.[39] Like the Metrovick engine a turbine-electric design, it drew on Brown Boveri's industrial gas turbine experience, and had been commissioned by the Swiss railways as an experimental unit for use on non-electrified lines.[40] Milne and Hawksworth were clearly impressed by the design, and upon their return recommended that the GWR investigate ordering a gas turbine locomotive from Brown Boveri. The GWR's board approved their suggestion at a meeting in late June 1946, and invited Brown Boveri to submit a tender. Such a large overseas order would have to be approved by government, not least because of the hard currency required for its purchase; at current exchange rates, this came to some £99,000.[41] After consideration, the Minister of Transport agreed that the project was worth funding, especially as his Ministry and the Ministry of Fuel and Power were interested in the gas turbine.[42] Before examining the further progress of the gas turbine locomotive, it is perhaps useful to consider the role of the Ministry of Fuel and Power.

The Ministry of Fuel and Power

Before the Second World War, government responsibilities for various energy supplies were distributed between a number of departments. Faced with the demands of coordinating a

[38] *Metropolitan-Vickers Gazette*, Jan-Feb 1950, 155. The somewhat clumsily-named Metropolitan Vickers-Beyer Peacock produced some two hundred electric and diesel-electric locomotives (the majority for export) before the company's 1961 voluntary liquidation.
[39] Robertson(1989), 10. The Swiss locomotive first ran in 1941.
[40] The gas turbine powered an electric generator that in turn drove electric motors at the axles.
[41] Letter Sir James Milne to Sir Reginald Hill, 12 Sep 1946, NA MT 6/2801; a copy of the Brown Boveri tender can be found in this file.
[42] See the correspondence for Aug-Oct 1946 in NA MT 6/2801. Approval was received by mid-September 1946; see the quote in Robertson(1989), 11.

wartime economy, these responsibilities were gradually concentrated under the Board of Trade, which was already responsible for gas, mining, and petroleum. In June 1942 the responsibilities were transferred to a new Ministry of Fuel and Power, which was to administer controls over fuel supplies, and to coordinate their distribution; a role which was made permanent by the 1945 Ministry of Fuel and Power Act. The Act charged the Ministry with 'securing the effective and co-ordinated development of coal, petroleum and other minerals and sources of fuel and power in Great Britain, of maintaining and improving the safety, health and welfare of persons employed in or about mines and quarries therein, and of promoting economy and efficiency in the supply, distribution, use and consumption of fuel and power'.[43] However, the Ministry's initial post-war efforts were concentrated on the nationalisation process for the coal, gas, and electricity industries, as well as the continuing administration of rationing and controls.

These industries were crucial to Britain's postwar economic recovery, as energy costs affected the overheads of all other industries. In addition, coal was a major export for the UK, and though employment was lower than prewar levels, it remained a major employer; the miners' unions were also an important constituency for the government. In this respect it was unsurprising that the Minister of Fuel and Power had a seat in the Cabinet.[44] The Ministry was the route to power for Hugh Gaitskell, who was first assistant to the Minster, then Minister of Fuel and Power, then Minister for Economic affairs, and finally Chancellor of the Exchequer; in the latter two roles he still had a professional interest in fuel and power. Though not one of the great Departments of State, the Ministry clearly had an important economic role to play; its research programme should be seen in light of this economic importance.

The Ministry's relationship with the fuel and power industries was less close than their nationalised status might have suggested; though the Minister of Fuel and Power was responsible for the appointment of boards and could control capital investment, appointing staff of high calibre meant allowing them a degree of independence.[45] In January 1957 the Ministry was renamed the Ministry of Power, and gained a supervisory function over the industrial uses of nuclear energy; the following year, controls over coal pricing and distribution were abolished. Though the nationalised industries had the power to carry out and sponsor their own research, under the 1945 Act the Ministry had a supervisory and coordinating role over research and

[43] Text of the act taken from http://www.legislation.gov.uk/ukpga/Geo6/8-9/19/section/1, accessed 12 Jun 2012. Unfortunately, as for many of government's less glamorous departments, no institutional history of the MFP exists.
[44] At least until the 1947 Cabinet reshuffle in which the Minister Manny Shinwell was sacked.
[45] See Hannah (1979); Ashworth and Pegg (1986). At the local level, many staff had been managers in private power stations or collieries.

development. Consequently, in June 1948 the Minister of Fuel and Power appointed a Scientific Advisory Council to the Ministry, as well as a Chief Scientist. Harold Roxbee Cox was recruited from the National Gas Turbine Establishment to fill the Chief Scientist's post, and the chemist and combustion expert Professor Sir Alfred Egerton FRS was appointed as chair of the Advisory Council.[46]

The gas turbine locomotive and fuel supply

Why did the Ministry of Transport (MoT) support the procurement of a Swiss locomotive as well as a British one, when the former required precious hard currency? Apart from Brown Boveri's proven track record, the answer may be due to considerations of fuel supply. The UK was plentifully supplied with high-grade coal and water, both factors which made the use of steam engines attractive, and indeed were factors in the UK's comparatively late replacement of steam traction for mainline services.[47] However, steam engines were not particularly thermodynamically efficient, and used high-grade coal that could be exported or used in industry – hence the Ministry of Fuel and Power's interest in alternative fuels. Among the projects that the MFP sponsored was the conversion of a number of the GWR's steam engines from coal to bunker oil (i.e. low-grade fuel oil) firing. As coal supplies were diverted to industry to support post-war reconstruction, the GWR had carried out a number of experimental conversions, but in 1946 the MFP asked the company to prepare for a large-scale programme. In his annual report for 1946, the GWR's chief engineer stated that the planned conversion of 184 engines would save some 173,000 tons of coal per annum.[48] Crucially, the Brown Boveri engine was to run on heavy fuel oil, whereas the Metrovick unit used higher-grade kerosene. Unfortunately, even low-grade fuel oil had to be obtained from abroad, and with the currency crises of the late 1940s the necessary foreign exchange could not be spared; from 1948 onwards the 35 or so GWR locomotives converted were returned to their original coal-burning state.[49]

However, this reconversion did not affect the decision to order the Brown Boveri (or the Metrovick) gas turbine trains; whether this was an oversight on the Ministry's part, or whether the units were considered merely experimental, is unclear. The railway historian Kevin Robertson has suggested that part of the GWR's reason for pushing on may have been a desire on its to present the nationalised railways with the *fait accompli* of technically advanced new locomotives

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[46] See the press notes in June 1948 NA POWE 25/168. Egerton had advised MAP and the RAE on combustion issues affecting gas turbines during the Second World War.
[47] Clough(2011), 1;11.
[48] Robertson(1989), 13-14.
[49] Details are given in Appendix B of Robertson (1989)

on order, thereby preserving something of the company's engineering heritage.[50] As the 1947 book *Next Station: A Railway Plans for the Future* put it, referring to the GWR's gas turbine programme: 'The Great Western intends to maintain its position of leadership in the application of new forms of energy to railway traction.'[51] The publication also cited ease of maintenance and the high power-to-weight ratios achievable as advantages for the gas turbine.[52]

Initially the GWR was to design and manufacture the 'mechanical parts' of the locomotive (presumably the chassis and bogies) and Metrovick the 'equipment,' but in November 1946 the GWR informed the Manchester firm that they could not now undertake this work, and asked them to organise subcontractors themselves. Metrovick's Bailey agreed to do this, but noted that most of the locomotive foundries were busy with other work, and that MV was having finding qualified draughtsmen to do the work in-house. The situation had clearly not improved by March 1947, when Milne wrote to the Minister for Transport to ask whether the Ministry might assist in obtaining permits for qualified German locomotive draughtsmen, as 1950 was the earliest locomotive delivery date a UK works could give.[53]

Railway nationalisation seems to have had little effect on the progress of the work, which remained slow; Brown Boveri's initial tender had given a completion date of 1948, but the engine was not completed until late 1949, and was not shipped to the UK until early 1950. There does not seem to have been a great deal of pressure from the railways for completion, though as a nationalised industry its staff tried – in vain – to convince the Board of Trade to waive import duty on the locomotive, which at 20% was a not inconsiderable sum.[54] Though it had been ordered earlier, the Metrovick engine's progress was even slower; erection of the locomotive did not start until 1948, and the first test of the turbine was not until 1950.[55] Originally the company had intended to use an engine based on the F.2/4 and similar to the naval G.2, but fitted with a heat exchanger. However, worries about how the bearings would stand up to railway vibration caused Metrovick to design a new design closer to industrial practice, with a 15-stage compressor and a 5-stage turbine driving both the compressor and the generators for the wheel motors. Enthused by the first tests, the Railway Executive asked whether the engine would be ready for the

