5TH EDITION

WORLD ENCYCLOPEDIA OF AERO ENGINES

FROM THE PIONEERS TO THE PRESENT DAY

BILL GUNSTON

'An indispensable guide for all aviation enthusiasts.'

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FEATURING new entries and updated throughout, this fifth edition of Bill Gunston's highly successful reference work describes and lists every major aeroplane engine produced. From the earliest piston engines of the Wright brothers from Dayton, Ohio, in 1903 to the latest multinational collaborative projects, every significant engine manufacturer in the world is included, conveniently arranged in alphabetical order.

Engine development has been critical to the evolution of aircraft and each engine is placed in its historical context. The author discusses all the important design features, incorporating the latest research into engines developed across the world over the last hundred years.

With the design of something as complex as an aero engine, there is scope for triumph and catastrophe, violent argument, crises and nagging doubt. The author has not ignored the human element, and some of the personal struggles that resulted in world-beating power plants such as the Rolls-Royce Merlin and the Pratt & Whitney PT6 are to be found under the relevant company entries.

Incorporating an informative glossary and illustrated with diagrams and photographs, some previously unpublished, this indispensable guide to the world's aero engines will be of interest to all aviation enthusiasts.

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BILL GUNSTON is perhaps Britain's best-known aviation writer, with some 380 books to his name, including *World Encyclopedia of Aircraft Manufacturers: From the Pioneers to the Present Day* (2nd edition, 2005). He lives in Surrey.

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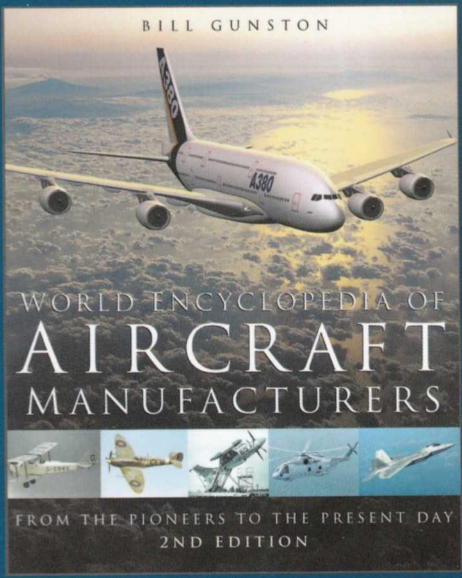

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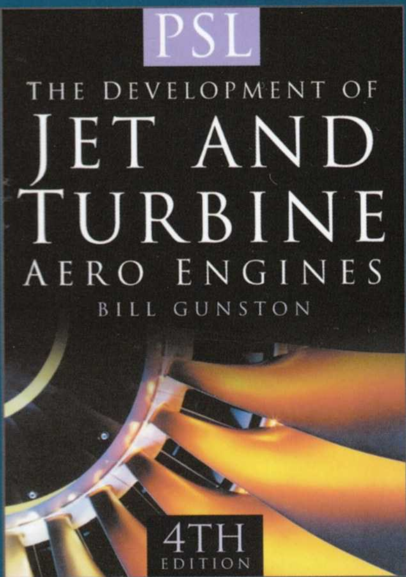

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Jacket illustrations. Front: three-shaft family – this family of engines uses three shaft technology to make them shorter and stronger (Rolls-Royce plc); back: a mécanicien, possibly of Air Union, photographed at Croydon c. 1923 with a Lorraine-Dietrich V-12 of 400 hp (Author's collection).

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World Encyclopedia of
Aero Engines
From the Pioneers to the Present Day

5TH EDITION

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FROM THE PIONEERS TO THE PRESENT DAY

BILL GUNSTON, OBE, FRAeS

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Facing title page: **The Rolls-Royce Eagle piston engine was in production when Alec McWilliams started his career which culminated in his appointment as Production Director. He is pictured at 83 with young fitter Matthew Hadden, who works on the Trent 800, almost 1,000 times as powerful as the Eagle.**

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CONTENTS

INTRODUCTION

As my wife used to fly gliders I had better go easy on the notion that a flying machine is nothing without an engine, but the importance of engines is obvious enough. In recent years popular books about aircraft have seen almost explosive growth, but these books inevitably only skate over the surface. The authors of these works would no more think of describing the engine(s) than they would think of explaining how a wing gets its lift.

It was no small surprise when the British *Aeroplane Monthly* conducted a readership survey and found that the majority of responding readers had ticked the box labelled 'Aero Engines'. This triggered a short series of articles on some classic engines, which in turn led PSL to wonder if there might be a market for a book.

I am grateful to the publisher, in particular to Editor-in-Chief Bruce Quarrie and Graham Truscott. There have been very few attempts since 1921 to produce a book which sets out to give a quick guide to *all* significant aero engines. It is only just possible, in a book of affordable size. Obviously one has to be selective, and I have tended to include the companies and other producers whose engines were in some way important. I have attempted to include also the lesser-knowns from the big companies, and I would like to thank many people who have helped me track down scarce photographs. I may have to face criticism from people asking why I did not include particular favourites of theirs (apart from a mass of minor pre-1914 engines most omissions are in the low-power or home-built category), and I apologise in advance. You just cannot include them all.

This book is concerned with engines for aeroplanes and helicopters, and has little to say about missiles or spaceflight. It is logically arranged in alphabetical order of manufacturer, each entry then attempting to trace the history chronologically. I have concentrated on the engines, and often omitted mention of the applications. I suspect there are few people who wish to read about the Merlin or J79 who have no idea what aircraft these engines powered; in any case, it would add many pages just to list them all. Most readers will already be familiar with the applications, and will, I hope, use this book to provide background detail.

Where possible I have mentioned key people involved and it will be obvious to the thinking reader that, behind the story of every engine, there is a wealth of drama, violent argument, moments of triumph and catastrophe, and often nagging doubts, or uphill struggles that seem to get nowhere. In a few cases I have commented on the way that men with highly paid secure jobs threw them up because of their inability to penetrate the closed minds of a technically illiterate board of management. Even today one occasionally finds companies – not often in aviation – run by people who do not understand the firm's past success and have no idea how to sustain it. One day the Oxford Union might like to debate 'That this house considers that every manufacturing company should be run by (a) accountants or (b) engineers (please state your preference)'. Lord Hives of Rolls-Royce inclined to the engineers, saying, 'If the engineers are wrong, then we are all wrong.' Others might claim that too many engineers and too few accountants brought about the bankruptcy of that great company (though long after Hives' time). But one cannot even skim across stories of modern aero engines without appreciating that this is no place for the small man, nor for the fainthearted. To make even a seemingly trivial change to a major high-thrust turbofan swallows up not just a few million dollars or pounds but a few hundred million. A great engine designer, Sir Stanley Hooker, said of a famous banker, 'We added a zero to his stature; he used to think £5 million a lot of money, but after a few weeks on the RB.211 he came to understand that £50 million is peanuts.'

It is all very well merely to read about such sums. Spare a thought – I almost wrote 'spare a copper' – for the people who actually have to find the money. Afterwards everything seems obvious, and one wonders how company presidents or investors or ministers could be so stupid. At the time, without a fully certificated crystal ball, it is a bit harder. Let's imagine you are a representative of the Quebec government, or of a group of Montreal investment banks, and a chap named Thor Stevenson arrives, saying he wants to borrow about $10 million, to build an aero engine. It is to be a small turbine in the 600-hp class to replace the famous Pratt & Whitney Wasp designed in 1925. There were lots of Wasps once, but there are no small turbines to speak of. To the obvious question, 'How many of these engines have you sold?' Stevenson replies, 'We know we can sell 40. Beyond that we are certain there is a big market.' What do we do with the $10 million? Most sensible people would reluctantly say it was too much of a gamble; and that is just what they did say, back in 1958. But somehow the first PT6 got built. Then one was sold, to power a Hiller helicopter that was promptly cancelled. Phew! What a good thing we didn't part with our $10 million.

I like this story, because, as I write, the total number of PT6 engines sold is about 23,000. At least, that is what it was a few days ago. They've probably sold a few dozen since I began to write. Like I said, aero-engine development is a great place for people who can get it right.

Of course, if you write a book about the many hundreds of types of aero engine, you cannot in the same book explain how they work, or present any kind of coherent history of the species.

Which was the first aero engine? One could argue indefinitely, but one thing I have always found puzzling is why the many great would-be aviators of the nineteenth century spent so much effort trying to create massive and complicated engines to turn a propeller or flap the wings. All they needed was a bit of thrust for a short time, and they could get that, reliably and at modest cost, with a few of Mr Congreve's rockets. Even the few inventors who did think of rockets then spoilt it by trying to make rockets fed by a steam boiler.

For the record, the first man to drive a piston down a cylinder by igniting petrol vapours – then a very rare commodity – was Robert Street in 1794. But he was a bit late. Three years earlier Samuel Barber had invented the gas turbine. Or maybe we should give the credit to Hero of Alexandria, around AD 100?

I have used both imperial and metric units in this book, depending on which were published by the original manufacturer. I have avoided abbreviations except: hp, horsepower; lb, pounds of thrust; h and s, the SI abbreviations for hours and seconds; TBO, time between overhauls; sfc, specific fuel consumption; rpm, revolutions per minute; PN, fuel performance number; and pr, pressure ratio.

Bill Gunston
October 1985

INTRODUCTION TO THE SECOND EDITION

When Patrick Stephens Limited published the first edition they were uncertain about the sales prospects. In the event the book has done splendidly and I am delighted to have been asked to prepare an updated edition. This second edition contains numerous additional illustrations as well as entries on such new engine groups as CFE and Eurojet.

Bill Gunston
February 1989

INTRODUCTION TO THE THIRD EDITION

This edition is noticeably larger than its predecessors. This is partly because new engines keep being developed, but most of the extra material is due to previous ignorance being replaced by knowledge. I have added a brief section called simply 'China', which gives an overview of the many aero-engine manufacturing activities in the People's Republic. But a major part of the additions are because, since the second edition appeared in 1989, a vast amount of information has become available about the aero engines of Russia and Ukraine. Both countries are doing their best to produce engines that will sell in global markets. Among these are high-power propfans. Similar engines were also being developed in the United States, but since the previous edition the American propfans have been shelved and largely forgotten. The reason is that the price of fuel has fallen slightly. The Russians and Ukrainians are strange people and, instead of following the whims of fashion, they believe simple arithmetic. Even if the fuel were to cost nothing, a more efficient propulsion system means that the aircraft can either fly further or else carry a bigger payload. One Ukrainian propfan aircraft is the An-70. I wonder how many Western air forces will evaluate it? Sadly, this aircraft crashed on 10 February 1995, following a mid-air collision. As Ukraine is short of money this catastrophe might terminate the programme.

Bill Gunston
February 1995

INTRODUCTION TO THE FOURTH EDITION

Engineers tend to think in pictures. It was only when I had to plot the thrust of the most powerful airline engines against time that I realised the amazing achievement that, without being reported in the mass media, had just been achieved by GE, Pratt & Whitney and Rolls-Royce. The thrust of the most powerful jet engines had previously been increased at the rate of about 1,000 lb per year, climbing from 1,000 lb in 1942 to a little over 50,000 lb in 1992. In 1992–7 it leaped by a further 50,000 lb. The shock came when I looked at the plotted graph: the line shot up almost vertically.

This rate of 10,000 lb of extra thrust per year is unprecedented, and I very much doubt that we shall ever see anything like it again. As I write, the Rolls-Royce Trent 800 has been tested at almost 115,000 lb thrust. Like the rival American engines this enormous power has been demanded by just one aircraft, the Boeing 777. In the 1970s there were cries of dismay when Airbus proposed their first aircraft, the A300B, intended to carry 250 people on only two engines. Shrill voices said it wasn't safe. Today nobody seems to be bothered by the fact that the 777-300 carries up to 520 on two engines. This reflects the fact that modern engines hardly ever fail, and the days when it was commonplace for multi-engined aircraft to make crash landings or ditch in the ocean because they had suddenly become gliders are long in the past.

It will be many years before engine thrust has to climb beyond 115,000 lb. An airliner with four of these engines could be a 1,500-seater, and the airlines are not ready for this. Indeed, the increasing ability of airliners to navigate with great precision without following the historic 'airways' means that increasingly the traffic is avoiding the congested hubs and is instead meeting the needs of the customers. For example, today we could fly direct from Birmingham (England) to Birmingham (Alabama). Until now the passenger had to fly Birmingham–London–Atlanta–Birmingham. This is diminishing the need for giant airliners, and partly explains why Boeing gave up the idea of building a stretched 747. This puts the 1,500-seater even further off, and it may well be that today's engines, probably burning new fuels, will suffice for the next 50 years.

Another noteworthy trend is the increasing popularity of collaborative efforts. In the recent past virtually all the largest engine projects have been multinational, for various reasons which are at least in part political or concerned with winning markets. For example, GE makes only 59 per cent of the GE90, and shares the rest with foreign companies. Today we even find the two biggest engine firms in the world, GE and Pratt & Whitney, both of them American, joining forces in order to compete against a single version of the Rolls-Royce Trent. Not only is this a massive endorsement of the British company's engineering capability but it is also indicative of the sheer scale of investment needed to launch big engines, even when they are derived from existing ones.

In 1982 I asked British Aerospace why their mock-up of the European Fighter Aircraft didn't have vectored nozzles. They explained that there was no requirement, and seemed to think the question ridiculous. In about 1990 I asked a Eurofighter spokesman why this next-generation aircraft didn't have vectored nozzles; he replied (in a public press conference), 'I do wish you'd stop rabbiting on about vectored nozzles, they are entirely inappropriate, as you have repeatedly been made aware.' A few months ago I was standing next to Chris Yeo, British Eurofighter chief test pilot, as we watched a Sukhoi demonstrate with vectored nozzles. Chris said, 'That's awesome . . . I can't wait to be able to manoeuvre like that . . . maybe we'll get vectored nozzles at the Mid-Life Update.' What the people who got so irritated by my endless 'rabbiting on' may have failed to take on board is that in any kind of air combat there's not much point in coming a good second. I am relieved to hear that the Spanish partner in the Eurofighter engine programme is 'making good progress' with vectored nozzles. Better late than never.

On a totally different tack, this expanded fourth edition contains details of two completely new families of piston engine. One, made by Orenda in Canada, is notable in being turbocharged and liquid cooled and designed for up to 750 hp – a power previously regarded as solely the province of turboprops. The other, the French Morane Renaults, are notable in being turbocharged diesels claiming fuel savings of up to 60 per cent. There's never a dull moment in this business.

Bill Gunston
March 1998

INTRODUCTION TO THE FIFTH EDITION

This edition appears in the new century, which already takes the bypass ratio (BPR) of the latest turbofans to 11. Further increase in BPR is likely to require the addition of a speed-reducing gearbox, which will partly cancel out the advantage of a simplified low-pressure turbine. Geared fans were pioneered by Garrett, which has now, together with the gas-turbine business of Lycoming, vanished into Honeywell. Snecma has become part of Safran and, in partnership with Russia's Saturn, has created PowerJet to build engines for a Russian Regional Jet. It has also joined with other European *motoristes* to create the turboprop and single-rotation eight-blade propeller for the A400M airlifter. BMW Rolls-Royce has become Rolls-Royce Deutschland, Fiat has become Avio, and among many new start-ups are Agilis, GE Honda and Innodyn.