[50] Robertson(1989), 16-17.
[51] Barman(1947), 40. Christian Barman was the GWR's publicity officer; his book presumably had official sanction.
[52] Though the former was presumably somewhat speculative, given that no detailed data were available for the only gas turbine locomotive in service.
[53] Letter Sir James Milne to Sir Cyril Hurcomb, 25 Mar 1947, NA MT 6/2801
[54] The Board of Trade and Ministry of Supply were not unsympathetic, but remained adamant that as the locomotive was 'non-productive machinery' it was liable for duty, and did not wish to set a precedent. See the correspondence in NA MT 6/2801 for April 1949.
[55] Whyte (1978) gives the figure of 264 hours of turbine bench testing between July 1950 and July 1951.

upcoming Festival of Britain, but Metrovick indicated that this was unlikely; the locomotive first ran in November 1951.[56] Despite the locomotive not being there, Metrovick did use the Festival to display many of its products and to burnish its modern credentials; models of the locomotive were at the South Bank and in the travelling exhibition, and the Metrovick-powered MGB 2009 and the Saunders-Roe SR.A/1 were moored on the Thames for visitors to admire.[57] The display of gas turbines at the Festival reinforced both their modernity and their Britishness, making them powerful symbols of technological prowess. Though it was now mainly a patent holding company, Power Jets (R&D) Ltd. produced a 'Festival Survey' of British gas turbine designs and technologies, for sale to festival-goers.[58] Not for nothing was the first of many technological cutaway drawings in the *Eagle* comic a gas turbine locomotive roaring out of a tunnel.[59]

The slow progress on the gas turbine locomotive was perhaps a consequence of the fact that its place in the future rail system was uncertain. In December 1948 the Railway Executive set up a committee to examine the benefits of the various types of traction, and to advise on the experiments needed to ascertain accurate costs for each.[60] It reported back in October 1951, recommending a pilot scheme of electrification, as well as large-scale trials of high-powered diesels for mainline services.[61] However, by the time it had reported back, the Railway Executive's Engineering Member, RA Riddles, had already embarked upon a new programme of steam construction. He was sceptical about the benefits of diesels, and argued that the railways should invest in mainline electrification and in the interim stick with steam.[62] However, as part of the 1953 reorganisation of the British Transport Commission, the Railway Executive was abolished and Riddles retired; the railways then adopted the '1955 modernisation plan,' comprising the electrification of some main lines, and the large-scale adoption of diesel locomotives for non-electrified lines.

Yet even with this decision the technical issues were still not clear-cut; even with the decision to adopt diesel engines, there remained the choice of transmission type – electric or hydraulic?[63] In addition, the MFP had not entirely given up hopes for a gas turbine locomotive. In late 1955, together with the British Transport Commission, the Ministry funded a series of design studies for

[56] Robertson(1989), 58-9; The locomotive was, however, featured in Festival of Britain publications, and models were displayed at the South Bank exhibition and the travelling exhibition; see Power Jets (1951), 21.
[57] See the illustrated articles in the *MV Gazette* for Jan/Feb 1952.
[58] Power Jets (1951)
[59] Even if, alas, it depicted the Swiss Brown Boveri unit.
[60] Clough(2011), 59.
[61] Clough(2011), 59.
[62] Clough(2011), 59; As Clough points out, this was the path followed in much of continental Europe, albeit earlier than the UK. See also Chick (1996), 162-3.
[63] See Clough (2011).

gas turbine locomotives of medium and high power to be more efficient than existing locomotives. This may have been due to the 1955 modernisation plan; as not all lines were to be electrified, if a more economical alternative to diesels could be found it would be of value. However, though the studies concluded that high efficiencies were theoretically feasible, their attainment would require the design of new turbines or the extensive modification of aircraft-style units.[64] The actual testing of the gas turbine locomotives had done nothing to further their case against the alternate technologies such as diesels then under consideration. Though the Metrovick locomotive was one of the most powerful on the rails, full power was only required when leaving a station or climbing a gradient; at all other times, running at part load, the gas turbine powerplant was not very efficient, and so it was ill-suited to railway use.[65] Estimates for its running cost put it at over twice that of the steam locomotives it was intended to replace.[66] In addition, the complexity of the machinery made it unpopular with the maintenance staff, and by May 1956 the railway operators were writing to the British Transport Commission for permission to abandon the project. This was granted in late 1957; at the final settlement of accounts the cost of the project was some £347,880 19s 3d. As half of this amount was to be paid by Metrovick, it had been an expensive experiment (by comparison, a 1954 contract for electrical gear for 70+ units on the Mersey and Wirral line was for £286,000).[67] The gas turbine locomotive was returned to Metrovick for conversion to a fully electric locomotive, and served as a training unit for the West Coast Main Line electrification project of the late 1950s. As noted, for Metrovick the gas turbine had been one –unsuccessful – option among many, and it concentrated on its electrical and diesel-electric business. In contrast, this made the gas turbine work look like a sideshow; for instance, one 1959 contract for the South African railways was valued at £7.5m.[68]

Research scope

One of the initial issues with the planned nationalisation of gas, coal, and electricity was that there was no consensus as to whose responsibility research should be. The various industries had their research associations (e.g. the British Coal Utilisation Research Association) that were expected to continue under the nationalised industries, but the MFP's coordinating role meant that it could stake a claim to broader control of these research institutions. As early as August 1945 the Deputy Secretary at the MFP was considering proposals for a body that would coordinate research across the nationalised fuel and power industries. The obvious institution

[64] See the note on the Draft Research Programme for 1957-58, NA POWE 25/235.
[65] As indeed the Admiralty were discovering at about the same time with the complex RM60 gas turbine.
[66] Robertson (1989), 138.
[67] *Metropolitan-Vickers Gazette*, Sep 1953. The contract was for traction motors and control equipment for 24 motor coaches, 26 trailer coaches, and 26 driving trailers.
[68] *Metropolitan-Vickers Gazette*, Jul 1959.

was the DSIR's Fuel Research Board (FRB), which had been set up in 1917 amid wartime worries about the UK's coal stocks.[69] The Board was responsible for a National Coal Survey, which worked in conjunction with local coal boards, and a Fuel Research Station, whose laboratories were built in Greenwich in 1919.

The Coal Survey was a logical candidate for transfer to the National Coal Board, and the MFP's staff saw the Fuel Research Station as an ideal nucleus for their wider research organisation.[70] One argument put forward for the transfer was the need for a closer liaison between the research organisation and the production and utilisation of fuels. In an example of how wartime experience was shaping postwar research, the relationship between the armed forces and the supply ministries' research establishments was held up as a model to be emulated.[71] Unfortunately for the Ministry of Fuel and Power, the DSIR was implacably opposed to the transfer of control; Sir Edward Appleton, the Department's secretary, argued that the fundamental character of much of the Fuel Research Station's work meant that it was best suited to a non-executive government department, and that any necessary coordination of fuel research could be carried out on a consultative basis.[72]

This was not acceptable to Manny Shinwell, the forceful Minister of Fuel and Power, who insisted on control of the Fuel Research Station, and who took the matter to Herbert Morrison the Lord President for a decision. However, by late January 1947 Shinwell was embroiled in a crisis over fuel supplies in the coldest winter for a generation, and so for the moment he begrudgingly accepted DSIR control of the Station, with the proviso that the matter be reviewed once nationalisation of the fuel and power industries was complete.[73] Shinwell tried to raise the issue again in the summer in the wake of a report by the Advisory Council on Scientific Policy (ACSP), but shortly thereafter Shinwell was moved to a non-Cabinet post as Minister of War, and the matter was left to lie.[74]

One recommendation that had been made by the ACSP was that the MFP should appoint its own Chief Scientist and a Scientific Advisory council, and, as previously mentioned, the gas turbine

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[69] DSIR (1960)

[70] See the memos for August 1945 in NA POWE 25/147; among the staff discussing the issue were the head of the fuel efficiency division and the Ministry's Deputy Secretary.

[71] As discussed in the memo of 28 Aug 1945, NA POWE 25/147.

[72] E. Appleton to G. Nott-Bower, 5 Nov 1946, NA POWE 25/147.

[73] See the copy of the letter from Shinwell to Morrison, 31 Jan 1947, NA POWE 25/147.

[74] The matter was raised again in 1950 by the Ministry of Fuel and Power, and though a sub-committee of the Advisory Committee on Scientific Policy recommended the transfer of the Research Station to the Ministry, this did not happen; possibly because of resistance from other departments and because of the change of government. See the correspondence from Feb 1950 and ff. in NA DSIR 8/95.

expert Harold Roxbee Cox was appointed as the Ministry's Chief Scientist in June 1948. The research supported by his Division was varied, ranging from coal gasification to combustion research. Yet the gas turbine was the only technology to be supported at the development stage by the Ministry. Given the importance of energy to the economy, the gas turbine held great promise for industry; the ministry's experts considered large advances in efficiency from the current state of the art possible. This did not seem implausible, given the improvements in jet engine performance over the past decade. Gas turbines seemed especially suited to applications of a few thousand horsepower, where the capital costs could be much lower than for alternative power sources such as steam turbines or diesel engines. Due to their combustion systems they could also potentially run on low-grade indigenous fuels, such as coal, peat, and firedamp (methane produced in coal mines).[75] This emphasis on the efficiency of the gas turbine, coupled with its ability to produce useful power from low-grade fuels, suggested that the development of this technology – in which the UK was one of the world leaders – could be a route to improved national economic performance, as well as easing reliance on foreign fuel supplies. In this sense, the development of the civil gas turbine fits with Bud's characterisation of 'defiant modernism'; an added attraction was that this was a prime mover potentially applicable to all sectors of industry. Having gained its own research organisation in the Chief Scientist's Division, the Ministry of Fuel and Power was now to become a player in the struggle for control of gas turbine research.

Control of research

As noted previously, the jet engine was the result of generous state support; post-war, as the sponsoring Ministry for the National Gas Turbine Establishment, the Ministry of Supply (MoS) was the government department responsible for its development. In August 1947, the MoS's permanent secretary, Archibald Rowlands, wrote to his counterparts at the various supply, scientific, and industrial departments, suggesting that they should consider support for other gas turbine applications. Rowlands noted that the civil and industrial applications of the gas turbine had been 'left almost entirely to private enterprise and it [was] here that the work seemed to be languishing for lack of Government support'.[76] He suggested that the Ministry of Supply should take a more active role in supporting civil gas turbine applications, as it controlled the NGTE, and asked for an interdepartmental meeting to discuss the issue. Rowlands pointed out that the gas turbine had enormous potential, with obvious applications in the fields of power generation and railway traction.

[75] 'History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, v.
[76] Letter A Rowlands to Sir John Lang, 22 Aug 1947, NA ADM 1/21691

The effect of Rowlands's note was presumably rather more dramatic than he intended, as it lit the touchpaper on a three-year effort by the Admiralty and other Ministries to wrest control of gas turbine research from the Ministry of Supply. The Admiralty's Engineer-in-Chief, Denys Ford, saw this move as a claim by the MoS to gas turbine research that might endanger the Admiralty's gas turbine work.[77] His arguments were based on the fact that industrial gas turbine applications were more similar to naval requirements than the aeronautical work sponsored by the MoS. Based on this similarity, Ford argued that in wartime naval turbines would be built by industrial firms, and worried that the switch in 'foster parent' ministry at the outbreak of a conflict would impair mobilisation.[78] He also argued that the approach at the Ministry of Supply led to a profligate attitude towards spending and costs, which meant that commercial development was less likely; though he conceded that the Admiralty was not always immune to this attitude, he pointed to the Admiralty's long relationship with the shipbuilding and engineering industries.[79] Ford concluded with a request for specialised testing facilities for naval and long-life gas turbines, as they would require long periods of endurance running, and noted that if the Admiralty were to take on more of a sponsoring role for turbine development it would require more staff; it currently had 'about four' staff working in the field, as opposed to the Ministry of Supply's 1,000-plus.[80] His feelings on the issue may also have been influenced by his feelings on the importance of engineering to the RN; as discussed in chapter 4, the status of Engineering Officers had been a vexed topic in the Navy, and Ford was the first (E) officer to be appointed Engineer-in-Chief.

In response, Admiral Charles Daniel, the Controller of the Navy, responded that the Admiralty should offer to sponsor roles in its field of requirement, as well as establishing a greater role in the control of the NGTE's research.[81] However, the Admiralty staff came back from the meeting at the Ministry of Supply frustrated.[82] The other ministries that might have challenged the MoS's control of gas turbine research (mainly the DSIR and the MFP) had not questioned the current situation, though the DSIR staff had indicated that they would like to review the matter in a few years' time.[83] Declining to press the point any further, the Admiralty staff decided to leave further

[77] DC Ford, Admiralty Engineer-in-Chief, 5 Sep 47, 'Gas turbine – Admiralty policy naval and marine applications,' NA ADM 1/21691; this was a briefing paper presented to the Controller of the Navy.
[78] DC Ford, Admiralty Engineer-in-Chief, 5 Sep 47, 'Gas turbine – Admiralty policy naval and marine applications,' NA ADM 1/21691
[79] DC Ford, Admiralty Engineer-in-Chief, 5 Sep 47, 'Gas turbine – Admiralty policy naval and marine applications,' NA ADM 1/21691
[80] DC Ford, Admiralty Engineer-in-Chief, 5 Sep 47, 'Gas turbine – Admiralty policy naval and marine applications,' NA ADM 1/21691
[81] DC Maxwell, 'Note on a Meeting at the Ministry of Supply and related action,' 24 Oct 1947, NA ADM 1/21691
[82] F Brundrett to JH James, 31 Oct 1947, NA ADM 1/21691
[83] F Brundrett to JH James, 31 Oct 1947, NA ADM 1/21691

questions of sponsorship and control for a later, more formal, meeting. The one bright point for the Admiralty was that there had been general agreement that control of the NGTE research programme was rather dominated by the air side, which would hopefully mean more research into industrial and marine research at the NGTE.[84] In the months after the meeting, the Admiralty's research and procurement staff discussed how best to respond. They concluded that the DSIR would be the ideal department to both control the NGTE and sponsor industrial gas turbine development; though sympathetic to the Engineer-in-Chief's concerns about control of marine engineering, they thought that challenging the Ministry of Supply's control of the wider engineering industry would endanger the attempts to get the DSIR to take over general research and development.[85]

Yet no progress had been made on this front by April 1948, when the MoS's Deputy Secretary Sir George Turner again wrote to the Admiralty to announce the formation of the Industrial Gas Turbine Development Committee. It was to comprise representatives of the interested civil and service departments, and was intended to 'keep under review the progress of gas turbine development for non-aeronautical uses.'[86] Turner also proposed the creation of a section under the MoS's Director of Engine Research and Development to coordinate industrial applications, to be staffed by technical officers from 'user' departments. From the Admiralty's point of view this did not provide sufficiently independent control of non-aeronautical applications. As the Secretary of the Navy noted, the MoS seemed to have a 'sense of proprietorship' over the gas turbine, which would have to be handled carefully.[87] After due discussion, the Admiralty's Under-Secretary sent a carefully-worded letter to the Ministry of Supply suggesting that the DSIR take greater control of gas turbine research, and the Navy's chief scientist, Frederick Brundrett, was asked to arrange an informal meeting with the DSIR's secretary, Sir Edward Appleton.[88] At the meeting, Appleton remarked that he had already informed Rowlands, the Secretary at the MoS, of his unhappiness with the current gas turbine research organisation, and had intimated that he would be happy for the Admiralty to make their proposals to the MoS.[89]

However, it soon became clear that the DSIR's secretary had changed his position; in response to queries, he pointed out that the bulk of the NGTE's work was for the services, and because a large proportion of this work was carried out through development contracts, it would not be

[84] DC Maxwell to JH James, 5 Nov 1947, NA ADM 1/21691
[85] See the series of internal minutes on 'Gas Turbine Development', 11 Nov 1947 – 5 Feb 1948, NA ADM 1/21691
[86] Sir George Turner to Secretary of the Admiralty, 2 Apr 1948, NA ADM 1/21691
[87] Minute, 6 Apr 1948, NA ADM 1/21691
[88] Letter CB Coxwell, 31 May 1948, NA ADM 1/21691; Minute PAS (Pr), 26 May 1948, NA ADM 1/21691
[89] Minute PAS (Pr), 26 May 1948, NA ADM 1/21691

appropriate for the DSIR to take over control, though he noted that this might change in future.[90] Rebuffed in this way, the Admiralty tried another tack. Writing to Rowlands at the Ministry of Supply, JG Lang, the Secretary of the Admiralty, pointed out that his department was committed to about £2M's worth of expenditure on medium- and long-life gas turbine projects. Given the value of this experience to the industrial field, he argued, it would be worth setting up a Medium and Long-life Directorate of Gas Turbines, jointly responsible to the Controller of the Navy and the MoS Controller of Supplies (Munitions), initially to be headed by a naval representative.[91] In addition, he suggested that the proposed advisory committee to the NGTE should be supplemented with an executive committee able to recommend a distribution of resources between the various aeronautical and non-aeronautical researches underway at the establishment. At the suggestion of the First Lord of the Admiralty, who did not want to invite a 'severe snub' from the Ministry of Supply on the grounds of 'advising them how to run their own show,' Lang discussed the contents of the letter with Rowlands and Turner before formally sending it; they agreed to consider its contents, though they would not make any commitments to its suggestions.[92] Rowlands conceded that the current proposed structure would need some provision for overseeing projects that overlapped the responsibilities of the industrial, marine, and aeronautical fields, but Lang agreed that for the moment this could be left to wait.[93]