Bill Gunston
February 2006

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The Engines

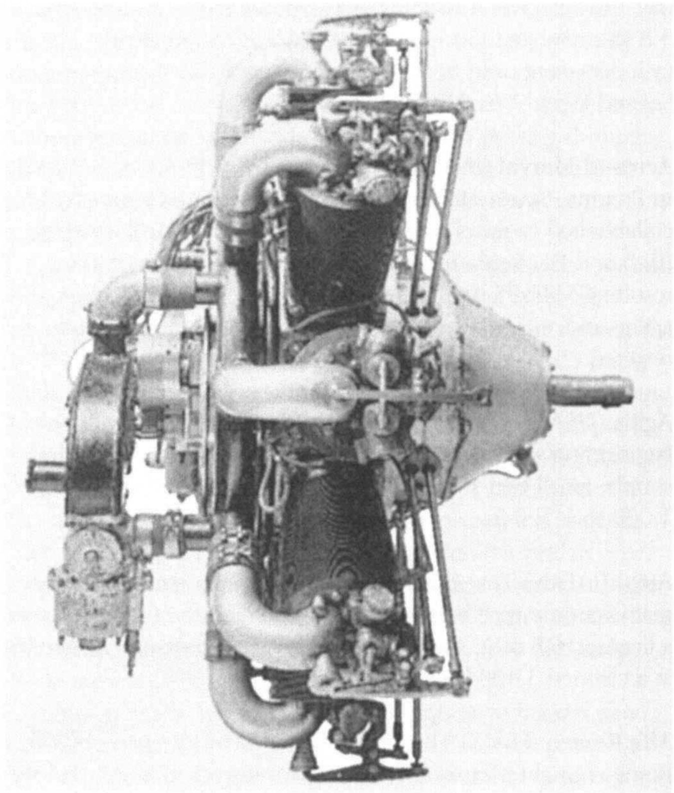
A–Z

A

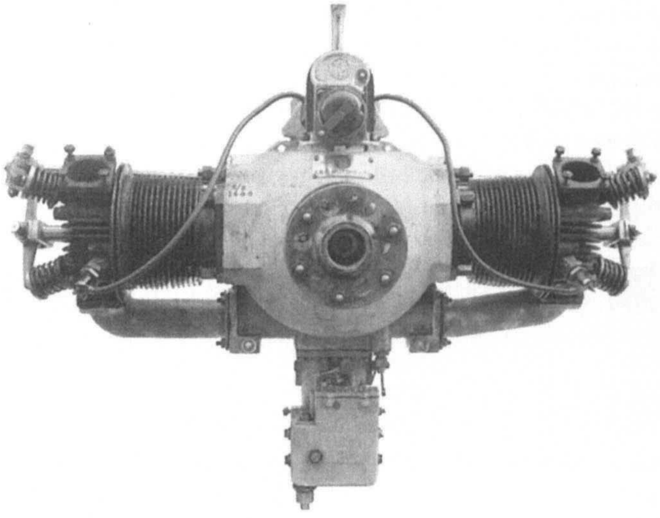
ABC (UNITED KINGDOM) ABC Motors, the successor to ABEC (All British Engine Company), was founded in 1911 by Granville Bradshaw, one of the flamboyant extroverts common in the early years of aeroplanes. He was a better salesman than engineer, though he designed his engines himself. The first aero engines were a 40-hp watercooled in-line and a 100-hp V-8. The latter failed to appear in time to power the Flanders B.2 at the 1912 Military Trials, and the 40 hp version had to be substituted. Despite this the B.2 flew at 55 mph with three adults aboard. In 1915 a small 5-hp flat twin drove the APU (auxiliary power unit) generator on the Pemberton-Billing (Supermarine) PB31 Night Hawk anti-Zeppelin patrol aircraft. A new range of engines was started with the Mosquito six-cylinder air-cooled static radial of late 1916. This had cylinders of 4.5 in bore and 5.9 in stroke, machined from steel forgings and with overhead valves. It was designed for 120 hp but completely failed its bench tests. In its stead Bradshaw produced the seven-cylinder Wasp, with similar cylinders and designed throughout for ease of production. Weighing 290 lb dry, and of 657 cu in capacity, it ran reasonably well and gave 170 hp. It powered numerous prototypes, and was developed into the 200 hp Wasp II.

This encouraging background was unfortunate. When Bradshaw produced his bigger Dragonfly in 1917 he claimed it would replace every other engine. An enlarged Wasp, its nine cylinders were of 5.5 in bore and 6.5 in stroke, giving capacity of 1,389 cu in. It was claimed to give 340 hp for a weight of 600 lb, and was clearly simple and easy to mass-produce. The director of aeronautical supplies, Sir William (later Lord) Weir, took the rash decision to standardise on the Dragonfly in almost all new fighters and bombers planned for 1918. Production on a colossal scale was organised, and soon 1,000 had been delivered and hundreds more were appearing each month. Only then did it emerge that the engine was a disaster. It gave only 295 hp, weighed 656 lb, quickly became red-hot (it had what S.D. Heron called 'probably the worst example of air cooling ever used on a production aircraft engine') and, as it had, by chance, been designed to run at the crankshaft's critical torsional vibration frequency, the unhappy result was that this component usually broke after an hour or two. So severe was the vibration that propeller hubs quickly charred from the friction. The British aircraft industry was thrown into chaos, the old Bentley BR.2 and other engines were put back into production and Bradshaw was, to say the least, unpopular.

His one saving grace was his family of small opposed engines, which continued in December 1915 with the Gnat. Bore and stroke respectively were 4.3 in and 4.7 in, giving capacity of 139 cu in, and the engine was rated at 45 hp in its geared version. This failed its tests, so the PV.7 (Grain Kitten) had to use the 35 hp direct-drive version. Some hundreds of these were used in almost all the British 'cruise missiles' of the



The author's long talks with Captain Norman Macmillan and Major Oliver Stewart MC left him in no doubt that the ABC Dragonfly would have necessitated a frantic re-engining programme for thousands of aircraft had the First World War lasted into 1919.



Unlike the disastrous Dragonfly, the ABC Scorpion was made in useful numbers for dozens of kinds of light aircraft.

day, as well as the manned Sopwith Sparrow and a few other types. From the Gnat came the Scorpion of 1921, with small cylinders of 3.6 in bore and stroke, giving 73 cu in capacity, and rated at some 24 hp. Many were used in ultralights of the day, the Scorpion II having bigger cylinders of 4 in bore and 4.8 in stroke and giving up to 40 hp. Four Scorpion II cylinders were used in the 82 hp Hornet of 1924. In the Second World War ABC produced APUs.

Aerosud-Marvol (INTERNATIONAL) In 1989 Aerosud, based in Pretoria, South Africa, and Marvol, based in Moscow, collaborated to redesign the Klimov RD-33 to suit the Mirage III, 5 and F1. Replacing the original Snecma Atar with the resulting SMR-95 has dramatically increased service ceiling, agility and, especially, range, but no production orders have resulted.

Agilis (USA) Formed in 1993, this Florida-based provider of engineering services is also developing a family of extremely simple, small two-shaft turbofans. Thrust ratings range from 1,000 to 1,500 lb.

Aichi (JAPAN) This aircraft firm built engines from 1927, the main wartime type being named Atsuta after the factory; it was a licensed DB 601. The Ha-70 was a twinned Atsuta 30 rated at a claimed 3,400 hp.

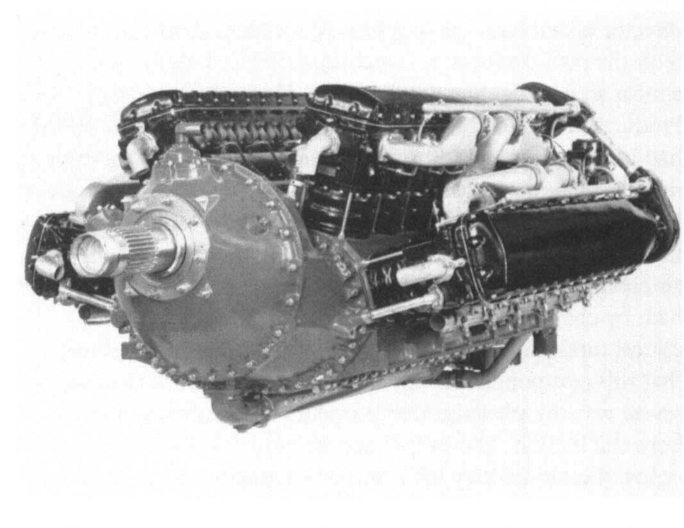
Alfa Romeo (ITALY) The famous automotive company of Alfa Romeo bought a licence for the Bristol Jupiter in 1925, and via the Pegasus and Mercury developed the 125.RC series of 1933. This was a Pegasus with only two valves per cylinder, and thus the company was able to do what eluded Fedden at Bristol: double up and produce an 18-cylinder two-row version. This engine, the 135.RC34 Tornado of 1935, was eventually developed to 1,800 hp. The company also produced an original nine-cylinder radial in 1930, the 215 hp D2, developed to 240 hp by 1935. The DH Gipsy Six was the basis of the Alfa 115 family of 1936–56, but the 121 inverted V-8 had only 110 mm stroke, and was typically rated at 380 hp. In 1952 licence production of the DH Ghost turbojet started, followed by such engines as the GE J79, J85, T58, T64 and T700. In the 1970s the company was again developing its own engines, based on the simple AR.318 turboprop in the 600-hp class originally designed in partnership with Rolls-Royce. From this was derived the ARTJ.140 turbojet, but there were no takers. Today this famous firm relies on the T700 and contribution to the RB199, Spey and Tay.

AlliedSignal *See* Honeywell.

Allis-Chalmers (USA) This famous engineering company was a licensee of Brown-Boveri of Switzerland producing industrial gas turbines. This brought it into the field of aircraft gas turbines. In October 1941 it was invited to work on a ducted fan (turbofan) for the US Navy, and received a contract in January 1942. Progress was so slow that in June 1943 the Navy cancelled the contract and instead ordered licence-production of the DH Goblin turbojet as the J36. This was flown in the Lockheed XP-80, Curtiss XF15C-1 and Grumman XTB3F-1, but again the company failed to perform on schedule and the contract was cancelled after the delivery of seven engines.

Allison (USA) This Indianapolis company got into aviation in 1926 with the V-1410, an inverted version of the wartime Liberty with air-cooled cylinders. It did extremely well on test in a DH-4. In 1927 came the 765 hp two-stroke diesel airship engine for the US Navy, and it was largely Navy efforts to find a US replacement for the Maybach in its airships that led to the contract of 28 June 1930 for a single example of the proposed V-1710-A, to deliver 650 hp at sea level. This launched the only US liquid-cooled production engine of the Second World War.

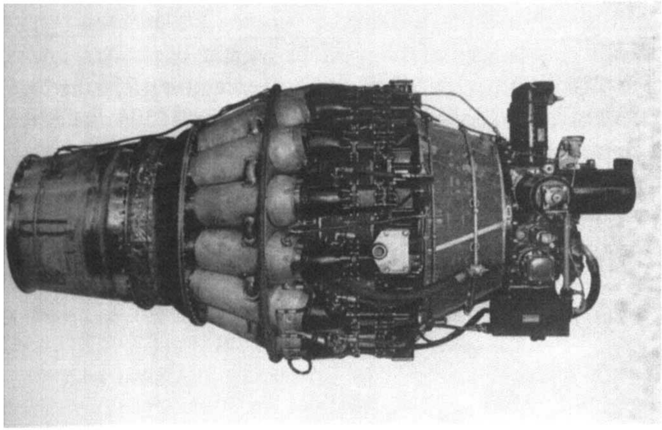
The original V-1710 was a sound V12 with each bank of six cylinders cast as one block of light alloy. Bore and stroke were 5.5 and 6 in respectively, giving the 1,710 cu in displacement denoted by the designation. There were four valves per cylinder and an excellent reduction gear based on work going back to the company's copy of the RR Eagle gear in 1924. Allison was a pioneer of plain bearings with lead/copper backed by steel, and the V-1710 was also the first engine designed from the start to use not water for cooling but ethylene glycol, a viscous fluid pumped round under pressure at much higher temperature (typically 250–300°F, 121–149°C) and thus carrying away the excess heat through a smaller radiator giving



The Allison V-3420 was essentially two V-1710s with the inner blocks set 30° apart. There were several versions, this V-3420-A15 having both crankshafts geared to a single propeller. Weighing only 2,600 lb, this engine was rated at 2,600 hp at 3,000 rpm, which on a 15-minute basis could be maintained to 25,000 ft. Photographs of six versions of V-1710 appear in the author's 'The Development of Piston Aero Engines'.

reduced aircraft drag. The V-1710 was also planned from the outset to use a turbosupercharger, but this was not needed for airships. The engine first ran in August 1931 and was ready for delivery on 12 February 1935. On this very day the giant airship *Macon* was destroyed, the Navy cancelled and James Allison sold out to General Motors. Allison remained a GM division until 1993.

Under new chief engineer R.M. Hazen, the engine was redesigned in detail, and the Army by this time began to think it might mature quicker than the Continental, so long regarded as the top future fighter engine. By March 1937 Hazen's C8 version passed a type-test at 1,000 hp on 87-octane fuel; this was more than any Merlin had done and the US engine was also lighter. The turning point was when Don Berlin, chief engineer of Curtiss Airplane Division, put a turbocharged C8 into a modified P-36. The resulting XP-37 reached 340 mph at 20,000 ft, a major jump in speed and height which confirmed Army belief in the liquid-cooled engine. Thus the Allison engineering staff of 25 found themselves suddenly not only clearing the V-1710 for production but also developing the pusher version for the Bell XFM-1, the shaft-drive model with remote reduction gear (with 37 mm cannon passing through it) for the Bell XP-39, the regular model for the Curtiss P-40 and left-/right-handed versions with remote turbos for the Lockheed XP-38.

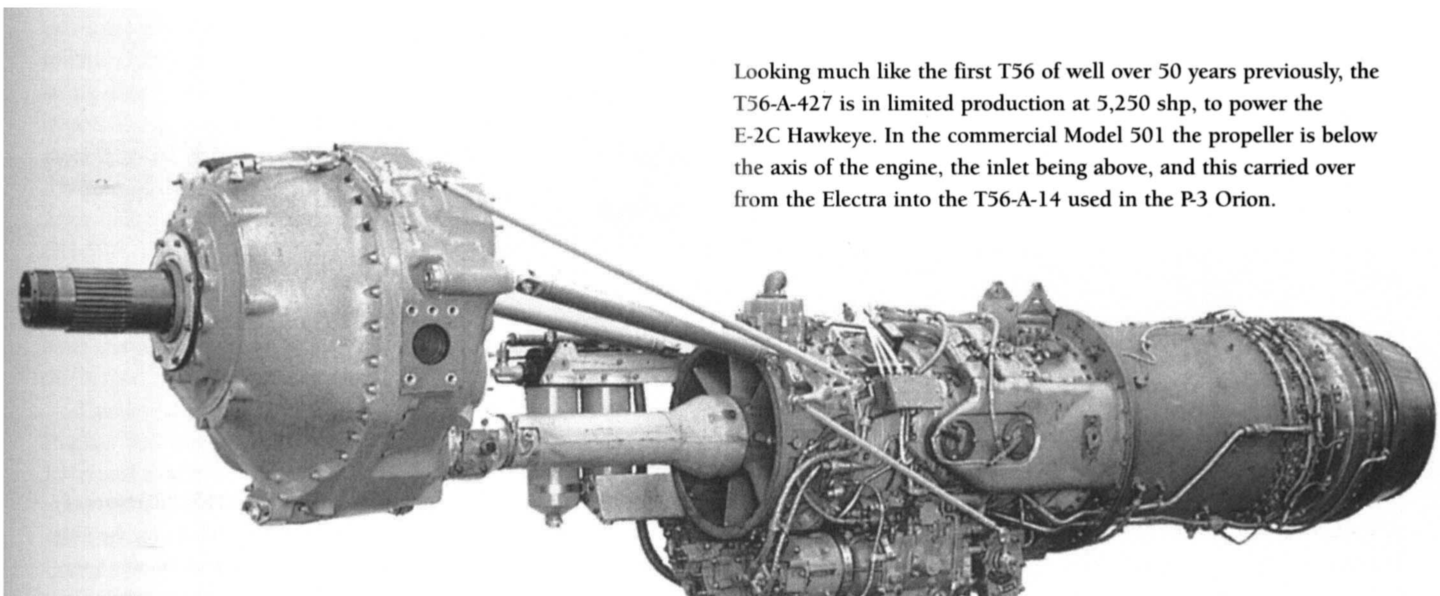


Handed over from GE, the J33 was further developed by Allison and built in very large numbers. This is a J33-16A of 6,350 lb rating, engine of the F9F-7 Cougar.

In 1939 the P-40 was selected for major production, at last bringing a reward for nine years and $2 million invested equally by the Army/Navy and Allison. Throughout the war the V-1710 remained in volume production, some 69,305 being built. A few dozen were of the advanced E-series, with various forms of two-stage supercharger to make up for the lack of a turbo (which was used only on P-38 engines). The V-1710-119 drove the lightweight XP-51J Mustang at 491 mph, and after the war the 2,300-hp V1710-143/145 replaced the Packard Merlin in the F-82 Twin Mustang. In general the British engine's superior supercharger(s) always kept it ahead at high altitudes, but the author can testify to the Allison's outstanding smoothness at low levels to which the P-39, P-40 and early P-51s were usually consigned.

Allison wisely refused the Army's request to build a new 2,000-hp engine in 1937; they could barely develop the V-1710. Instead it coupled two V-1710s together to form the V-3420, flown in a B-29. Thousands were ordered to power the Fisher XP-75 escort fighter; then this programme was cancelled. Piston-engine work was abandoned in 1947.

Looking much like the first T56 of well over 50 years previously, the T56-A-427 is in limited production at 5,250 shp, to power the E-2C Hawkeye. In the commercial Model 501 the propeller is below the axis of the engine, the inlet being above, and this carried over from the Electra into the T56-A-14 used in the P-3 Orion.