The Ministry of Supply's formal response to the Admiralty came in March 1949; the Minister had agreed that a separate directorate for industrial gas turbines was worth pursuing, and had sought Treasury sanction for the post.[94] He also agreed that the first Director could be chosen from Admiralty candidates, and asked for two or three nominees for the post. Yet on other matters, the MoS position was unchanged; the new directorate would be responsible to the Controller of Supplies (Air) rather than the Controller of Supplies (Munitions), and there would be no formal joint responsibility to the Controller of the Navy, though the director would maintain a close liaison with the Admiralty.[95] Lang was still not fully satisfied; noting the importance of effective research administration, he suggested a meeting of interested parties at the Treasury in order to fully discuss the points at issue.[96] However, by now the Admiralty was not alone in its struggle against the Ministry of Supply, as another industrial ministry had developed an interest in the gas turbine - the Ministry of Fuel and Power.

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[90] Sir Edward Appleton to F Brundrett, 7 Sep 1948, NA ADM 1/21691
[91] JG Lang to Secretary, MoS, 4 Jan 1949, NA ADM 1/21691
[92] Minute JG Lang, 29 Dec 1948, NA ADM 1/21691
[93] Minute JG Lang, 29 Dec 1948, NA ADM 1/21691
[94] Copy of letter Rowlands to Secretary, Admiralty, 7 Mar 1949, NA ADM 1/21691
[95] Copy of letter Rowlands to Secretary, Admiralty, 7 Mar 1949, NA ADM 1/21691
[96] Copy of letter JG Lang to Permanent Secretary, Ministry of Supply, 19 Apr 1949, NA ADM 1/21691

The Ministry's first interest in gas turbines seems to have arisen in May 1948, as the result of discussions at the Fuel Research Board. As Both the British Coal Utilisation Research Association and the Fuel Research Station had plans to carry out research work on coal firing applicable to gas turbines, but the FRB were eager that this part of a wider development plan to get coal-burning gas turbines into service as quickly as possible.[97] At the meeting, the Admiralty representative pointed out that the Admiralty had a general coordinating role for marine gas turbines, and the FRB had recommended that a similar coordinating authority be appointed for land turbines. Both the British Transport Commission and the British Electricity Authority were suggested, but they were not seen as ideal;[98] William Macfarlane, the MFP's representative, was able to report to Sir Guy Nott-Bower, the Ministry's Deputy Secretary, that 'if the [Ministry's] Scientific Advisory Council [were] well established, it would clearly have been welcome' in a coordinating role.[99]

The following month Harold Roxbee Cox joined the Ministry of Fuel and Power as its Chief Scientist. As noted previously, he was interested in the application of gas turbine technology to civilian uses, and shortly after his arrival he began to plan a programme of gas turbine research.[100] The Ministry of Fuel and Power now shared the Admiralty's concern that non-aeronautical research would struggle to gain resources under Ministry of Supply control, and by March 1949 Roxbee Cox had discussed the matter with the Admiralty's Engineering Branch.[101] Writing to the Ministry of Supply, Donald Fergusson, the MFP's Permanent Secretary, argued that his Ministry should be responsible for gas turbine projects in which 'the primary technical objective [was] overall economy from the fuel and power point of view'; in practice, this meant industrial gas turbines.[102] He suggested that the ministries with specialist interests in gas turbine applications should be able to place their own development contracts with industry, and that the NGTE should have specialist sections for air, naval, and industrial applications, controlled by their respective ministries.[103] He also agreed with the Admiralty that the DSIR should be in control of the NGTE. This now seemed to be a possibility again, as Sir Edward Appleton had been replaced as Secretary of the DSIR by Sir Ben Lockspeiser. As a former Director-General of research at the Ministry of Aircraft Production, Lockspeiser was familiar with the gas turbine, and the Navy's Chief Scientist

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[97] W Macfarlane, 'Gas Turbines to Run on Coal,' 18 May 1948, NA POWE 25/168.
[98] Both organisations had in fact previously consulted the Admiralty for advice on gas turbines; see the comment by DC Ford, Admiralty Engineer-in-Chief, 'Gas turbine – Admiralty policy naval and marine applications,' DC Ford, Admiralty Engineer-in-Chief, 5 Sep 47, 'Gas turbine – Admiralty policy naval and marine applications,' 5 Sep 1947 NA ADM 1/21691
[99] W Macfarlane, 'Gas Turbines to Run on Coal,' 18 May 1948, NA POWE 25/168.
[100] See 'History of the Gas Turbine Programme,' n.d. (but c. May 1958), NA POWE 25/278, v.
[101] See JH James's minute of 24 Mar 1949, NA ADM 1/21691
[102] Copy of letter Sir Donald Fergusson to Sir Archibald Rowlands, 4 May 1949, NA ADM 1/21691
[103] A view attributed by the Admiralty to the influence of Roxbee Cox; see See 'notes for use at internal meeting of Admiralty and M. of F&P,' n.d., NA ADM 1/21691, 2.

believed that he would take a more positive attitude towards the DSIR taking over control of the NGTE.[104] Unfortunately for the Admiralty and the Ministry of Fuel and Power, by July 1949 Lockspeiser had clarified his position, and was unwilling for the DSIR to take on the NGTE.[105] This may have been because by now he was aware of the department's workload, and did not wish to add to it, especially at a time when the DSIR's resources were limited.[106]

Meanwhile, in response to the Admiralty's suggestion, the Treasury had agreed to chair an interdepartmental working group to discuss gas turbine research, inviting representatives from the Board of Trade and Ministry of Transport, as well as from the Admiralty, Ministry of Supply, Ministry of Fuel and Power, and DSIR.[107] By October, a compromise had been reached by the interested parties. As the DSIR was unwilling to take on the NGTE, it was to remain under the control of the MoS, but under the control of the MoS's Chief Scientist rather than under the Controller of Supplies (Air); the Director of Industrial Gas Turbines was also to report to the Chief Scientist. In addition, there was to be an interdepartmental progress committee set up to review the research programmes at the NGTE, and the Industrial Gas Turbine Development Committee was to be able to report back to all interested ministers, rather than just to the Minister of Supply.[108] In addition, all departments were to be free to place development contracts in their areas of interest, subject to normal financial control.[109] All parties seemed reasonably satisfied with the outcome. The Admiralty indicated that they would no longer insist on a naval candidate filling the Director of Industrial Gas Turbines post, and in the event it was filled by a Ministry of Supply candidate, RH Schlotel.[110]

Despite the rather anticlimactic settlement of the issue, the vigour with which it had been pursued suggests that there was more than just bureaucratic politics at stake. If the Admiralty's claims fitted in a long tradition of naval concern about control of their own procurement, the

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[104] See 'notes for use at internal meeting of Admiralty and M. of F&P,' n.d., NA ADM 1/21691, 2.
[105] Note WG Cowland to JH James, 7 July 1949, NA ADM 1/21691
[106] This was the tenor of a discussion with the Ministry of Fuel and Power on other matters; see the correspondence from Feb – Aug 1950, NA DSIR 8/95. For more on the post-war resource constraints on the DSIR, see Melville (1962), 44-45. Whilst in post, Lockspeiser oversaw the department's change to five-year budgets, but this did not come into effect until 1953, and so was probably not a concern at this time.
[107] PD Proctor to Sir John Lang, 29 Jun 1949, NA ADM 1/21691. As the department nominally responsible for holding the purse strings, it was neutral ground for this kind of conciliatory meeting.
[108] HC Salmon (Chief Engineer's office) to CG Jarrett (US Establishments), 14 Oct 1949, NA ADM 1/21691. See also the note by EWG Haynes on the history of the Director of Industrial Gas Turbines post, 24 Nov 1953, NA BT 258/442
[109] Note by EWG Haynes on the history of the Director of Industrial Gas Turbines post, 24 Nov 1953, NA BT 258/442
[110] A Rowlands to JG Lang, 28 Feb 1950, NA ADM 1/21691. Schlotel had been involved at the MoS (and MAP before) in gas turbine R&D since the early 1940s.

discussion displayed a very real sense of the importance of the gas turbine.[111] Similarly, the MFP's insistence on civilian control of civilian gas turbine research was based on concerns about how issues such as coal burning were not being considered by the services. With these issues settled, the stage was set for Government ministries to take a more active role in civil gas turbine research.