A

Gas turbines

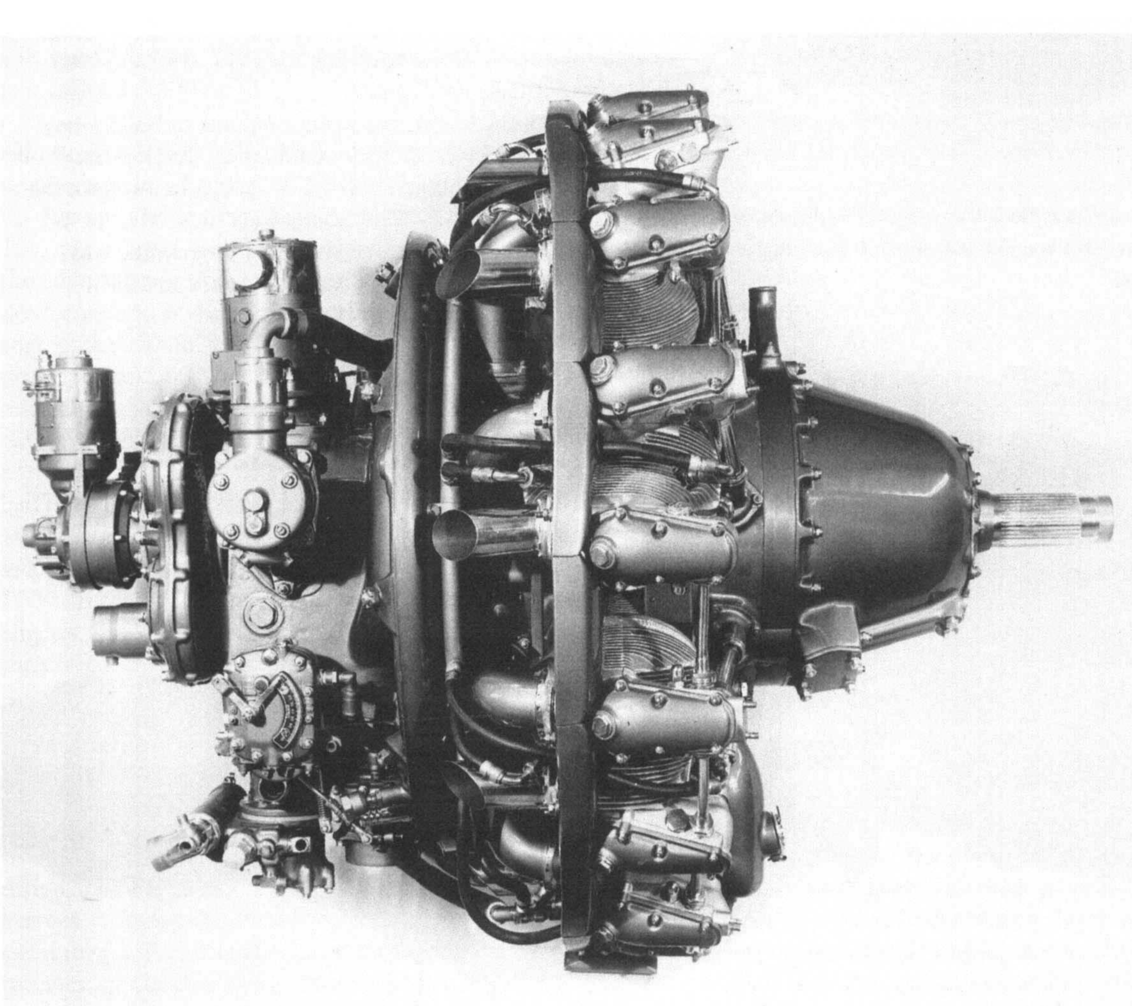
In September 1945 responsibility for the General Electric J33 turbojet was transferred to Allison, which thereafter produced the engines for many fighters, attack aircraft and trainers, and also carried out increasingly sure development including afterburning versions. In direct descent from Whittle's W.2B, the J33 typically had a diameter of 49.3 in, dry weight of 1,786 lb or 2,465 lb with afterburner, mass flow of 87 lb/s and maximum thrust of 4,600 lb or 5,400 lb with water injection or 7,000 lb with afterburner. Almost 14,000 were delivered.

In September 1946 Allison was also handed the General Electric J35, and this was made in even greater quantity (14,100). All versions had an 11-stage compressor handling 85 lb/s at a pressure ratio of about 4.9, eight combustion chambers and a single-stage turbine. Diameter was 37 in, weight about 2,260 lb or 2,695 lb with afterburner, and maximum thrust 5,600 lb, or 7,500 lb with afterburner.

Allison had sufficient confidence in August 1948 to start total redesign of the J35, at first (to ease the release of funds) calling this the J35-A-23 but later giving it the new designation J71. This had a 16-stage compressor, mass flow of 160 lb/s at a pr of 8, cannular combustor with 10 cans and a three-stage turbine. It powered various aircraft and missiles, including the Douglas B-66 and McDonnell F-3.

In 1944 Allison began the long struggle to produce a turboprop. With Navy funds the T38 (Model 501) was designed, with a 19-stage compressor (pr 6.3), eight combustion chambers and a four-stage turbine. This ran in 1947 and at a power of 2,250 shp flew in a company B-17 in April 1949. At 2,763 hp it powered the Convair Turbo-Liner, an Allison-owned CV-240. Two T38 power sections were joined to one remote gearbox in the T40 (Model 500), which flew at a design rating of 5,500 shp in the Convair XP5Y flying boat on 18 April 1950. Later T40s were developed to 7,500 hp in the XFV-1 and XFY-1 VTOL fighters.

From the T38 Allison derived the T56, funded by the USAF for the C-130. With only 14 stages this started life at 32 lb/s at pr of 9.25, and despite running at a constant 13,820 rpm instead of the previous 14,300, gave 3,460 hp plus 726 lb thrust, or 3,750 ehp. In September 1954 the USAF ordered 288 T56-A-1 engines for the C-130A. Today the T56 is passing from production with 16,950 examples delivered, including commercial Model 501 engines for the Lockheed Electra (which has the air inlet above the spinner, as



With a diameter of only 41 in, the Alvis Leonides was a very attractive engine in the 500–600-hp class.

do the versions for the P-3 Orion). The current T56-A-15 has almost the same mass flow and pressure ratio as in 1954, but runs hotter and is rated at 4,591 shp (4,910 ehp), for a weight of 1,825 lb. By 1985 the T56-427 was in production for the E-2C Hawkeye rated at 5,250 shp and with 13 per cent lower sfc. A free-turbine derivative in the 6,000-shp class is the Model 501-M80C, designed for all-attitude operation in the V-22 (previously called JVX) tilt-rotor aircraft in 1987. The YT701 (501-M62) is a largely new modular free-turbine engine originally developed in 1970–5 for the XCH-62 HLH (heavy lift helicopter). After almost a decade of marking time this is again an active programme. It served as the structural basis for the 501-M80C which in turn has led to several engines for the future.

One is the T406 turboshaft, flat-rated at 6,150 shp to 43°C. This powers the unique Bell/Boeing V-22 Osprey tilt-rotor aircraft, which despite prolonged opposition by Congress may be built for many Service and civil customers. In this application the T406 has to run in any attitude from horizontal to vertical. A civil version for tilt-rotors and helicopters is the AE 1107. The derived turboprop, the AE 2100, was picked by Saab for the 2000 high-speed transport, driving a Dowty six-bladed propeller. Though a 6,000-hp engine, it is flat-rated in the Saab 2000 at 4,152 shp. Other applications, with a similar propeller, are the Lockheed C-130J Hercules and Alenia-Lockheed C-27J and IPTN-250.

In June 1958 Allison received a US Army contract for development of a small but very advanced gas turbine in the 250-hp class, the T63. Unlike previous small turbines it had six axial stages of compression upstream of the centrifugal impeller that flung the air, at 3.1 lb/s at pr of 6.3, into two diffuser pipes leading to the rear of the single large reverse-flow combustion chamber with a single fuel nozzle. From the combustor the gas continued to travel forwards through the two-stage gas-generator turbine and separate two-stage power turbine before exiting through left and right exhaust stacks facing diagonally upwards. This engine created a great impression and appeared to have the world at its feet, but for more than 10 years virtually the whole output was tied up in the form of the T63-A-5 turboshaft for the Hughes OH-6A US Army helicopter and subsequently for the same customer's Bell OH-58A. The A-5 was rated at 250 shp, but by 1965 the A-5A raised this to 317 shp, and the same rating was agreed for the commercial Model 250-C18 and 250-B15 turboprop. In the latter the power section was inverted so that the jetpipes discharged diagonally downwards.

Thanks largely to continued sales of the JetRanger and Hughes 500 the production total rose steadily, to 11,000 by 1976 and to almost 22,000 by 1989. This includes substantial numbers of the B17B and B17C turboprops, rated at 400 and 420 shp respectively, and the 420 shp C20 turboshaft. In December 1977 Allison certificated the 250-C28, with a totally new mechanical layout the main feature of which was elimination of the axial compressor; the single centrifugal stage actually achieves the increased pr of 8.4, besides raising airflow to 4.45 lb/s, giving a 30-minute rating of 500 shp. Many features improve reliability and reduce noise and emissions, including IR (heat) – important for combat helicopters. Today the C28 and plain-inlet C28B of 550 shp remain in production along with the 700 shp C30 with a further-developed compressor, and the 735 shp C34 which introduced a new single-stage gas-generator turbine. The complete redesign of the C28 was accompanied by a sharp reduction in turbine temperature which opened the way to further growth, and even the C34 still runs cooler than the early versions. The C28, 30 and 34 are, however, physically bigger engines, weighing roughly 100 lb more than the 150 lb of the first turboshaft versions. The C30R introduced FADEC (full-authority digital engine control), and this is also a feature of the 'top of the range' C40 and C47 with ratings up to 820 shp (30 s) or 806 shp (5 min).

By 2006 Allison had delivered 29,200 Model 250 engines. These have powered 60 types of helicopters and aeroplanes, and they have flown over 105 million hours. Allison is also a partner in a totally different family of turboshaft engines, described under LHTEC.

For 20 years after, the J33 Allison designed no jet engines, but in 1959 it partnered Rolls-Royce in proposing an afterburning turbofan for the TFX (later the F-111). This was not selected, but in 1966 the same partners developed the British company's Spey turbofan into a slightly larger engine designated TF41. This was selected by the USAF at 14,500 lb thrust to power the A-7D Corsair II, and was later also adopted by the Navy at 15,000 lb for the A-7E, replacing the TF30. In 1968–83 Allison delivered 1,440 TF41 engines.

In July 1991 a pure-bred Allison jet went on test. This turbofan engine combines the high-pressure spool of the AE2100 with a new fan and low-pressure turbine. It was initially designated GMA 3007, for General Motors Allison, but in 1993 a management buyout resulted in the company becoming Allison Engines. In turn this company was purchased by Rolls-Royce, to the mutual benefit of both. *See* Rolls-Royce Corporation.

Alvis (UNITED KINGDOM) Famed builder of quality cars, Alvis took the decision in August 1935 to take a licence for various Gnome-Rhône engines, notably the 14K, thus completing the circle begun by GR's purchase of a licence from Bristol in 1921. Alvis boldly conjured up Greek names – Pelides, Pelides Major, Alcides and Maeonides for an impressive family of Anglicised GR engines, most of them with 14 or 18 two-valve cylinders of 5.75 in stroke and 6.5 in bore, but they failed to penetrate the market despite the accelerating RAF expansion. The one engine that did make it was largely Alvis's own creation, led by Captain G. Smith-Clarke: the neat Leonides. This was a conventional small radial with nine two-valve cylinders of 4.8 in bore and 4.41 in stroke, giving a capacity of 718.6 cu in. The prototype weighed 693 lb and ran in December 1936 at 450 hp. In 1938 the firm arranged with Airspeed (1934) Ltd for their test pilot, George Errington, to carry out flight tests. These were done using the much-rebuilt Bristol Bulldog K3183, which had previously done the same for the Napier Rapier.

Leonides' development was continued during the war at a reduced rate, and following testing in an Oxford and in Consul VX587 (itself a converted Oxford) Alvis was ready in 1947 to market the engine as the Series 500 (502 and 503 and subtypes) for aeroplanes and Series 520 for helicopters. The first production applications were the Percival Prince, flown in July 1948, and the Westland Sikorsky WS-51 and Dragonfly helicopters with the 550 hp Leonides 521/1 and successor versions with direct drive, centrifugal clutch and fan cooling. All Leonides had an efficient low-pressure fuel-injection system, and a vast range of accessories and equipment suited them to many applications. This excellent engine was Britain's last high-power production piston aero-engine, the last being delivered in 1966. From 1959 a proportion of production was of the Series 530 (mainly 531 for Twin Pioneers) with stroke increased to 4.8 in, rated at 640 hp.

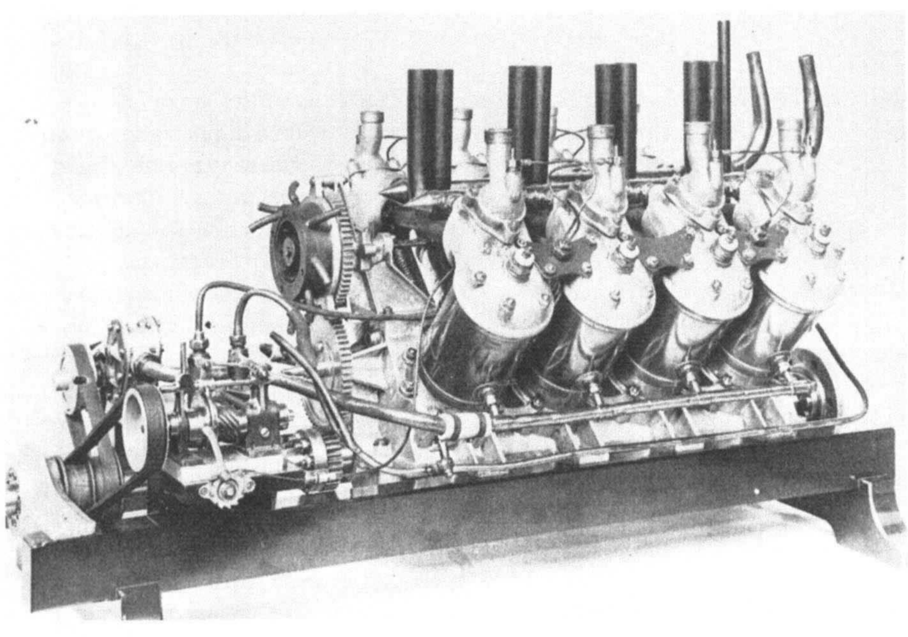
From 1951 Alvis developed the 14-cylinder two-row Leonides Major, eventually certificating the Mk 702/1 for aeroplanes at 875 hp and the 751/1 for helicopters at 850 hp. The only significant production was of Mk 755/1 inclined-drive engines for Whirlwind Mks 5, 6, 7 and 8. Alvis spent much of the 1950s working on an advanced engine with very small cylinders and high bmep (brake mean effective pressure), but wisely abandoned it.

Antoinette (FRANCE) This was the supreme aero engine prior to the appearance of the Gnome. It was one of the creations of the gifted Léon Levasseur, who named it for his patron's pretty daughter (though Antoinette Gastambide did not do as well as another French girl whose name was Mercédès). First run as a motor-boat engine in 1905, it was adapted for aero use in 1906. It was a 90° V-8 with cylinders 80 mm square (3.2 litres), cast separately with evaporative steam cooling using electroformed copper jackets. Left and right cylinders were offset to allow two big ends to run on each crankpin. A major feature was direct injection of metered doses of carefully filtered fuel into each of the automatic inlet valves. The crankshaft had gears or belts to drive the injection pumps, oil pumps and the magneto feeding the sparking plugs. Typical weight was 50 kg and rating 24 hp.

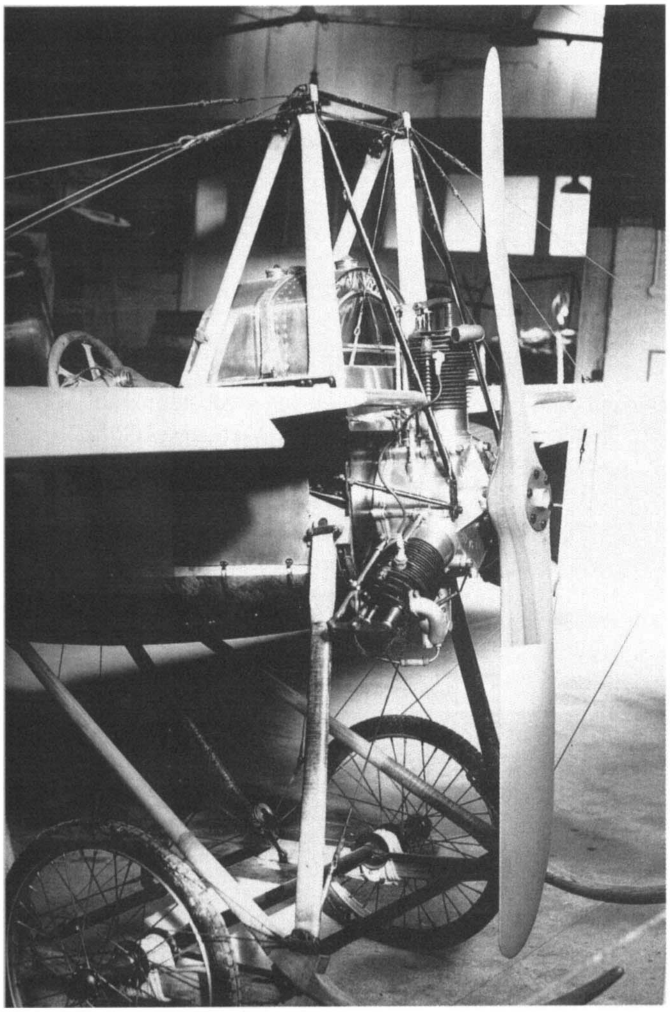
In 1908 a 50-hp model with cylinders 110 × 105 mm was sold at £480, compared with £328 for the original engine. By 1909 heads and cylinder barrels were machined from a single steel forging, this 60-hp model having a booster trembler-coil and usually a flywheel. An impressive V-16 gave 100 hp, but the author does not believe the amazing 32-cylinder Antoinette ever flew.

Anzani (FRANCE) Motorcycle builder Alessandro Anzani of Courbevoie sprang into eminence in 1909 with one of his first aero engines. A three-cylinder W or fan type (a V with an extra cylinder vertically upright) with crude air cooling and make-and-break ignition, it had a 105 mm bore and a 130 mm stroke, and a capacity of 3.75 litres.

Rating was 24 hp at 1,600 rpm, for a bare weight of 66 kg including a 26-kg flywheel. Provided it did not overheat it was fairly reliable, and one took Blériot to Dover on 25 July 1909. From April 1909 Anzani also sold the engine with 120 × 130 mm cylinders (35 hp) and 135 × 150 mm cylinders (45 hp). By December 1909 he was running a three-cylinder radial, with 120° between the cylinders. About three months later he had created the first two-row radial by adding a second 120° three-cylinder row behind the first, rotated 60° to give all cylinders equal cooling. He retained sprung auto inlet valves, and decided to use a kinked crank-web to bring



The classic Antoinette V-8 can be considered the first refined, factory-built aero engine. This example has an exceptional group of auxiliaries.



Deperdussin with three-cylinder Anzani. This one is a 1910 engine with the cylinders spaced at 120°.

the front and rear cylinders closer together, using very slim but broad connecting rods and driving via more refined slipper-type big ends. Using slightly smaller (90 × 120 mm) cylinders, the first of these six-cylinder radials was advertised as giving 45 hp at 1,300 rpm.

By late 1913 Anzani had no fewer than seven types of aero engine on sale, though they were hand-built in ones and twos. Biggest were the 10-cylinder radials; one of the 110 hp size (105 × 140 mm cylinders) being exhaustively tested at Farnborough in 1914. Anzani production in the First World War was mainly for trainers, but before the end of that conflict he had introduced push-rod operation of the inlet valves, with the exhaust valves in line directly ahead. There followed a further profusion of different types, some with water cooling, but none received the concentrated effort needed for high reliability. Small numbers continued to find buyers, one of them Clyde Cessna whose first aircraft had the 120-hp 10-cylinder Anzani engine. In 1928 Potez used Anzani cylinders in the first of his six-cylinder single-row radials.

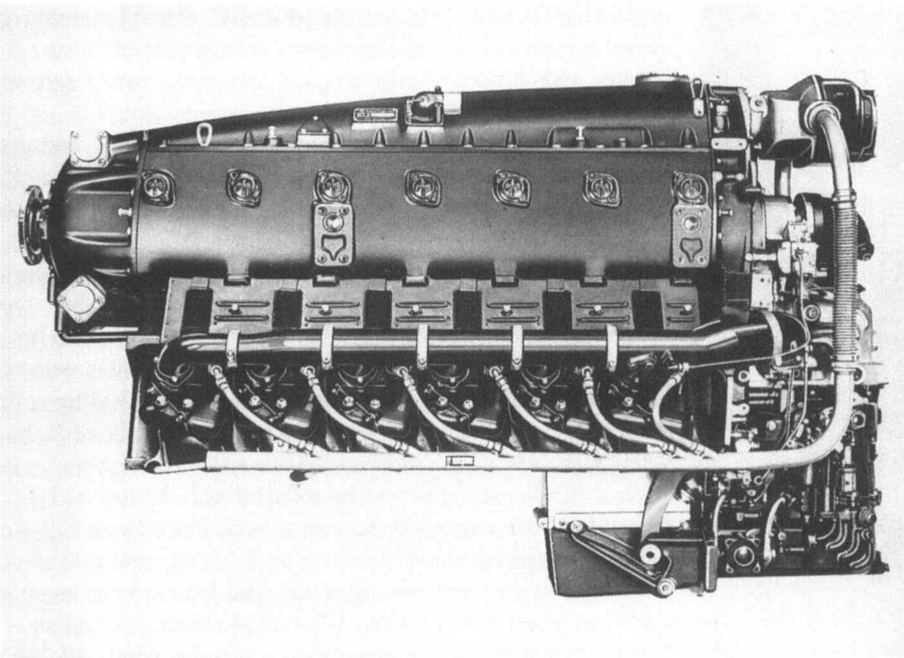
Argus (GERMANY) This company, for most of its life centred at Berlin-Reinickendorf, built its first car engine in 1902, an upright water-cooled four-in-line, and followed it with a derived aero engine in 1906.

Using cylinders initially measuring 124 × 130 mm, and then from 1909, 140 mm square, it was the chief German aero-engine firm until 1914, delivering 490 engines, over a dozen of which powered pre-war four-engined Sikorskys. Most went into Taubes and derived types. Continuing mainly at the 100 hp level, some thousands were delivered by 1918, by which time a few Argus engines had been delivered at 190 hp. Aero work ceased in 1919, but briefly returned in 1926 with two large 43.5-litre water-cooled V-12 engines of 1,300 hp, one upright and the other inverted. Only two or three of each were made.

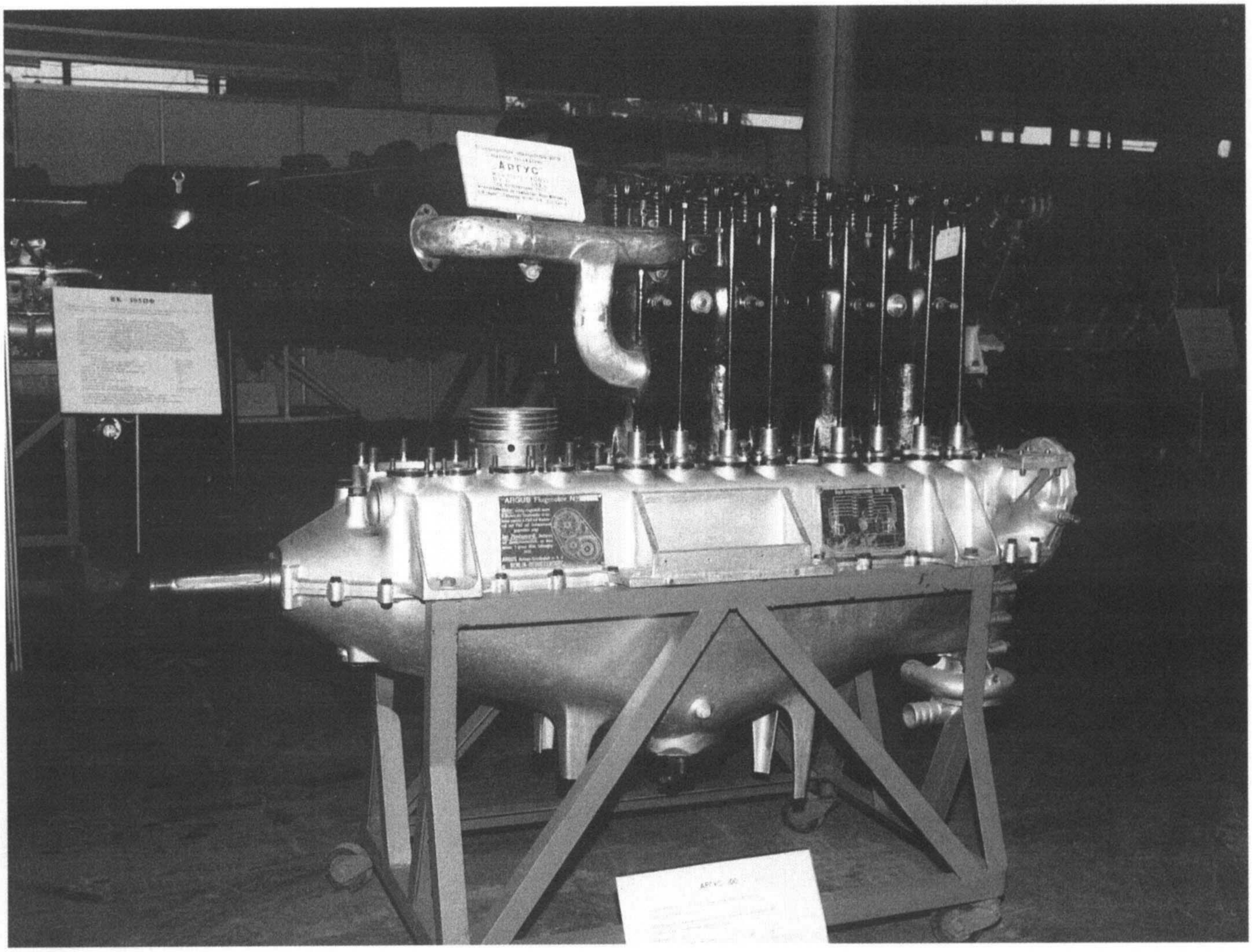
In 1928 Argus found its feet with the As 8, an inverted four-in-line with air-cooled cylinders of 120 × 140 mm, 6.3 litres, rated 110 hp at 2,100 rpm. It put the aero side of the company on a firm footing at last, and led to the corresponding inverted V-8, the As 10 of 1931. This was rated at 240 hp in later models, notably the As 10 C, of which 28,700 were delivered by 1945. In 1937 the firm developed a smaller cylinder, 105 × 115 mm, matched to greatly increased operating speeds, with deep-finned steel barrels and aluminium heads, and crankcases made from cast Elektron (magnesium alloy). The first production application of this advanced technology was the As 410 inverted V-12, which in geared and supercharged form weighed around 315 kg and was rated at up to 485 hp at 3,100 rpm. Production amounted to 20,900 units for such types as the Fw 189 and Ar 96B, but the final model, the As 411, was built in modest numbers (*c.* 2,600) by Renault in Paris, mainly for the Si 204D. The 411 was a highly rated engine weighing 385 kg as a complete power egg, giving 600 hp at 3,300 rpm. After the liberation Renault continued development.

Argus Motorengesellschaft's most notorious engine was the Type 109-014 Argus-Schmidt pulsejet used to power the V-1 flying bomb and various last-ditch manned aircraft of 1944–5. Made of wrapped mild-steel sheet, it contained a spring flap-valve grid in the inlet which, in operation, set up combustion resonance at about 45 Hz, giving some 272 kg thrust, equivalent at bomb cruise speed to 650–750 hp (bombs flew at various speeds depending on the fuel metering unit). The first, smaller, Argus-Schmidt pulsejet was tested under a Go 145 (itself Argus-powered) in April 1941. The actual bomb first flew on Christmas Eve 1942. Production of the 109-014 amounted to 31,100.

Armstrong Siddeley (UNITED KINGDOM) This famous Coventry company got started in aero engines when the Royal Aircraft Factory was forbidden to build production engines from February 1917. A month before this Major F.M. Green left the factory to join the Siddeley-Deasy Motor Car Company as chief aeronautical engineer, taking with him the RAF.8. His prime task, however, was to help Siddeley redesign the BHP,

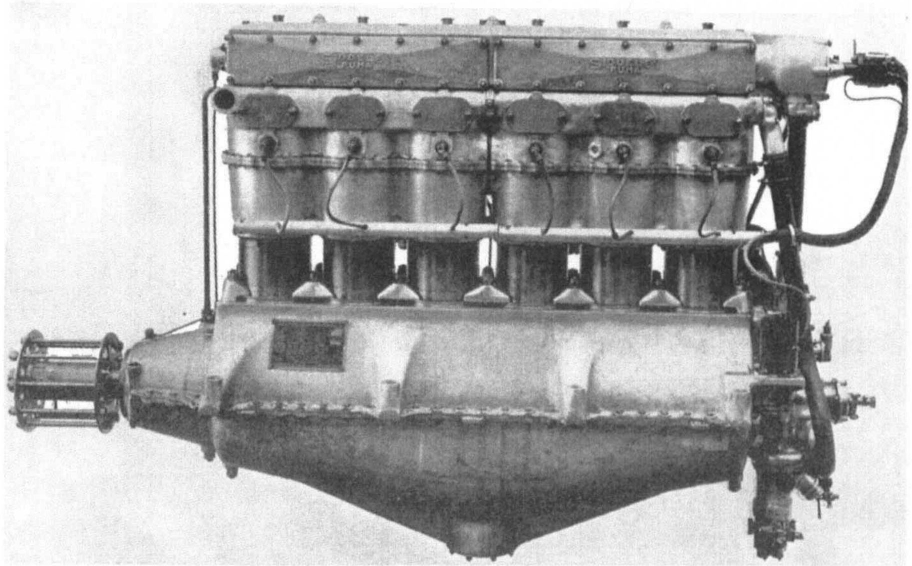


The Argus As 411 was the last of the company's range of inverted V air-cooled engines. Renault, despite claims of redesign, did little more than change the accessories and nameplate.

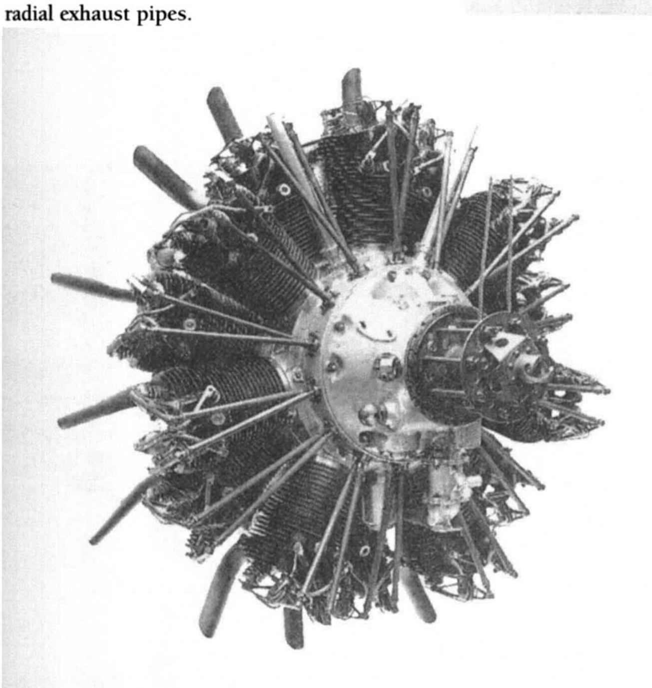


Shown with the front two 140 × 140 mm cylinders removed, this 100-hp Argus has been in Russia since 1910. It is believed to have powered Sikorsky's *Grand*, the first four-engined aircraft.

The Siddeley Puma was externally similar to the BHP, apart from having a single cast cylinder block.



The Armstrong Siddeley Jaguar was one of the most important British engines of the 1920s. This is an early mark with exposed valve gear, direct drive and unusual short radial exhaust pipes.

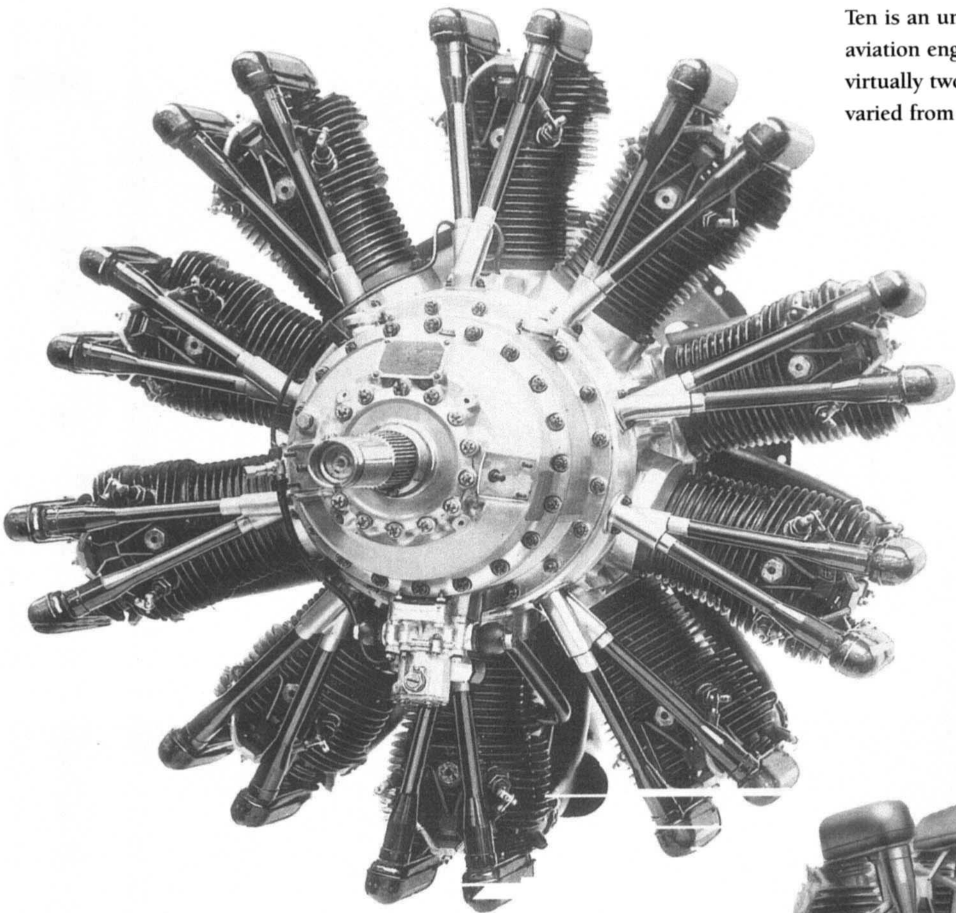


and he assisted chief designer F.R. Smith to turn this engine into the Siddeley Puma, a refined six-in-line with a cast aluminium block with open-ended steel liners and a separate bolted-on block for the heads. The Puma was built in larger numbers than any other British engine of the day, as described under BHP.