Commercial interest in the gas turbine

The civil field was not entirely empty; with the end of the Second World War, a number of companies had decided to develop gas turbines for commercial use. The gas turbine was seen as a new and promising type of prime mover, suitable for many applications in the same way as the steam turbine or the diesel engine were. Some of the companies developing civilian gas turbines had wartime experience of gas turbine work; as noted in chapters 3 and 4, both the work and the associated research facilities were generally funded by government; these companies also had some development experience to rely on.[112] However, swept up in the excitement of the new technology, other industrial power companies also began development, designing units with powers ranging from tens to tens of thousands of horsepower.[113] These ranged from WH Allen, who built auxiliary power units for the Royal Navy, to large civil engineering and shipping companies such as John Brown, who began to build turbines to a PAMETRADA design. [114] Even where designs started out as private ventures, they often gained a degree of support – direct or indirect – from state institutions. PAMETRADA, for instance, was part-funded by the Admiralty, and among the customers for promising private projects were interested ministries.[115] At one remove from the government, among the earliest customers for industrial gas turbines were newly-nationalised industries such as electricity generation.

Perhaps the most successful (and one of the earliest) companies to begin work on industrial gas turbines was the Lincoln firm Ruston and Hornsby. The company already produced a range of oil and diesel engines for industry, and was looking to develop its own range of industrial gas turbines. In 1945 its chief engineer drew up a specification for a 750 kW unit; the following year, Rustons hired the Power Jets engineer Bob Feilden. Feilden had been a BTH engineering apprentice before taking the Cambridge Mechanical Sciences Tripos; whilst a student he spent the

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[111] On the Admiralty's insistence on maintaining control over procurement, see Gordon (1988).
[112] Firms with wartime experience included Metrovick, BTH, Rolls-Royce, and Rover.
[113] A December 1950 review by the Director of Industrial Gas Turbines listed 33 projects under development; by December 1953 another 16 had been started. See RH Schlotel, 'A Review of British Industrial Gas Turbine Progress,' December 1953, NA AVIA 54/2269.
[114] Other firms included CA Parsons, English Electric, Rustons, and Harland and Wolff.
[115] The Ministry of Supply, the Admiralty, and the Ministry of Fuel and Power all ordered gas turbines; for more detail on the creation of PAMETRADA, see chapter 4.

summer of 1937 working at Brown Boveri in Switzerland, where he encountered their gas turbine work. In 1940 he was hired by Power Jets, and ended up in charge of the test programme and finally the experimental workshop. The son of Ruston's managing director was an RAF officer who had been seconded to Power Jets, and when he heard that the company was interested in industrial gas turbines, he mentioned Feilden's name. Feilden hand-picked his design team, including colleagues from Power Jets and promising engineering graduates from Cambridge, and began the design of an industrial gas turbine, which first ran in 1949.[116] In contrast to industrial and steam practice, the unit was built with comparatively light-weight components more like those used in jet engines. This allowed them to expand and contract more uniformly under the thermal loads of running, lowering thermal stresses and ensuring reliability and longevity. The test results were good enough for the Ministry of Fuel and Power to order a unit for experiments on burning peat; the Air Ministry and Ministry of Supply also placed orders. The design went into production as the Ruston TA gas turbine in 1952, and over 500 were to be built.[117] Ruston's success rested on a number of factors; it was already a successful producer of internal combustion engines for industrial power applications, and so had a good appreciation of potential markets. Crucially, the decision was taken early on that the gas turbine project would only be profitable if it were produced in large quantities, and so the unit's sound design was supported with an extensive sales effort, including a particular focus on oil and gas producers.[118] One fortuitous early showing for the TA was when a unit on display at the 1953 Engineering and Marine exhibition was used to power the lights during an electricians' strike, but Ruston's also managed to sell early units to a number of their existing industrial customers.[119]

Another company that managed to produce a number of production units for 'industrial' applications was the Bedford firm of WH Allen & Sons. Like Ruston's, the company had an existing business in industrial and marine engines, and had recruited a former Power Jets engineer, Arthur Pope. A major part of Allen's business was in marine equipment, and the Admiralty encouraged them to enter the gas turbine field, giving the company a 1948 contract to design a 1,000-kW gas turbine to provide on-board electrical power for warships.[120] With rising electrical power requirements for warships and their electronics, the gas turbine's low weight and bulk gave it an advantage over diesels. Allen's first gas turbine ran successfully in 1951, but by now the Admiralty's requirements had changed, and they asked the company to design a 500-kW gas

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116 Power Jets (1951); Bray and Moulton (2005)
117 Hunt (2011), 28-30.
118 Bray and Moulton (2005), 140; Newman (1957), 187-88.
119 Newman (1957), 186-7.
120 Pope (1958); Hunt (2011).

turbine for auxiliary power, intended for the warships due to be commissioned in the late 1950s and early 1960s. Allen's produced some 35 units for the County-Class destroyers and the Tribal-class frigates, but the company closed down its gas turbine department after the orders were complete.[121]

Metrovick and gas turbines for power

In contrast to Ruston's approach of designing an engine from scratch aimed at the industrial market, Metrovick's early civil gas turbines were based on their aeronautical engines. After the war Metrovick had installed an experimental gas turbine in its Trafford Park works, in part to gain experience of using a gas turbine for electricity generation, but also to provide peak electrical power to the works at a time of electricity supply restriction.[122] This unit used an F.2/4 engine as the gas generator, but was fitted with a heat exchanger to improve fuel consumption, and used an extra power turbine that drove a generator through a gearbox. In October 1948 it became the first gas turbine to be connected to the National Grid.[123] By the end of 1949 it had completed 300 hours running.[124]

After the Second World War, the electricity industry's first priority was to increase its generating capacity. The war had meant reductions in generating plant investment, as well as in maintenance. During the extreme winter of 1946/47, the system had been brought to breaking point, not least because restrictions on domestic coal led to an increase in electric space heating. In this respect, the 1948 nationalisation of the industry made little difference. Recognising the importance of electricity capacity to the wider economy, the government's central planners gave electrical plants construction priority, though with a power station taking at least four years to build and commission, power cuts were to be a fact of life until the early 1950s. As the ministry responsible for the engineering industry, the Ministry of Supply attempted (with some assistance from the Central Electricity Board) to standardise the size of generation plant and to allocate raw materials, but as the new British Electricity Authority built up its headquarters staff, it took over much of the coordination work from the various ministries involved in power station construction.[125]

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[121] The company's historian Michael Lane suggests that this was a response to Allen's business troubles; the firm was to merge with Amalgamated Power Engineering a few years later. See Lane (1995).
[122] Dummelow (1949), 200; Whyte (1978), 29.
[123] Whyte (1978), 29. It is possible the gas generator used a modified compressor; some sources state it had an 11-stage compressor, whereas the F.2/4 only had 10 stages.
[124] *MV Gazette,* Jan/Feb 1950, 155.
[125] Hannah (1982), 25-8. These included the Ministries of Works, Fuel and Power, Supply, and Labour, as well as the central planning staffs.

In October 1947, the Central Electricity Board had approached the Electricity Commissioners to seek permission for the construction of an experimental 15 MW gas turbine in the Stretford and District Electricity Board's Stretford power station, to be manufactured by Metrovick.[126] Another experimental gas turbine of the same capacity, designed by CA Parsons, was ordered for Dunston Generating Station in Tyneside. After inspection of the plans, the Electricity Commissioners gave their assent to the Stretford installation in March 1948.[127] The Metrovick plant ordered was a two-stage compound turbine; according to the Metrovick engineer RR Whyte, it was ordered against the recommendation of Karl Baumann, Metrovick's chief engineer, who would only guarantee the performance of a 5MW unit.[128] Nonetheless, construction of the plant began in 1949, and it first ran in August 1952.[129] Following Baumann's reservations – the plant was roughly six times larger than the most powerful gas turbine built so far by MV – the company seemed to be aware of the riskiness of the design, stressing its 'experimental character' in the publicity material about the plant.[130] Other company material noted that modifications were expected to be made to the plant in light of running experience.[131] This caution proved to be justified; in service, the unit proved to be troublesome, running below specification, and though it was eventually modified to run reliably, no further orders for the type were received.[132]

The company was slightly more successful in selling smaller gas turbines for peak power generation based on its aero-engine designs. In 1949, London's Metropolitan Water Board (MWB) ordered a 2,500kW industrial gas turbine to provide stand-by power for its Ashford Common pumping station; it was installed sometime after 1952. This was a design using a fifteen-stage compressor and a four-stage turbine, with a directly-driven alternator.[133] The MWB seems to have chosen the gas turbine over diesel engines because of the relatively low running times expected, high power needed, and the supposedly lower maintenance costs of the gas turbine.[134] Perhaps tellingly, the Ashford Common station was a brand-new facility built to meet the MWB's expanding demand; though the gas turbines installed promised to have advantages over

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[126] Commercial Manager, CEB, to Secretary, Electricity Commission, 13 Oct 1947, NA EL 67/2
[127] Copy of letter to Stretford and District Electricity Board, 4 Mar 1948,
[128] Whyte (1978), 31-2.
[129] See the photograph and caption in MOSI 1996.530/2/38.14/49
[130] See the articles in the *MV Gazette* for November 1952, and the year in review, Jan 1953.
[131] *MV Gazette*, Nov 1952, 267, and Jan 1953, 288.
[132] Whyte (1978), 31-2.
[133] *MV Gazette*, Jan/Feb 1950, 158. Given the number of compressor stages and industrial practice, the designs seem to have been been based on (or have evolved alongside) the locomotive gas turbine; see Frank Harris, 'The First British-built Locomotive Gas Turbine' (n.d.). My thanks to Nick Forder for a copy of this.
[134] This is the impression given in Askew (1961). The Ashford common also had Brush and English Electric industrial gas turbines installed; see Hunt (2011)

alternative technologies, it does not seem implausible that their veneer of modernity was also an attractive factor. Similar MV gas turbines were ordered by Shell for use in refineries in Venezuela and Burma; these seem to have been derated versions of the MWB design, to be used in the warmer ambient temperatures of these locations. Though these units seem to have been successful – the Venezuelan unit had completed over 20,000 hours running on natural gas by 1960 – Metrovick did not manage to sell many others.[135]

In part this was due to changing fashions in power generation. In 1953 it became clear on the basis of the Coal Board's production forecasts that there would be insufficient coal to meet the needs of industry and power over the next decade. As a result, the Minister of Fuel and Power, Geoffrey Lloyd, gained cabinet support for a programme of converting power stations from coal to dual oil and coal firing.[136] Though gas turbines were suited to oil firing, their high fuel consumption meant that they could only be used to provide peak load power. At the same time, the Government was enthusiastically supporting the development of nuclear power, both to provide cheap electricity and to provide plutonium for the UK's nuclear weapons programme. The Atomic Energy agency was formed in 1954, and shortly thereafter the government committed itself to a programme of nuclear reactor construction.[137] For now, the major market for industrial gas turbines was to be in medium-scale units where there was a ready supply of fuel, such as at oil and gas refineries.[138] Here the most successful units were either to be purpose-built small units such as those manufactured by Ruston and Hornsby, or, from the 1960s onwards, aeroderivative units based on advanced military jet engines. Somewhat ironically, AEI was reasonably successful in the latter market, but only as a packager of other companies' gas turbines; it sold a number of peak-load power stations to the Central Electricity Generating Board that used Rolls-Royce industrial Avon engines fitted with power turbines.

The Ministry of Fuel and Power's research programme

Meanwhile, as the commercial gas turbine field was beginning to establish itself, the Ministry of Fuel and Power was funding gas turbine research and development work, mainly aimed at using alternate sources of fuel. The MFP research programme lasted roughly a decade from 1948-1958, and seems to have been sustained in its initial stages by the enthusiasm of Roxbee Cox. It does not seem to have got properly underway until the early 1950s, at least with regard to the issuing

[135] Apart from a power station contract for Gach Saran in Iran, and an order for an oil refinery in Iraq; it is unclear whether these were MV-designed gas turbines, or installations of other firms' units.
[136] Hannah (1982), 169.
[137] Hannah (1982), 171-2.
[138] Or in niche applications for small gas turbines, where small size and light weight were more important than fuel consumption, such as firefighting pumps.

of development contracts. The 1951 change of government seems to have had little effect on the programme; the research programme does not seem to have had to justify itself until the time it was being wound down, when fuel and power research more generally was being curtailed. Whether this was due to government support, indifference, or successful defence of the programme is unclear. Somewhat ironically, by the time the programme was underway in the mid-1950s, its most vigorous proponent had left the Ministry; Roxbee Cox had left the civil service in 1953, as he did not think he would ever reach Principal Secretary rank as a scientist.[139] He was succeeded by another former RAE man, KT (later Sir Kelvin) Spencer. The programme itself covered a variety of areas, mainly related to the use of indigenous fuels. It was this aspect of the programme that perhaps most typified defiant modernism, in that the modern British technology of the gas turbine would allow the use of British energy resources, thereby releasing resources for the rest of the economy.

The most important research programme was devoted to coal; post-war, coal was still by far the UK's most important energy source, but in the face of increased demand the worn-out industry had difficulties meeting production targets; combined with the very severe winter of 1946-47, this led to the fuel crisis of 1947, and coal stocks remained low for the following year.[140] As a result, there was a clear case for research into more efficient coal usage, and in August 1949, the Treasury approved the expenditure of £350,000 for the first two years of a MFP coal-burning gas turbine research programme.[141] It was to examine a number of ways of burning coal: both directly in a gas turbine, in a closed-cycle unit with external combustion, and the production of coal gas as a gas turbine fuel. The MFP placed orders for direct-burning gas turbines with English Electric and CA Parsons in August and September 1949 respectively, with assistance on combustion chamber design coming from the DSIR's Fuel Research Station.

Metrovick were involved in the coal gasification programme, being given a contract in 1950 for the design of a 2,000 kW gas turbine similar to their existing industrial units. However, the prototype coal gasifier encountered delays, and it was not until 1954 that it produced gas suitable for use in the Metrovick unit, which was tested on heavy oil in the meantime.[142] Parsons chose to adapt an experimental gas turbine which the company had designed during the Second World War, and which was first run in December 1948.[143] The turbine was fitted with a combustion

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[139] Roxbee Cox (1999), 129-30
[140] Cairncross (1986), ch.13.
[141] History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, vi
[142] This may have been in an attempt to gain data for the locomotive gas turbine, which was being modified for heavy fuel burning about the same time.
[143] For more information on this unit, see Bowden and Jefferson (1949)

chamber adapted from a Fuel Research Station design, and first ran on coal in February 1951. It provided some useful information on the effects of coal particle size on fouling and deposits, and the tests themselves were relatively cheap; the Ministry later calculated the costs for the research as £43,719.[144] By contrast, the English Electric project was rather more expensive (£378,172 by March 1958,) not least because the contract covered the design and manufacture of a complete 2,000 kW gas turbine. It encountered severe problems with ash deposition and blade fouling, and on the basis of the high cost of the tests the company and the Ministry agreed to continue with small-scale rig tests instead.[145]

For the closed-cycle turbines, the Ministry placed contracts with John Brown & Co., who held the exclusive Empire rights for the closed-cycle system developed by the Swiss Escher-Wyss company.[146] John Brown had built a 500hp gas turbine to a PAMETRADA design in 1948, which was converted to closed-cycle operation. In December 1949 the Ministry of Fuel and Power placed a contract for the company to test this unit using coal as the fuel, and in 1953 the contract was amended to include the testing of a larger 1,000hp unit on pulverised coal. Testing began in 1953 and 1955 respectively, and by the end of the contract both units had run for over 1,000 hours each; Ministry expenditure on the test programme was some £123,227. The tests were promising enough for the National Coal Board to order a 2,000 kW plant for pithead power generation, as the costs were expected to be lower than for a comparable steam plant.[147]

Another fuel linked to coal was firedamp, or methane that collected in coal mines. In seeking Treasury approval for a research programme, the Ministry of Fuel and Power explained that if 2/3 of the firedamp produced yearly could be harnessed and burned, it would produce enough power for the needs of the whole coal industry. The proposal was given strong support by the Industrial Gas Turbine Development Committee, and Treasury approval was duly given for expenditure of up to £200,000. Contracts were issued to English Electric for a 2,000 kW open-cycle gas turbine, to the Incandescent Heat Co. for a regenerative heat exchanger, and to Ruston and Hornsby for an auxiliary combustion chamber. Unfortunately for the MFP, as ventilation in mines was improved to help safety and working conditions, the methane concentration dropped, which made the project uneconomical; the unit was installed at Stafford Colliery and first ran in 1956, but it was