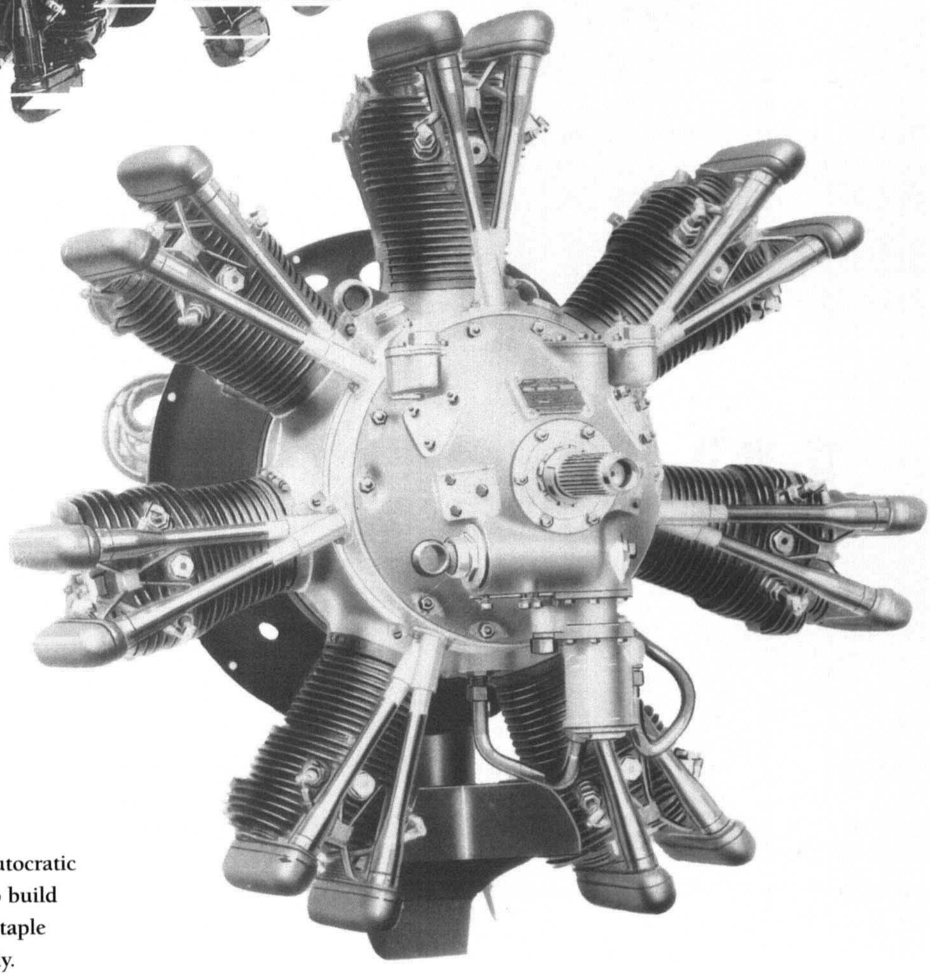
By 1918 pressure on getting the Puma right had eased, and work began in earnest on the RAF.8, which Siddeley named the Jaguar. This compact 14-cylinder two-row radial was probably the best aero engine in the world from 1919 until at least 1922. It incorporated all the knowledge and philosophy of Green and S.D. Heron, the pioneers of the modern air-cooled cylinder. By 1919 the Jaguar was running with close-finned steel cylinders with aluminium heads attached by short 'quick-threads' and housing two valves each inclined at almost 45°. Siddeley eliminated the supercharger, but after 1920 consented to a direct-drive blower to improve mixture distribution. It had cylinders 5 × 5 in, and gave about 300 hp with fair reliability. By 1921 stroke was increased to 5.5 in, giving a capacity of 1,512 cu in, and the Jaguar then became top engine in Britain at around 400 hp for such aircraft as the Flycatcher, Siskin and Argosy transport. In 1925 it became the first engine in production with a geared supercharger, Green and Heron having invented the necessary centrifugal slipping clutch back in 1918. After 1926 it was surpassed by the Jupiter and Wasp.

Siddeley's Tiger, a fine-looking V-12 with Puma cylinder blocks, ran on the bench in early 1920 at 486 hp and powered the first Sinaia bomber in June 1921. In 1920 a mere test rig with two opposed cylinders did so well the Air Ministry ordered a small production run as the 40-hp Ounce for ultra-lights. In the same year the prototype of the Lynx, effectively one-half of a Jaguar, began testing, and from 1923 it was made in increasing numbers at around 200 hp with hardly any need for development. It avoided the Jaguar's weakness, the two-throw crankshaft, and over 6,000 were built by 1939, a good share of them for the Avro 504N trainer and its successors. Income from the Lynx sustained the company through lean years caused not only by the economic situation and competition from Bristol but, to an increasing extent, the refusal of Siddeley (later Lord Kenilworth) to understand that his often good flashes of inspiration needed to be backed up by solid development.

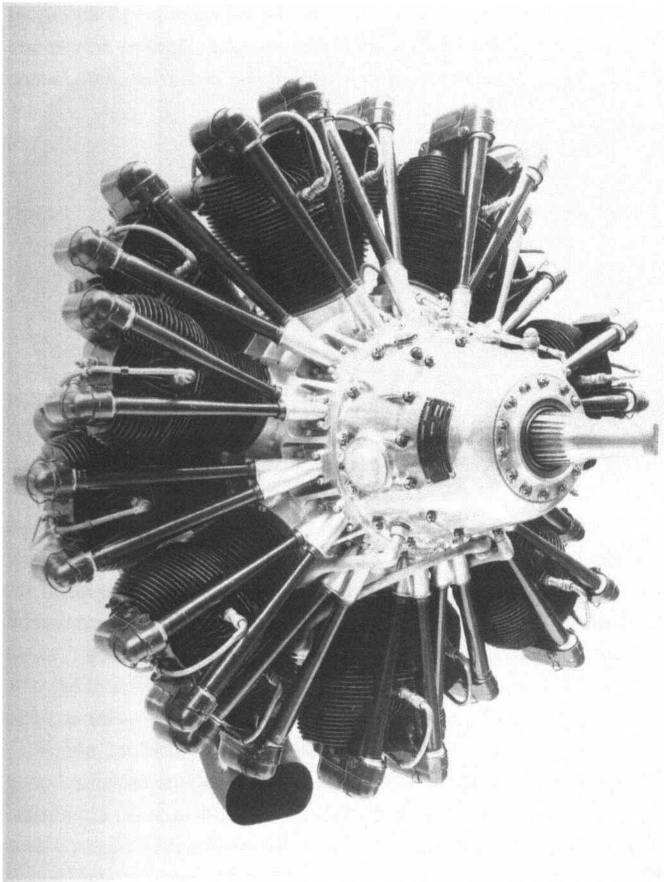
In the absence of this, ASM (Armstrong Siddeley Motors) was doomed never to be in the front rank, despite the talent of chief designer Harry Cantrill. Engines appeared aplenty: the Genet emerged in 1925 (five 4 × 4 in cylinders, 82 hp), the Mongoose in 1926 (five 5 × 5.5 in Jaguar cylinders, 150 hp), the Civet in 1927, Double Mongoose (later named Serval) in May 1928, the Genet Major in 1928, the massive 14-cylinder Leopard (6 × 7.5 in cylinders, 800 hp) in 1928, the Panther



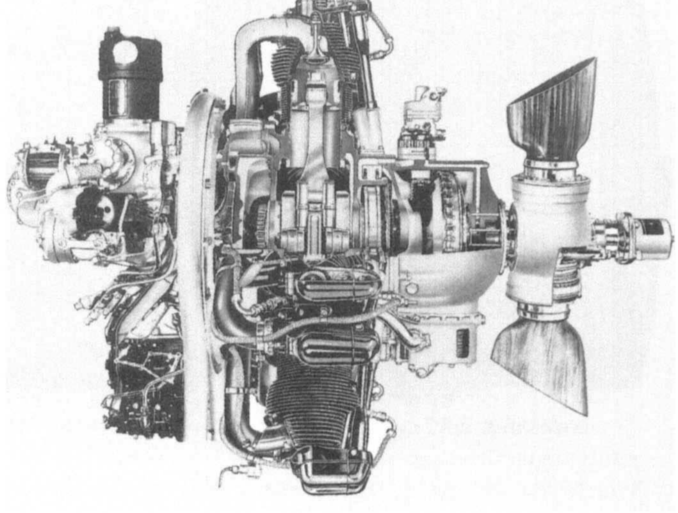
Ten is an uncommon number of cylinders for an aviation engine, but the Armstrong Siddeley Serval was virtually two Mongooses on one crankcase. Ratings varied from 295 to 340 hp.



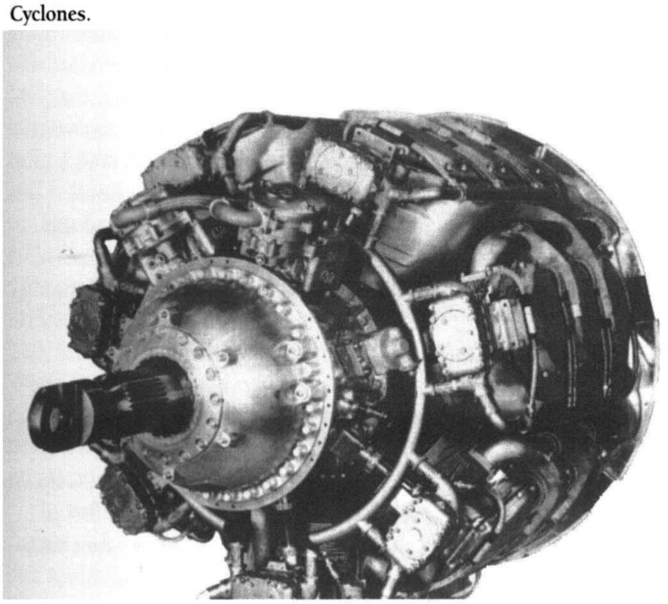
Armstrong Siddeley Motors not only had an autocratic non-engineer head but also lacked the drive to build competitive high-power engines. The Lynx, a staple product for 19 years, suited their style perfectly.



There was nothing slipshod about Armstrong Siddeley quality control, but their big engines lacked both power and reliability. This Tiger IX of 850 hp was replaced in the A.W. Ensign airliners by Wright Cyclones.



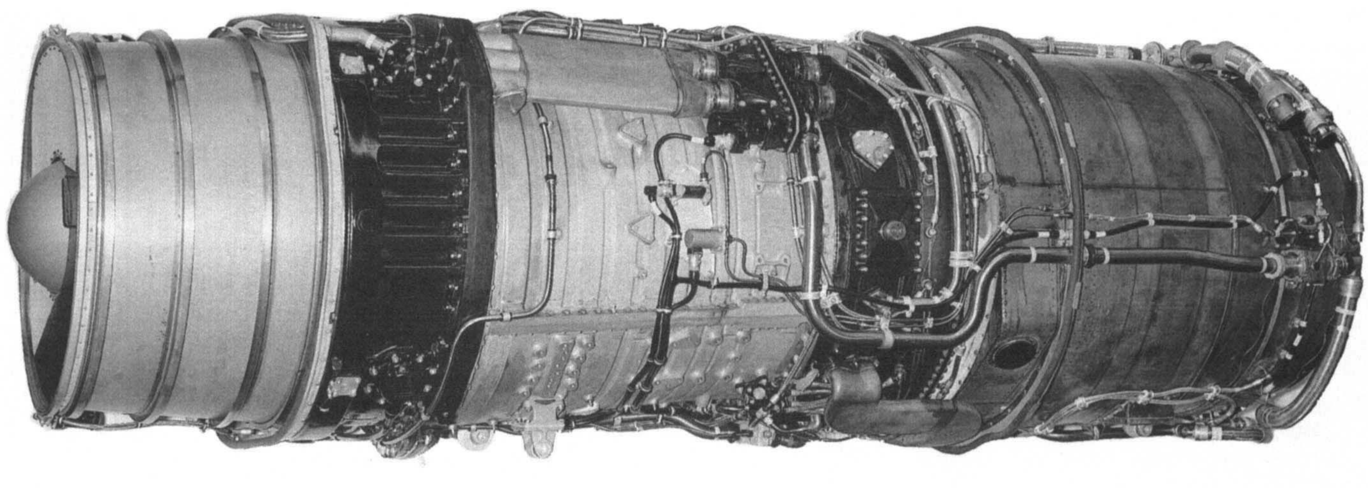
A beautiful cutaway illustration of an Armstrong Siddeley Cheetah of 1947 vintage, with geared drive to a Rotol constant-speed propeller.



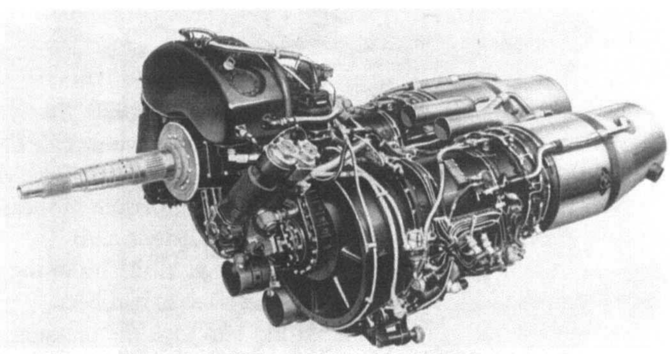
Last of the ASM piston engines to fly, the Deerhound was compact and showed promise, but was simply not sufficiently powerful to be worth producing. As in the Boarhound, each row of cylinders was in line.

(14 cylinders 5.3 × 5.5 in, starting at 525 hp) in 1929, the 250-hp Lynx Major in 1929, the Cheetah (seven cylinders 5.25 × 5.5 in) in 1930, and the Jaguar Major (later renamed Tiger, 14 cylinders 5.5 × 6 in) by 1931. The most important of these was the Cheetah, which suited the company's style and capability. Starting at 295 hp, it went on to give 425 hp in the last Ansons in 1952, by which time over 37,200 had been delivered. This filled the Parkside works and took the pressure off the big engines. From the original Jaguar all these had suffered from crankshaft deflections that cried out for a centre bearing. The Tiger gave 800 hp, and was coaxed to 920 hp by 1938 for Whitleys and Ensigns, but reliability was poor; the former aircraft switched to the Merlin and the underpowered Ensign to the Cyclone.

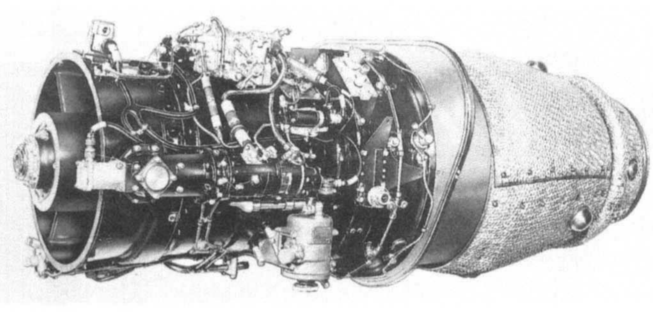
The final fling comprised three superficially attractive three-row radials, starting with the Hyena flown in 1933. In 1934 Colonel L.F.R. Fell came from Rolls-Royce to be chief engineer, and with Cantrill he planned not only the interchangeability between contrasting types of engine – demonstrated, for example, on the Hampden/Hereford, Wellington, Beaufighter, Halifax and Lancaster – but also the final two completely new high-power engines. The Deerhound and Boarhound were again three-row radials but owed little to the more traditional Hyena. Extremely compact, the Deerhound had 21 air-cooled cylinders with each line of three served by an overhead camshaft. The prototype gave 1,115 hp on test in 1936, and in 1938 it flew in a Whitley II, the final cowling looking like that of a modern C-130. The Boarhound, a bigger 2,250-hp engine, never flew.



Despite its initial superiority to the rival Avon, the Armstrong Siddeley Sapphire was ordered in much smaller numbers (if one excludes US Wright J65 production). Last variant was this Mk 203/204 for the Javelin 7 and 9, with a low-augmentation afterburner boosting thrust to 13,390 lb.



The Armstrong Siddeley Double Mamba not only pioneered the use of two power sections joined to one gearbox but each half drove its own propeller as in the earlier Fairey Prince. This is a 3,035 ehp Mk 101 (Gannet AS.4 powerplant).



An Armstrong Siddeley (later BS, later still RR) Viper 11 of 2,500 lb rating. Vipers went into production at 1,640 lb (as a 'short life' engine) and remain in production more than 50 years later at 5,000 lb.

Gas turbines

By 1940 ASM had 'got its feet wet' in the challenging new field of gas turbines. In 1939–41 it built on Ministry contract the contra-rotating contraflow gas turbine suggested by A.A. Griffith at the RAE 10 years earlier. Thus, when ASM were given their first gas-turbine contract on 7 November 1942 the company chose to go for an axial machine, and finally picked the ASX, a reverse-flow 14-stage axial with 90° elbows at the front feeding 11 slim combustion chambers discharging through a two-stage turbine. The ASX ran in April 1943, flew in the Universal Testbed Lancaster and by 1944 was giving 2,800 lb thrust at 8,000 rpm for a weight of 1,900 lb.