[144] 'History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, viii
[145] 'History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, vii
[146] Power Jets (1951)
[147] 'History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, xi

removed in 1958 when the colliery was expanded. The cost of the unit also exceeded estimates by over 50%.[148]

Peat was also an indigenous fuel that it was hoped could be used for power generation on a wider scale. In 1949 the Scottish Home Department applied to the Development Commission for a grant to fund research into its use as a gas turbine fuel. Following a series of interdepartmental meetings, a panel chaired by the head of the Industrial Gas Turbine Development Committee recommended that grants be made to the Scottish Department for Agriculture for peat bog surveys and research into peat extraction methods; to the North of Scotland Hydro-Electric Board for the funding of research into peat heaters for a closed-cycle gas turbine; and to the Ministry of Fuel and Power to fund an R&D contract for a peat-fuelled open-cycle gas turbine.[149]

A closed-cycle contract was given to John Brown,[150] and the Ministry of Fuel and Power issued a contract to Ruston and Hornsby for a TA gas turbine in August 1949. The unit was to be tested on dry peat at first, and then to be fitted with a combined peat drying and combustion system to allow the use of wet peat as a fuel. After manufacture and initial testing, running on peat began in September 1952, and over the next few years several hundred hours of running were carried out. In practice the unit suffered severe fouling from the peat ash, which was even more corrosive than coal ash. Rustons estimated the cost of completing a full test programme at a further £125,000-250,000, and so in 1957, with the agreement of the Scottish Peat Committee and the Development Commission, the project was terminated.[151]

Retreat from the gas turbine

The support given to Rustons was probably the most successful use of Ministry of Fuel and Power resources. In the decade from 1948, the Ministry spent some £2 million on its civil gas turbine programme; yet by the end of the period, its support had not resulted in any production civilian gas turbine.[152] About a third of this money had gone into the capital assets of turbines and associated equipment; the rest had been spent on the testing itself. In providing research contracts and funding for individual turbines, the Ministry had perhaps helped provide a funding cushion for companies to develop their designs. Indeed it argued that the major benefit of the programme was intangible; the experience and know-how gained by manufacturers had helped

[148] 'History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, xiv-xv
[149] RH Schlotel, 'A Review of British Industrial Gas Turbine Progress,' December 1953, NA AVIA 54/2269. 8.
[150] To adapt their (much-used) experimental turbine, according to Power Jets (1951)
[151] 'History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, xii-xiii. The North of Scotland Hydro-Electric Board did build two experimental closed-cycle turbines that produced power for the grid, but Hunt (2011) suggests that they were all decommissioned by 1960 due to their high running costs.
[152] Figures from 'History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, iv.

them further develop their oil-burning turbines, 'with the result that 80 machines worth about £3 million have been sold to date [1958] against foreign competition.'[153] This may have been the case for the Ruston TA, where the early order for the type would have helped support development into production, but for Metrovick's coal gasification turbine it seems to have mainly funded the construction of one more industrial set similar to most of its other designs. Arguably the research into coal gasification and firedamp burning had provided experience that would be applicable to other industrial sectors, and the experience of solid fuel burning had provided a negative result of sorts; without treatment, the ash and corrosive combustion gases made burning in a gas turbine too expensive. Yet given the fact that most of these problems were known as the potential issues with alternate fuels, cost cannot have been decisive; it was precisely the hope of overcoming these issues that supported the defiant modernism of civilian gas turbine development. A larger factor was the changed industrial environment for gas turbines: with the prospect of nuclear power and cheaper grid supplies, there was less need for higher efficiency in coal burning; indeed, the Ministry predicted coal surpluses. The 1955 railway modernisation plan had selected electrification and diesel-electric power as the future choices, which meant a much smaller possible market for a gas turbine locomotive, even one that could run on coal. As a result, the Ministry decided to wind down its remaining projects.

This was against a background of general retrenchment in fuel and power research; in the mid-1950s, the DSIR planned the construction of a new laboratory in Stevenage. In 1958, when this opened, the Greenwich Fuel Research Station was shut down, with some of the work being transferred to the new site; at the same time, the Fuel Research board was disbanded. Perhaps unsurprisingly, given the issue's previous history, the Ministry of Fuel and Power's Chief Scientist suggested that his department take over the work that would not be transferred, but the DSIR seemed unenthusiastic.[154] Nothing further came of the issue; as one of the MFP's officials noted, pressing the issue would mainly give the Treasury ammunition to cut both the Ministry's and the DSIR's research expenditure.[155] In practice the Ministry had some input on the DSIR's programmes, but it was never to launch such large-scale development programmes again.

Conclusion: Business failure?

Metrovick seemed to have all the necessary attributes for success in the industrial gas turbine field: it had extensive experience of gas turbine development, funded by the Ministry of Aircraft

[153] 'History of the Gas Turbine Programme', n.d. (but c. May 1958), NA POWE 25/278, xx. It is unclear as to whether these were foreign sales, or merely total sales.
[154] See the memos by KT Spencer, Sep 1956-Jan 1957, NA POWE 25/235
[155] Memo, MT Flett, 28 Dec 1956, NA POWE 25/235. Flett presumably knew what he was talking about, as before he moved to the Ministry he had been a Treasury official.

Production, and it had long familiarity with the markets that were interested in the technology, such as railway traction, electricity, and to some extent industrial power. Why, then, did Metrovick fail to create a viable gas turbine business for itself? The main reason seems to have been that it treated the industrial power market as similar to the heavy electrical plant business. What customers in the industrial power business wanted was mostly off-the-shelf equipment that did not require lead times of many months or years; Metrovick failed to realise that they were competing against diesel manufacturers rather than steam turbine producers. As a company that prized engineering competence above all else, projects seem only rarely to have been subjected to scrutiny from a cost basis. From the point of view of a government customer that wanted results, this was a not a huge drawback, and the cost-plus basis for most of the contracts meant that Metrovick could still make a profit. However, by their very nature research and development contracts were speculative and the likelihood of production work uncertain; In the case of projects like the Stretford power station or the MFP's coal gas turbine, this turned out to be the case. Perhaps ironically, the programme that was most explicable as a rational approach to technological uncertainty in a sector where Metrovick had existing business was the gas turbine locomotive, which was a commercial failure.[156] Yet in some senses the gas turbine was marginal to MV, given the profits to be made in rail transportation and heavy electrical plant; it was overinvestment in production capacity for the latter that caused the company's financial difficulties.

In comparison, Ruston's were a company in the industrial power field that designed a gas turbine explicitly as a replacement for industrial engines at a power rating where they would be able to sell large numbers, and were able to hire the engineering talent to carry out this work, drawing on wartime jet practice. They then followed this with a concerted commitment to series production and a sales effort targeted at key markets that were most likely to benefit from gas turbines, such as the oil and gas sector. This allowed them to keep unit costs low enough to compete with other technologies in this area, and create a successful niche for themselves.

What, then, about government support for the civilian gas turbine? As I have shown, apart from the nationalised industries, both the service ministries and the MFP were concerned with the industrial gas turbine. The service ministries' interest was partly due to their perceived need to support technologies of potential use to their users, but also due to a genuine sense that the gas turbine was a valuable technology. In the case of the MFP, the presence of a gas turbine expert at the head of the Ministry's research organisation meant that the gas turbine was seized upon as a

[156] And not necessarily an inherent one; under the different market conditions of the United States, gas turbine locomotives were successfully used for freight services.

technology of defiant modernism; a way of transferring wartime experience to help civilian industry make the best use of constrained resources and national fuels. Though attempting to burn peat and firedamp has overtones of impoverished self-sufficiency, I would argue that it fits the label insofar as it was attempting to defiantly overcome harsh economic constraints by through the application of a new technology that was constructed as typically British. That the New Jerusalem was not ultimately fuelled by the gentle hum of a coal-fired gas turbine does not make defiant modernism a failure; it is perhaps merely a reminder of the difficulties of managing complex and contingent technological change, no less then than now.

Metrovick, the state, and the gas turbine: conclusions

Metrovick and the gas turbine

In the early 1960s, as work tailed off on the G.6 contracts, Metrovick's (or, as it was now known, AEI(Manchester)'s) gas turbine department was merged with the company's small steam turbines department; with no follow-on gas turbine development work, the company had decided to withdraw from the field. The MV gas turbine projects were remembered with some pride within the turbine division; some of the equipment built for the programme was still being used for steam turbine testing, which provided daily reminders. However, within the rest of the company the work was not particularly well-known.[1] In part this may have been because of changes in the company's identity as it went through mergers, but it is also a reminder of the fact that Metrovick's gas turbines were only ever part of the business of a large diversified engineering company. Today Trafford Park, the site where Metrovick began their gas turbine work, has largely been demolished; even the history of MV itself has largely been forgotten, not least because the last staff who joined the company under its Metrovick identity are now very close to retirement.