This was not competitive, so a propeller gearbox was added to produce the ASP, run in April 1945. This gave 3,600 shp plus 1,100 lb thrust for the rather ponderous weight of 3,450 lb. It was inferior in almost all respects to the Rolls-Royce Clyde, but Hives declined to continue the latter so ASM got a production contract for the ASP, renamed Python. Tested in the outer positions of Lancaster TW911 and Lincoln RF403, the Python and its eight-blade Rotol contraprop suffered prolonged development and lagged the Clyde by more than four years, but at last entered service with the Royal Navy in May 1953 as the powerplant of the Wyvern S.4. The Python 3 had an airflow of 52.5 lb/s, pr of 5.35, weight of 3,505 lb and take-off rating of 4,110 ehp.

Under technical director Bill Saxton and chief designer A. Thomas, ASM went flat-out for axial gas turbines. A contract was received in mid-1945 for a unit in the 1,000-hp class and the prototype Mamba ran in April 1946. At first it was judged a better bet than the rival Dart, but the latter was picked by George Edwards for the Viscount. Mambas flew from 14 October 1947 in Lancasters, a Dakota and the Marathon 2, but found few applications (Apollo and Seamew). Far more important was the Double Mamba, comprising two Mambas, each driving a four-blade propeller but sharing a common inlet casing and installed as a single powerplant, the propellers being a single coaxial unit. The advantages were that one engine and propeller could be shut down for long-range cruise, and it could burn diesel or other fuel already on board warships, eliminating high-octane gasoline. The ASMD.1 first flew in the Fairey GR.17 on 29 September 1949, this leading to the very successful Gannet ASW and AEW aircraft, the final AEW.3 version having the Bristol Siddeley Mk 102 engine of 3,875 ehp.

An extremely important feature introduced hesitantly with the original ASX was the use of vaporising combustion. There are inherent problems with high-pressure atomising burners, but with the ASM system the fuel is sprayed at low pressure into a 'walking-stick' 180°-curved tube where it vaporises, not quite as in a blowlamp, to give near-perfect burning at all fuel flows, which can vary 100-fold between sea-level take-off and high-altitude flight idle. When Dr Stanley Hooker became technical director of the combined Bristol Siddeley firm in 1959 he found the ASM system superior to the more common scheme, and ordered it used on former Bristol engines; he would have had it on the RB.211 at Rolls-Royce but this engine was already planned with the traditional arrangement. Vaporising combustors were on all ASM gas turbines from 1943.

Removing the gearbox from the Mamba in November 1948 gave the Adder turbojet, rated at 1,050 lb thrust for a weight of 580 lb and used in the Pika and Saab 210, and for ASM's first afterburning experiments on 1 January 1950. Saxton and W.H. Lindsey now had enough experience to start afresh, and quickly designed the Viper, a simple short-life turbojet intended for the Jindivik target drone. The Viper had a new seven-stage compressor (32 lb/s, pr 4), 24-burner vaporising annular combustor and a variety of external or integral starting systems. Rated at 1,640 lb for a weight of 365 lb, it set entirely new standards. Soon a 'long life' version was flying in the Midge and Jet Provost, and under chief engineer John Marlow its development continued through Bristol Siddeley and Rolls-Royce right up to the present, at ratings up to 5,750 lb and with sales close to 6,000.

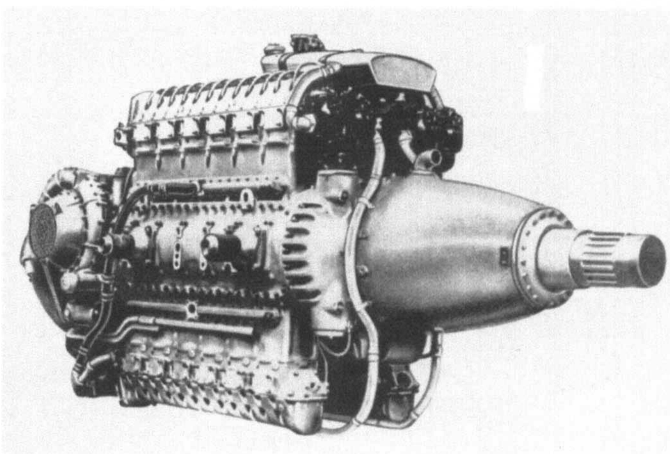
Under Sid Allen ASM thrust ahead in 1946 into liquid rocket engines. Funding was slow until the Korean War in 1950; then the 2,000-lb Snarler quickly appeared, pump-fed on lox/alcohol, followed by the 8,000-lb Screamer for the Avro 720, but all such work was stopped by the 1957 Defence White Paper that terminated new fighter projects. It also cancelled the Avro 730 canard bomber/reconnaissance aircraft designed to fly at Mach 2.5 on P.176 afterburning turbojets in two four-engine box nacelles.

By far the most important of ASM's engines was the Sapphire, handed to the company in 1947 when Metrovick was told to stop aero work. The former F.9 was a superb engine, and in particular its 13-stage compressor was the best in the world when ASM began bench running on 1 October 1948. Other features were an annular combustor with 36 walking-stick burners, and a two-stage turbine. An ASSa.3 was type-tested at 7,500 lb in November 1951, and an ASSa.6 passed the test at 8,300 lb in May 1952. Weight was 2,550 lb. Subsequently 200-series Sapphires were cleared at dry thrusts exceeding 11,000 lb, and with a simple afterburner at 13,390 lb for the Javelin. Wright licensed a US version designated J65 (*qv*).

The last ASM project to run was the P.181, a completely new engine in the 1,000–2,000-hp class for aeroplanes or helicopters. The HPR.5, the rebuilt Mamba-Marathon 2, was being readied to fly it in 1958 when the project was abandoned. The company was merged with Bristol Aero-Engines into Bristol Siddeley in 1959.

Arrow (ITALY) Arrow Engineering produces a range of light-plane engines of modular design, based on standard parts, such as cylinders of 74.6 mm bore and 57.0 mm stroke. The two largest are 'flat' (horizontally opposed) engines, the four-cylinder GP 1000, rated at 120 hp, and the six-cylinder GP 1500, rated at 180 hp. They run at the high speed of 6,800 rpm, and so even with a reduction gear weigh only 1 lb per hp.

Arsenal (FRANCE) The Arsenal de l'Aéronautique at Châtillon-sous-Bagneux had many fine engineers, some of whom wasted years developing flexible couplings for tandem engines. From 1944 it improved the Jumo 213 as the Arsenal 12H, rated at 2,250 hp with water injection. These saw active service in the Nord 1402 Noroit amphibian. The unwieldy 12H-Tandem comprised two of these engines linked by the Arsenal coupling, giving 4,500 hp and intended to replace 12Z engines in Arsenal's own VB 10 fighter. The culmination was the monster 24H, with four 12H cylinder blocks in vertical opposed pairs driving two crankshafts geared to a common propeller shaft. A cross-shaft drove two superchargers, that on the left feeding the upper blocks and that on the right the lower. The 24H weighed



The Arsenal 24H with four Jumo 213 cylinder blocks was only half of a vast tandem engine with 140 litres and 8,000 hp. Even at the time this appeared to be a colossal solution to a non-existent problem.

1,900 kg and was rated at 4,000 hp. The propeller drive was arranged to allow a shaft to pass through from a second 24H in the rear; the 24H-Tandem (140 litres) was actually run. The 24H was tested in the inner positions of a Languedoc, driving tiny five-blade Rotols unable to transmit even half the power.

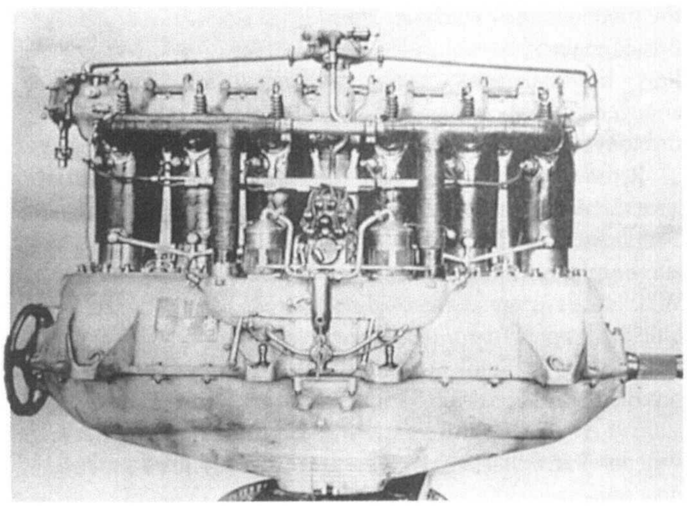
Austro-Daimler (AUSTRIA) The first engines designed by Dr-Ing Ferdinand Porsche included an outstanding six-in-line of late 1910. It was possibly the first of the vast numbers of such engines used in almost all the Central Powers' aircraft of 1914–18 to have been designed from the start for aero use. By 1911 cylinder size had settled at 130 × 175 mm, giving a capacity of 13.9 litres; rating was almost always 120 bhp at 1,200 rpm, and dry weight about 260 kg. Advanced features included welded steel (originally copper) water jackets, seven main bearings and inclined inlet/exhaust valves of large diameter operated by push-pull rods.

From the start the modest rpm and general stress levels resulted in good reliability, and it was competition from this engine that spurred Mercedes, Benz, Hiero and others to enter the aero field. One of the first foreign customers was S.F. Cody in Britain, in April 1911. The same engine had already flown 15 hours and crashed twice when it was the sole reason for Cody's Cathedral winning the 1912 Military Trials at Larkhill. In 1911–14 the Austro-Daimler was one of the best-selling engines, the original size being partnered by a smaller-capacity model of 90 hp.

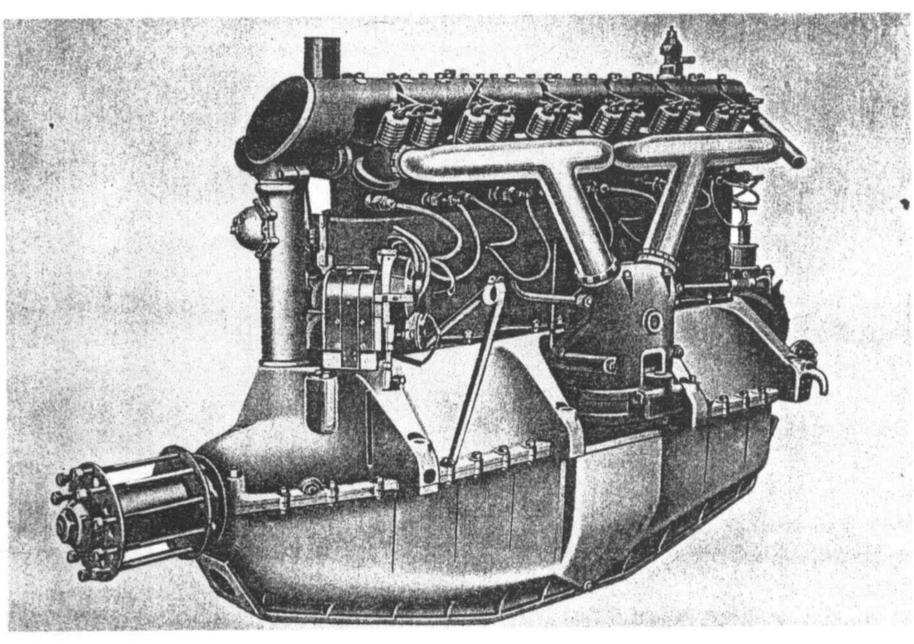
The 1913 Austro-Daimler was built in fair numbers for second-line aircraft during the war, and in Britain served as prototype for the first Beardmore. By 1916 the chief production engine was rated at 185 hp, and in December of that year it was cleared to run at 1,350 rpm giving 200 hp, being used in many Austrian-Aviatik, Hansa-Brandenburg and Phönix aircraft. By late 1917 the power had risen to 210 hp and finally to 225 hp, without change in cylinder size.

Avco Lycoming *See* Honeywell.

Avia (CZECHOSLOVAKIA) In 1915 Breitfeld-Daněk made under licence the Austrian Hiero (designer Hieronimous), a Germanic six-in-line with 135 × 180 mm cylinders giving 200 or 230 hp. Own-design engines marketed under the name Praga followed in 1921–39. In 1930 what had become CKD took over the Skoda R-7 five-cylinder radial of 140 hp, and after 1945 the nationalised industry operated as Motokov and Omnipol. The only engines in production were versions of the Walter Minor (see that company's entry), which from 1960 were marketed under the Avia name. Today these Walter engines are produced and marketed by a company called



The Hiero water-cooled six-in-line was the first engine to go into production in the newly created Czechoslovakia (see Avia).



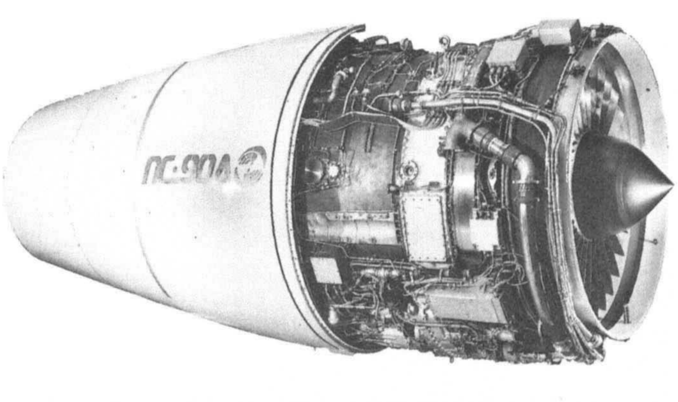
The final wartime Austro-Daimler was rated at up to 225 hp. Note the front drive shaft to the overhead camshaft, with one of the six-cylinder magnetos beside it, and the carburettor group amidships.

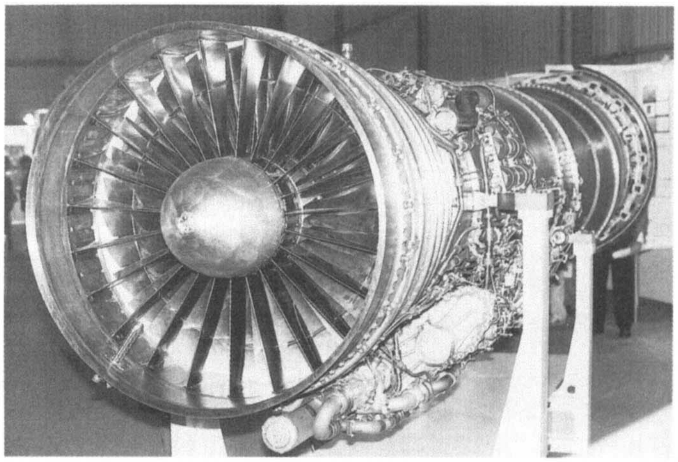
LOM Praha. Back in the 1960s Avia also produced the 330 hp M462 nine-cylinder radial and the 42 hp M150 two-stroke for self-launch sailplanes.

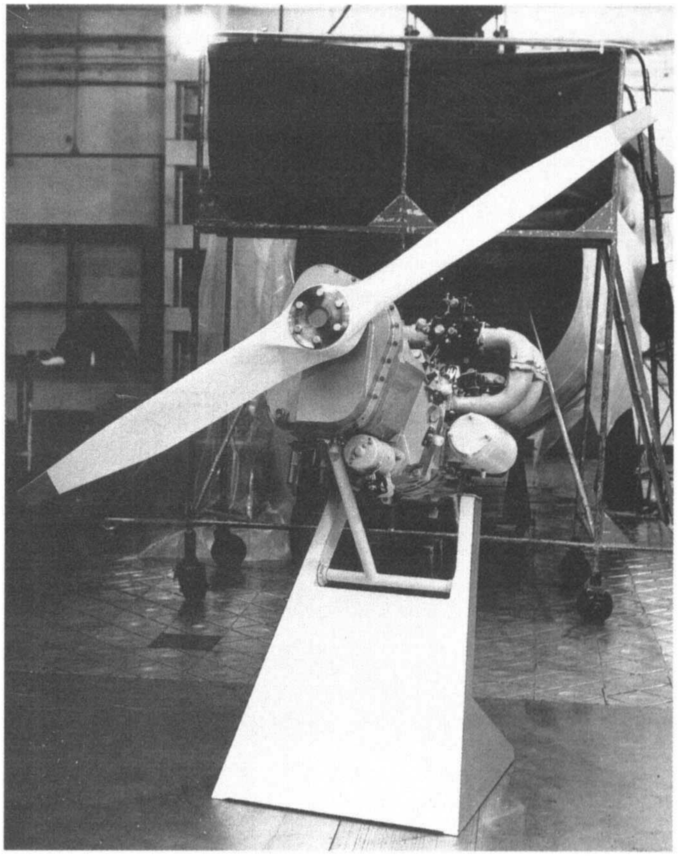
Aviadvigatel (RUSSIA) This large design bureau, based at Perm, has a name meaning 'aircraft engine'. It was founded by Shvetsov (*qv*), who was followed in 1953–89 by Soloviev (*qv*). Since 1989 the General Director has been Yuri E. Reshetnikov, who has unexpectedly seen his PS-90 having to compete with the Rolls-Royce 535 in the Tu-204 and with the PW2000 in the Il-96. In 1972 work began on the D-30F6, an awesome augmented turbofan to power the MiG-31. Its core is derived from that of the D-30 (not D-30K), but the complete engine is 277 in long and weighs 5,326 lb; maximum take-off thrust is 41,843 lb. Reshetnikov has a series of future engines based on the core of the PS-90. The General Designer is A.A. Inozemtsev.

In a contrasting programme, Aviadvigatel is developing Wankel-type rotating-combustion engines based on the VAZ series designed at the Togliatti car factory which makes Fiat cars in Moscow. The furthest developed is the D-200, based on the VAZ-4305, a liquid-cooled twin-rotor engine for the Mi-34V helicopter. It weighs 320 lb and is rated at 217 hp. The propeller version illustrated has a geared drive.

Avio *See* Fiat.







Top: **The PS-90A is described under Soloviev.**

Centre: **The Aviadvigatel D-30F6 is cleared to Mach 1.25 at sea level and Mach 2.83 at altitude.**

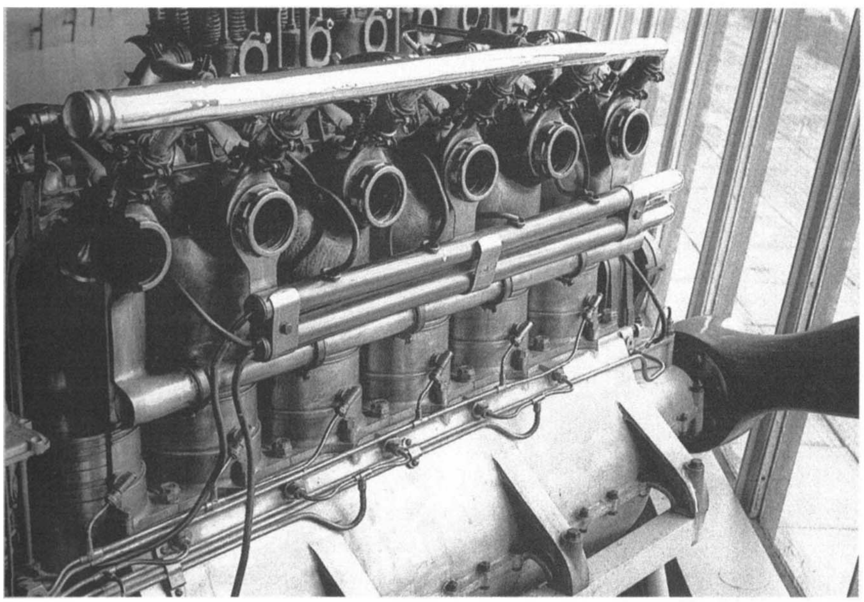
Bottom: **A D-200 rotary engine on test in propeller-driving form.**

B

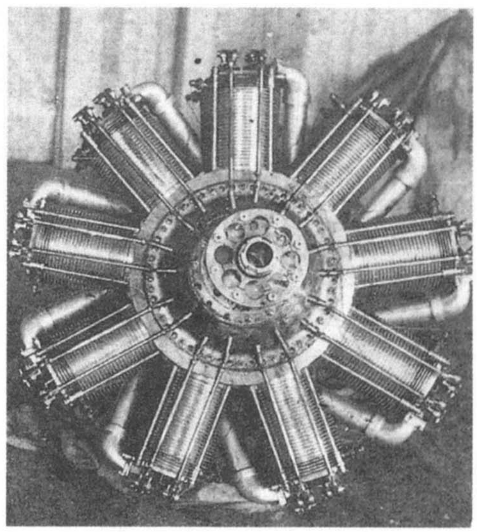
Beardmore (UNITED KINGDOM) William Beardmore, of Dalmuir, Scotland, a famed engineering firm, obtained a licence to build the Austro-Daimler engine in 120 hp size not later than March 1914, and quickly introduced a number of changes including dual ignition and twin carburettors. Several thousand were built, terminating in 1917. In 1915, by which time a subsidiary, Beardmore Aero Engine Company, had been registered, the company felt able to effect a more complete revision which included increasing bore to 143 mm giving a capacity of 16.4 litres; take-off rating went up to 160 hp, later cleared to 192 hp at 1,450 rpm, and price from £825 to £1,045. The bigger engine, weighing 592 lb, came into production in March 1916. Like the 120 hp, most of the early output had been reserved by the Royal Aircraft Factory, mainly for the FE.2B. Historian Jack Bruce comments that it was not as reliable as the lower-powered engine. F.B. Halford was instructed to develop the 160 hp version to give greater power, resulting in the BHP series (*qv*). One version of this engine was built by Galloway. In 1919–22 Beardmore worked on the 840-hp Cyclone, a giant six-in-line of 8.562-in bore and 12-in stroke.

When the British government at last decided in 1924 to build large commercial airships, it decided to allocate one to private enterprise and the other to a government organisation. The latter ship, *R-101*, was created on the basis that money was no object, and special giant four-stroke diesel engines, later named Tornado, were ordered from Beardmore. Each was an eight-in-line with cylinders 8.27 × 12 in, rated at 585 hp at 900 rpm for a weight of 4,225 lb. The massive weight was accepted as being less than the saving in weight of fuel on long journeys, but in May 1930 the *R-101* crashed (having run more than three years behind schedule) with her engines still unable to give their design power and liable to break down at any moment. A distant relative was the Simoon diesel of 1,000 hp, first run in 1923 and flown in the second Blackburn Cubaroo.

Bentley (UNITED KINGDOM) Already an established motor engineer, Lieutenant W.O. Bentley, RNAS, was sent by Commander Briggs at the Admiralty to study the overheating problem in rotary engines in late 1914. Predictably he decided the best long-term answer was a new engine, and starting with the very expensive Clerget produced an engine with aluminium-alloy pistons designated AR.1, for 'Admiralty Rotary'. It was greatly improved from the manufacturing viewpoint, price being reduced from some £950 to £605, while power was increased to 150 hp, largely by increasing stroke to 6.7 in (capacity 1,055 cu in). By 1915 he was completely redesigning the cylinder, with an aluminium barrel, cast-iron liner and steel head tied to the crankcase by four long bolts, with two valves operated by pushrods. This is believed to have been the first production air-cooled cylinder with an aluminium barrel. Bentley also introduced dual ignition. Capacity was the same as the AR.1, and weight increased still further to about 397 lb, but the engine's efficiency and reliability were transformed, the rating of 150 hp at 1,250 rpm being reliably obtained without deterioration over at least 100 hours. Designated BR.1, for Bentley Rotary, this engine was mass-produced for the Admiralty by several contractors, and



A typical Beardmore six-in-line, in London's Science Museum.



A Bentley BR.2, the most powerful of the wartime nine-cylinder rotaries. A major application was the Sopwith Snipe fighter.

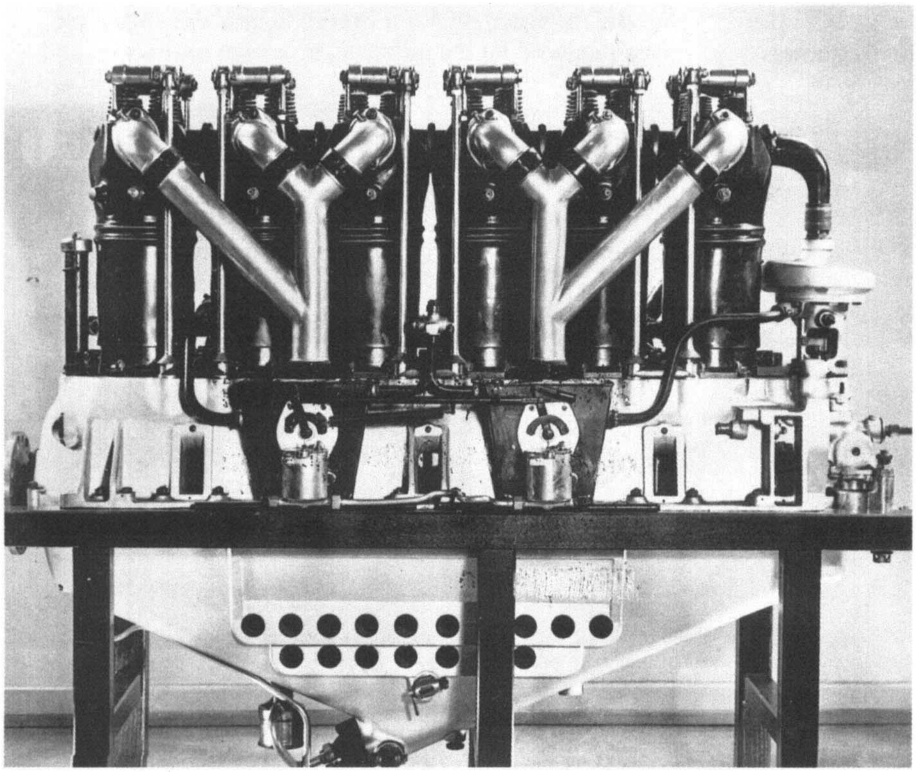
used to power Sopwith Camels among other types. (Despite this, the Clerget continued to be made under licence in even greater numbers.)

During 1916 Bentley, still a lieutenant, completed the design of an entirely new and challenging rotary using the same principles but with larger cylinders 5.5 × 7.1 in, giving a capacity of 1,522 cu in. Three prototypes were ordered in April 1917. Cleared to 1,300 rpm, the first BR.2 gave 234 hp on its first run in early October 1917, yet weighed only 93 lb more than the BR.1 at 490 lb. The BR.2 was an instant success, and Major-General Sefton Brancker exclaimed that it could with advantage 'be put into every type of aeroplane in France, except bombers'. A production programme was organised for 1,500 per month, the eventual price of £880 still being well under that for the Clerget of half the power. The BR.2 represented the pinnacle of rotary engine development, and in the Snipe continued in RAF service until November 1926.

Benz (GERMANY) Benz & Cie, of Mannheim, was the pioneer of the motor car from 1885. A four-in-line water-cooled engine of 100 hp powered the RWMG non-rigid airship of 1909, and several types of derived engine powered aeroplanes and did well in the Kaiserpreis of 1913. In that year the Bz II was put into limited production at a rating of 100 hp, with cast-iron cylinders each with two valves 180° apart worked by pushrods from camshafts on both sides of the steel crankcase. The capacity was 14.34 litres, and operating speed was 1,200 rpm. In 1914 the Bz III introduced a higher compression ratio and ran at 1,400 rpm to give 160 hp. The Bz IIIa, the first mass-production Benz, increased capacity to 17.5 litres (cylinders 140 × 190 mm) to give 180 hp, while the final mass-production engine, the Bz IV, increased the bore to 145 mm and was rated at between 200 and 230 hp, though usually called the '200 hp'. More than other engine firms in the Central Powers, Benz dabbled in V-form engines. An oddity was the Bz IIIb of 1918, a 60° V-8 with small 135 × 135 mm cylinders, because even running at 1,750–1,800 rpm this gave only 200 hp. In contrast the Bz VI was a big V-12 – effectively two Bz IVs on a common crankcase but with various changes to give a take-off power of 550 hp, more than any other German wartime engine. Two of these, with two Bz IVs, powered the final Zeppelin Staaken Giant, the R.XVI.

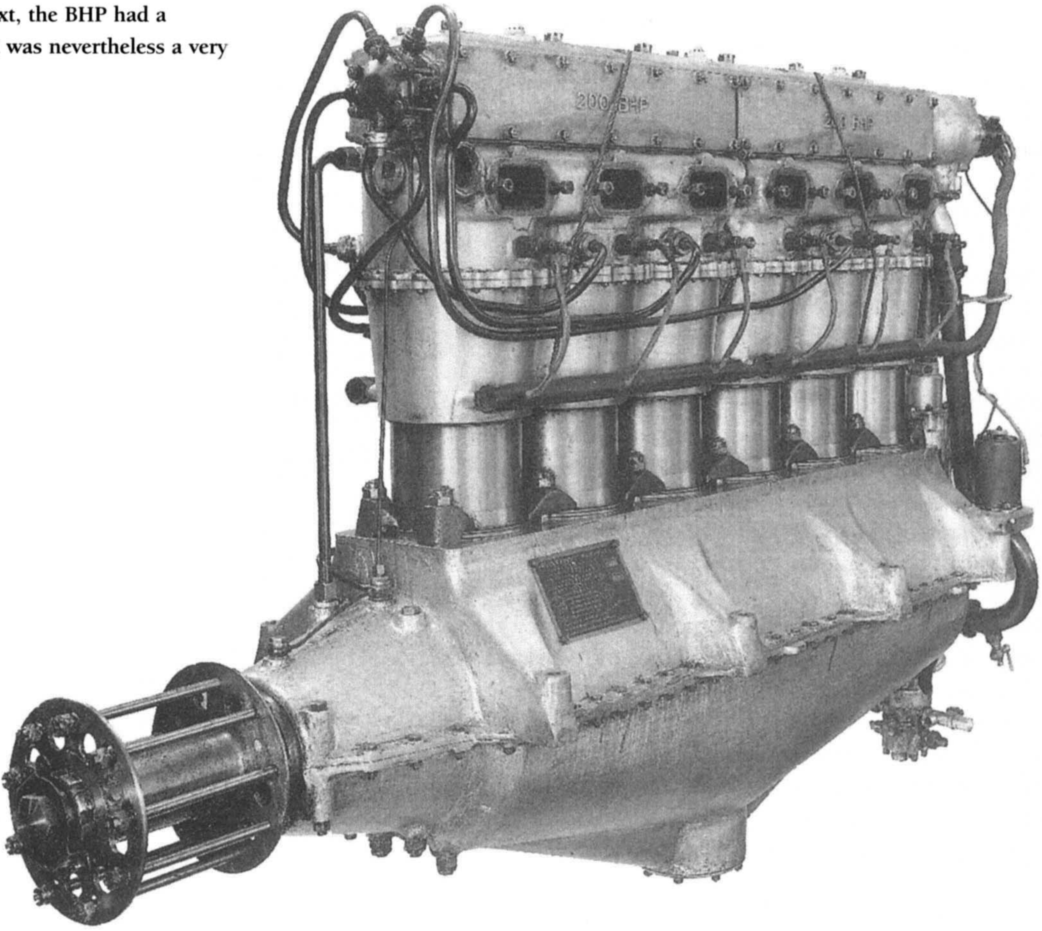
Bessonov (SOVIET UNION) Anatoli Alekseyevich Bessonov qualified at Petrograd in 1915, served in the air force, and by 1923 was working in the Ikar (Icarus) factory on turning the Liberty engine into the Soviet M-5. He then worked on or designed many engines, including the M-18 of 1927 (W-18 of 35.32 litres, 1,050 hp), M-19 of 1928 (V-12 of 27.47 litres, 700 hp), FED-3 and FED-24 of 1933–5 (X-24, 950–1,000 hp), MG-40 of 1933 (inverted four-in-line air-cooled, 145 hp), MM-1 (inverted six-in-line, 300 hp), and the massive 36-cylinder M-300 of 1941, rated at 3,000 hp.

BHP (UNITED KINGDOM) In 1916 Frank B. Halford, by this time a captain in the AID (Aeronautical Inspection Directorate) at Farnborough, was sent to the Beardmore company to develop their six-in-line (Austro-Daimler) to give 200 hp. He



Weighing 606 lb and rated at 180–185 hp the Benz IIIa was one of the most important German First World War engines. The propeller flange is on the left, the centrifugal water pump high on the right, and the twin updraught carburettors can be seen feeding the two distribution manifolds.

As described in the text, the BHP had a chequered history but was nevertheless a very important engine.



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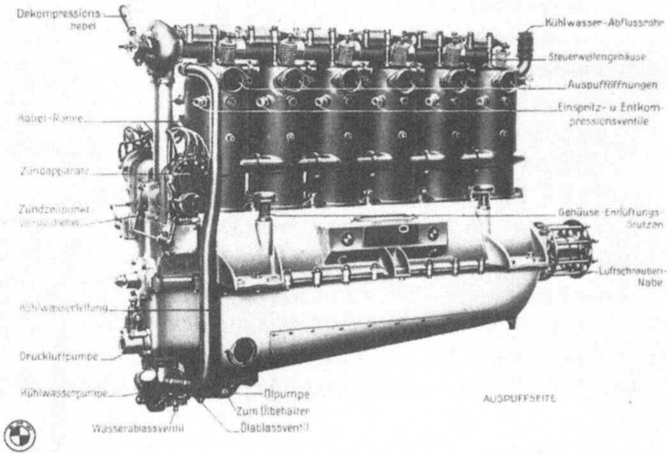
set up an experimental shop in the nearby Arrol-Johnston car works at Dumfries, and within six months was running the prototype BHP (Beardmore–Halford–Pullinger, but having the additional connotation of brake horsepower). Larger than the Beardmore, it had cylinders 5.7 × 7.5 in, giving capacity of 1,148 cu in. Each was made up of a closed-end steel liner threaded over its whole length (Halford copied the Hispano) into a massive cast aluminium barrel to which the cast-iron poultice-type hemispherical head was bolted. On the outside was a welded steel water jacket terminating well above the crankcase. Weight was 690 lb, and rating 236 hp at 1,400 rpm. The prototype ran in June 1916, and despite the several unsatisfactory features showed fair reliability. The same engine was installed in the prototype Airco DH.4 which flew on 5 August 1916. The 42.91 in height of the BHP resulted in an unsightly step in the fuselage top line, the aircraft having been designed for the Beardmore. Flight test results were good, but the BHP needed modifications before it could go into economic production. Various changes, all of a mechanical nature concerned not with performance but with facilitating manufacture, were organised at the Siddeley company and took until spring 1917 to complete.