As this thesis has shown, the requirements of fighter air defence gave rise to a number engine projects of various degrees of speculativeness; yet similar technologies – in particular compressors and high-temperature materials – underpinned all of them. In this sense the gas turbine was not at the time the most obvious option, merely one among many. This was the environment in which the Air Ministry funded gas turbine projects both at the RAE and at Frank Whittle's Power Jets. In selecting a development partner for the RAE, Metrovick's pre-war technical prestige, and its steam turbine and high-temperature metallurgical expertise, were instrumental in the company being awarded a development contract. Yet the crucial factor in Metrovick's selection was perhaps the personal links between the company and the aeronautical research community, even if it was not itself a member of that community. Both indirect (such as those between Tizard and Guy via the Royal Society) and direct (Ricardo's consulting arrangement) links meant that the company came to mind as a likely candidate in the ESC's discussions.

[1] Personal communication, Terry Burnett. Somewhat ironically, the closest thing to an institutional memory of Metrovick's gas turbine work is at the Rolls-Royce Heritage Trust; because of aero-industry mergers, they eventually took over the Sapphire from Armstrong Siddeley's successors.

But the quest to provide a useable aircraft power unit soon meant that both the RAE and Metrovick were working on multiple schemes, each with varying degrees of plausibility as an aircraft power plant. Despite Metrovick having been chosen as a development partner, progress was slow, not least because the company's technical style was shaped by steam turbine practice. This placed a premium on design over development, and emphasised reliability over quick build times. The company's style also meant that it did not place as high an emphasis on such factors as weight reduction that were central to aero-engine practice.

Though the Metrovick design team developed a greater facility with aerodynamic design methods, and became part of a maturing community of axial turbomachinery designers, the company's basic technical style remained unchanged. Despite the creation of a development section and the expansion of the company's testing facilities, progress towards a flight engine was slow. As a result, MAP sought an aero-engine partner for the company, but Metrovick failed to take advantage of Armstrong Siddeley's expertise, in part because of a sense of possessiveness about the F.2's design; MV's technical style also meant that it did not fully take on the importance of A-S's suggestions. Metrovick's failure to commit to full collaboration with an aero-engine manufacturer or to invest its own resources in production meant that by the time it was ready to think about this step, disillusionment with the gas turbine had set in at MAP, and though the F.2 was further developed into the F.2/4 and the augmented F.3 and F.5 engines, no production orders were forthcoming. This problem was exacerbated by the fact that from mid-1940 onwards even partners such as the RAE had seen that the technological momentum was with Power Jets; whilst it seems unlikely that the Engine Department's support for Whittle's engine delayed progress on the F.2, the shift in focus meant that MV was unlikely to gain the large development resources it would require.

Metrovick made one last attempt to remain in the jet business; recognising the company's axial design skills, the Ministry of Supply gave it a jet development contract for the F.9 Sapphire. However, again MV's lack of development and production capacity meant that it would not gain a production order; faced with this, the company made the decision to sell its jet projects to an aero-engine manufacturer. Ironically, the Ministry of Supply now intervened and guided the sale of Metrovick's designs to Armstrong Siddeley – the company with which MV had been unable to forge a fruitful collaboration during the Second World War. But Metrovick had not wholly dispensed with its military gas turbine business, as it became a supplier of naval engines to the Admiralty. As I show in chapter 4, the Royal Navy's embrace of gas turbines for both light craft and heavy warships was driven by fears about the performance of its pre-war propulsive plant.

The failings of the RN's plant were in part due to the strained relationships between the Engineering Officer corps and the rest of the Navy, but a new generation of engineers rising through the Engineer-in-Chief's department led to changes in procurement and an embrace of new technologies during the late- and post-war period. For the small craft engines, MV was able to adapt its jet engine designs; it gradually adapted these to conform more to industrial practice, but drawing on the aerodynamics of its jet engines. The design of large warship plants better suited the company's technical style and manufacturing resources, but by the late 1960s the RN had decided to take advantage of the investment in aircraft engines to move once again to aeroderivative plants; with no jet business, Metrovick was no longer able to compete in this market.

However, in the post-war period the company was also to enter the civilian market, in which it would engage with the development plans of government ministries. The first market it entered was that for a gas turbine locomotive; Metrovick already had a strong existing traction business, and the gas turbine was a speculative venture expanding its portfolio of technologies. It also produced gas turbines for power, and attempted to build units to run on coal. The latter was for the Ministry of Fuel and Power, which took up the gas turbine as a technology that would allow better use of indigenous fuel resources; this 'defiant modernism' attempted to mobilise the technologies of the war for national performance in the peace. The struggles within government institutions for control of gas turbine research suggest that it was seen as an important technology across many domains. Yet Metrovick never seems to have attempted to turn its gas turbine projects into a viable business in the way that Rustons did, by building a design for a wide market, committing to series production, and aggressively selling its products.

Against this elegiac backdrop it may seem like the whole gas turbine enterprise was a failure for the company; yet even if this were the case, it does not necessarily tell a declinist story. If one considers gas turbines a commercial failure for Metrovick – and, despite the losses on the railway locomotive it seems likely that the company broke even at worst, as most of the work was funded by government contract – then in some sense this was because the company was too ambitious in taking on technically interesting work without sufficient development resources. This is not meant to be an apologia for Metrovick – throughout its two decades of gas turbine work the company failed to capitalise on government-funded development work by manufacturing production units in any quantity– but rather to suggest that the very attributes that denied the company commercial success were those that raised the possibility in the first place. MV's design-intensive approach was responsible for much of the company's reputation, without which it would not have been asked to partner the RAE for a venture into technological parts unknown.

Returning to Braun's taxonomy of failures set out in the thesis introduction, the major failings of Metrovick's gas turbine business were on the development and market considerations side. The company was able to produce reliable gas turbines, but given its slow deliberative style and lack of development resources, it just could not do this on the kind of timescales required by aviation customers. Related to this point was the fact that Metrovick management never backed the gas turbine to the extent that would have been needed to make it a commercial success in the industrial arena. Given the power ratings of the early industrial gas turbines, they were replacements for power sources such as diesels, which meant that they had to be ordered with comparable lead times. In order to achieve this, the company would – like Rustons – have had to commit to series production and actively sought out potential markets. Given the lack of interest in this area, it seems that the gas turbine may have had a similar relationship to Metrovick's core electrical business as the company's research department did to the firm as a whole: nice to have, and adding a gloss of high-tech prestige, but ultimately somewhat marginal to the company's success, which would rise and fall with the heavy plant business.

The state and the gas turbine

What did the state and its institutions gain from the collaboration with Metrovick? Across the three domains of air, sea, and land, the gas turbine was the subject of a recurring pattern: initial enthusiasm for a potentially revolutionary new technology; frustration as it became clear it was subject to the same development problems as other technologies; and a more realistic appreciation of its strengths and weaknesses. For the RAE, the collaboration put the Establishment at the heart of UK gas turbine development, and allowed it to further its axial aerodynamic expertise through a testing and development programme for a variety of designs. For the Ministry of Aircraft production, from 1942 onwards the F.2 engine was always likely to be a reserve design at best, due to the resources committed to other jet projects and the difficulty of finding production capacity, but with the post-war transfer of the Sapphire it gained an engine that helped keep one of its favoured aero-engine firms in business, and was a genuine alternative to Rolls-Royce's Avon. Similarly, the Admiralty's initial hopes for gas turbines were proven to be over-optimistic, and by the time Metrovick had a mature small-craft engine (the G.4), the RN was cutting back its coastal forces. Nonetheless, the work proved that aeroderivative gas turbine units could be successfully employed at sea, and with the Y.102 and Y.111A COSAG plants proved that they had a place in major warships. The wartime experience of the gas turbine carried through to the peace, where the enthusiasm for the technology's potential led to a wide array of projects, many of which were state-funded. If the military gas turbine was almost entirely a creation of the state, then the civilian unit was only marginally less so; the Ministry of Fuel and Power saw in the technology a chance to help improve efficiency and provide power across the economy using indigenous fuels; for a while it held out a promise of defiant modernisation for electricity, industrial power, and transport.

This, then, is the legacy of Metrovick and the gas turbine; it reveals a story of confident state, working with technically-skilled industry, to create technologies of use for both war and peace.

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