By this time the BHP was being built by both Galloway Engineering and by Siddeley. The first batch of BHP engines was received by Airco for the DH.4 in July 1917; it was then found that the engine mountings had been changed, unknown to Airco, and the aircraft production line had to be altered. The DH.4 was powered by almost every high-power water-cooled engine on the Allied side, but at least 220 had the BHP in a neat installation with a straight top line and close rounded cowling. Only a handful of Galloway Adriatics were delivered, one being fitted to the prototype DH.9 in July 1917.

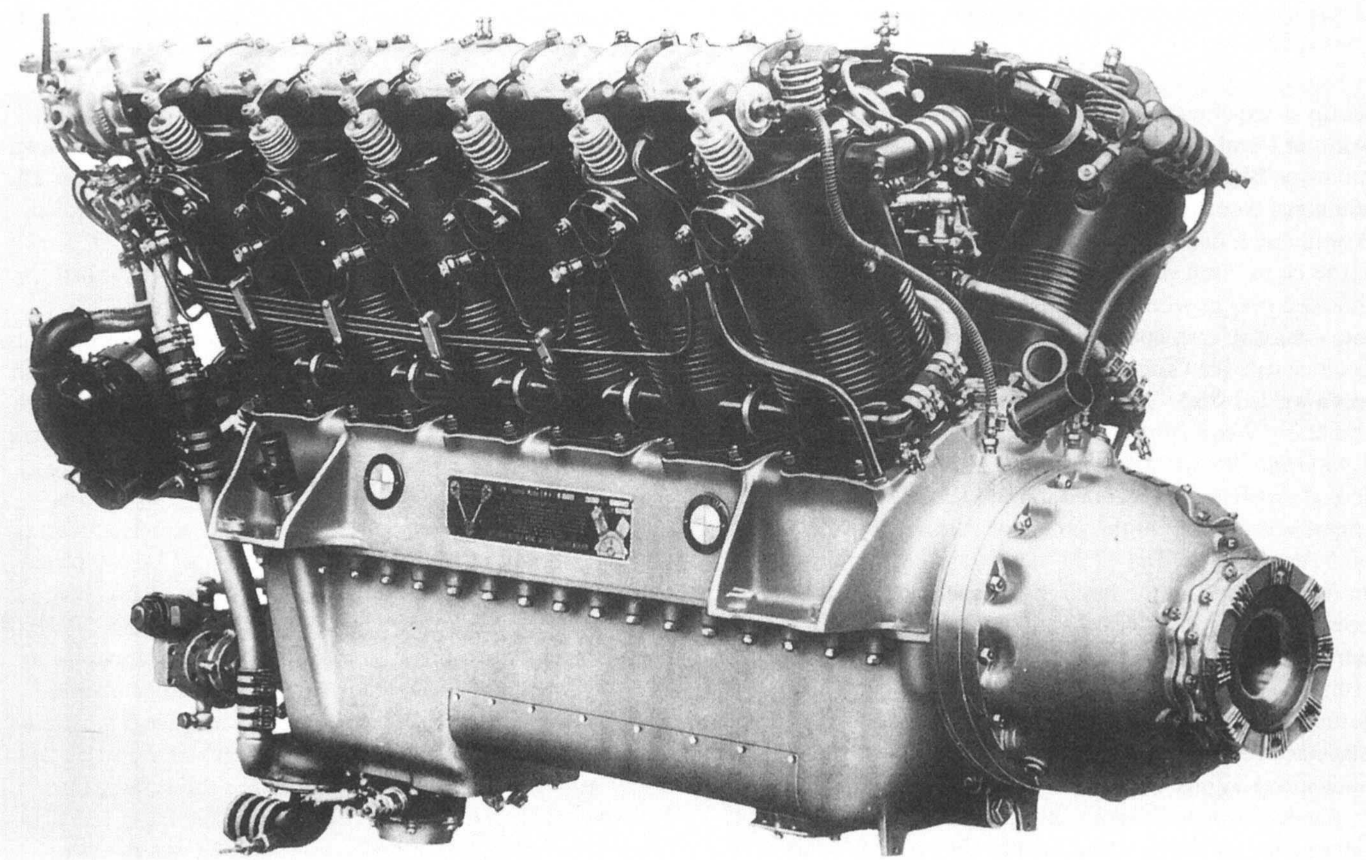
The DH.9 had been planned as the standard tactical bomber of the RFC, and its selected engine was the BHP. Such was the importance attached to the programme that in January 1917 Major F.M. Green was detached from Farnborough to serve as chief engineer (aero) of Siddeley-Deasy, which was tooling up to build the engine at ten times the previous rate of 25 per week. An order was placed for 2,000, to be completed by October 1917, by which time more were to be on order. Green's brief was to improve reliability and ease of manufacture, with minimum delay. He had no instructions to increase power, but was confident 300 hp could be obtained and this may have led to the exciting performance estimates for the DH.9. John Siddeley himself had no technical training but did have flashes of inspiration, and against the advice of his own designer, the famed S.D. Heron, he insisted that the BHP cylinder be redesigned completely. The result was an open-ended steel liner with a short thread at the upper end for attaching the cast aluminium head. This arrangement, also used on the contemporary Jaguar, was revolutionary but gradually became universal for poppet-valve engines. More serious, the welded water jacket was replaced by a single cast aluminium cylinder block. The redesigned engine was named Siddeley Puma. Production began as early as October 1916, at a rating of 300 hp, the weight being reduced to 625 lb. Most unfortunately, once engines were in mass production in January 1917 it was found that exhaust valves were burning out rapidly and that 90 per cent of the cylinder blocks were riddled with porosity or machining flaws. All that could be done was to derate the Puma back to 230–40 hp, and even then the faulty raw material caused numerous failures. A few DH.9s had the fully rated engine, officially named 290-hp Puma (High Compression), but most suffered with an engine which had become obsolete, deficient in power and inherently unreliable. For later Siddeley engines see Armstrong Siddeley.

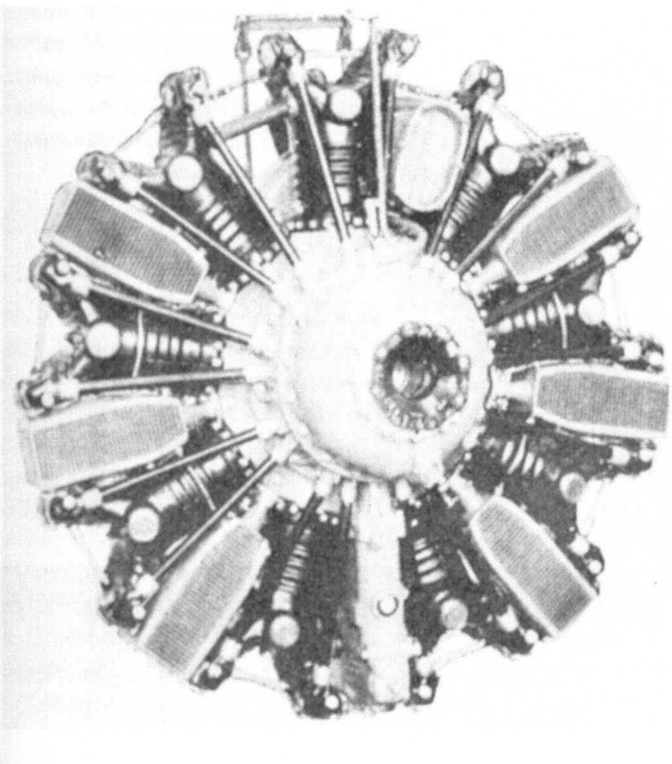
BMW (GERMANY) The Bayerische Motorenwerke AG (Bavarian Motor Works) was founded at Munich-Allach in 1916, and immediately began designing yet another water-cooled six-in-line. This progressed through 'I' and 'II' stages, with slight variations, and entered production in February 1917 as the BMW III, with steel cylinders with welded water jackets with bore and stroke 150 × 180 mm and capacity



Designed near the end of the First World War, the BMW IIIa was a fine modern engine that led to many others. Note the twin six-cylinder magnetos, the vertical cooling water pipe from the pump under the rear of the crankcase, and the decompression lever at the rear of the camshaft drive box. (Original BMW training manual).

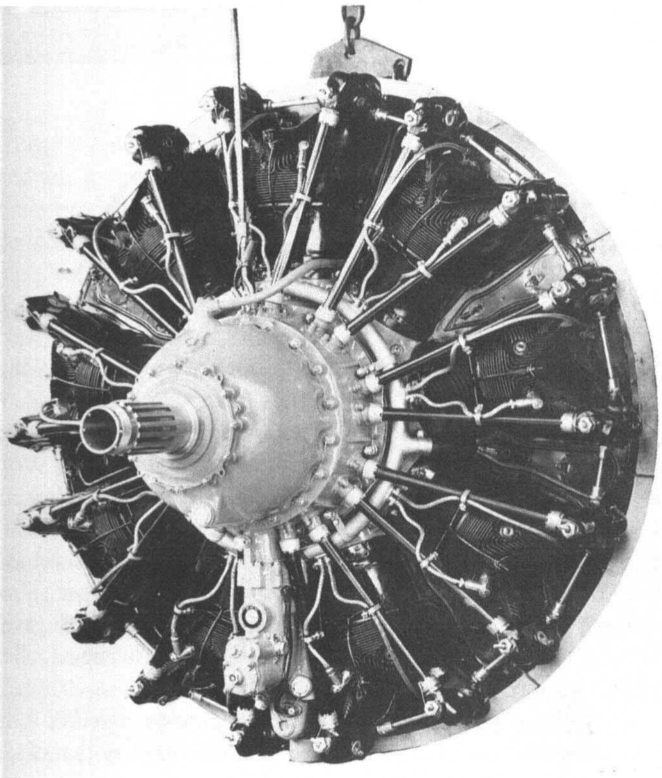
One of the most important engines of the inter-war period, the BMW VI was further developed in the Soviet Union as the M-17 and made in vast numbers (total 27,534). The Munich-built engines played a key role in Hitler's first generation of warplanes.





The supercharged BMW Lanova 114 V-4 was a four-stroke diesel of 1938. It was a water-cooled radial, installationally interchangeable with the BMW 132 series.

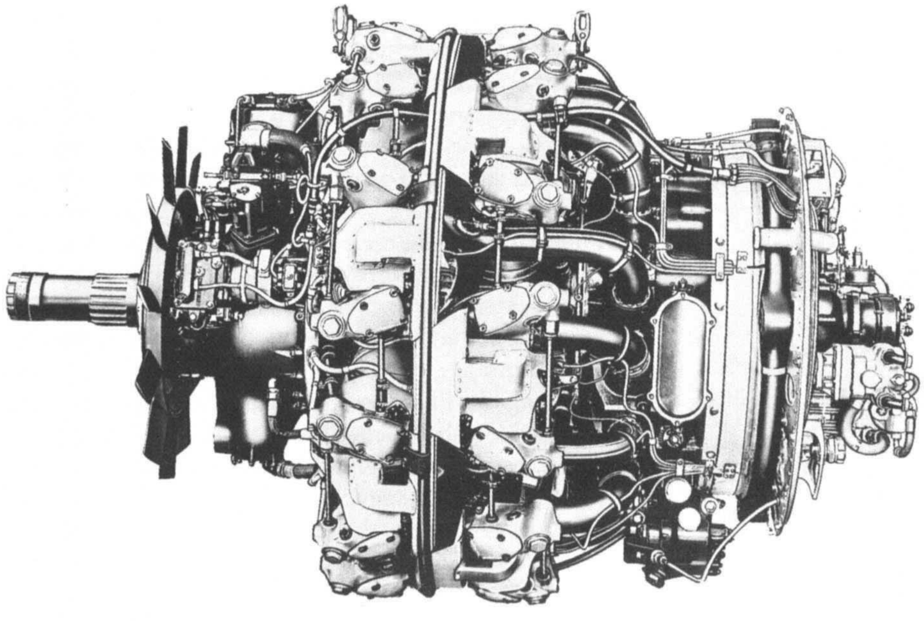
The BMW 132 was distantly descended from Pratt & Whitney's Hornet. This wartime 132 Dc powered several Luftwaffe types.



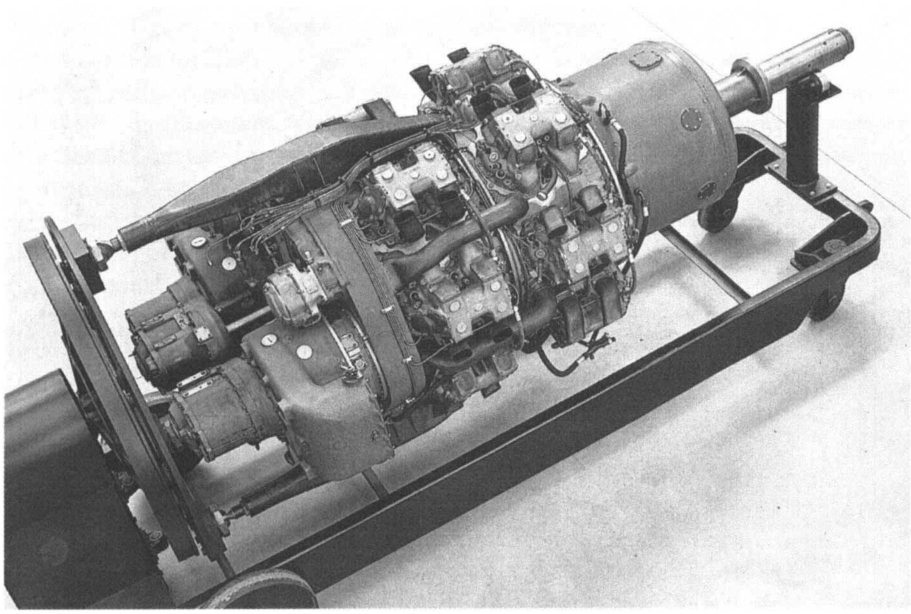
19.08 litres. Almost all the production engines were deliberately designed with high compression, typically 6.4, taking advantage of the relatively high octane number (not then numerically understood) of the benzole-blended fuel. Run at full power at sea level the engine would have blown apart, so the throttle was gated and only opened progressively as the aircraft climbed, reaching fully open at 2 km (6,560 ft) or more. Often the pilot had three throttles, one being opened fully for take-off and the other two opened slowly in sequence. Take-off power varied between the usual figure of 185 hp for the IIIa and 220 hp in strengthened versions, in each case at a modest 1,400 rpm.

After the war the BMW company was able to keep its design team, headed by Helmut Sachse, occupied in a series of water-cooled engines which gradually assumed a dominant position in Germany and were licensed to other countries. The BMW IV was a six-in-line with greater capacity than the III and was typically rated in 1921 at 250 hp. The BMW V of 1926 was a V-12 broadly equal to two IIIa engines, rated at 360 to 420 hp. The BMW VI and VII also appeared in 1926, and were V-12s equivalent to a pair of BMW IVs, with the same large-size cylinder (160 × 190 mm) and capacity 46.95 litres. Both began life at a modest 420–40 hp, but the former was intensively developed and built in increasing numbers for a growing proportion of Germany's civil transports and the first generation of Luftwaffe warplanes. Adopted as the standard V-12 of the Soviet Union in succession to the M-5 Liberty it was designated M-17, and subjected to independent development, the 17F being rated at 715 hp. The BMW engines were distinguished by a 'z' suffix denoting compression ratio, the most important versions being the 660-hp 6z and, for military use, the 7.5z rated 750 hp. At least 9,200 BMW VI engines were built in Germany, terminating in 1938, with Soviet M-17 output being considerably greater. In addition, the Soviet Mikulin bureau (*qv*) developed the BMW VI further into the monobloc AM-30 series.

At one time BMW was purchased by BFW (Messerschmitt), which changed the name to BMW Flugmotorenbau GmbH. Development broadened in 1927 to embrace air-cooled radials, the first production type being the small BMW X and Xa, with five cylinders 90 × 92.5 mm (2.93 litres), rated at 68 hp. In 1929 the company decided it could do better by purchasing a licence from Pratt & Whitney for the Hornet, and by the end of that year the BMW 114 had been developed and run, with cylinders almost identical to the US engine (155.5 × 162 mm, 27.7 litres) but with direct fuel injection. This remained a research and development engine, and in 1937 Dr Schwager's team produced the BMW-Lanova 114 four-stroke diesel version, rated 650 hp at 2,200 rpm, with liquid-cooled cylinders and radiators arranged between them at the sides. Production centred on the refined BMW 132, initially with a float-chamber carburettor. By 1945 total deliveries of 16 production versions exceeded 21,000, the 132A, E and H being the main float-chamber models and the Do, Dc, F, J, K, L, M, N, T, U, W, Y and Z having (usually Bosch) direct



The compact BMW 801 was by far the most important radial in Hitler's Luftwaffe, and generally regarded as an unbeatable engine at low altitudes. This view shows the BMW 801A, with cooling fan and oil return pipes across the top of each cylinder.



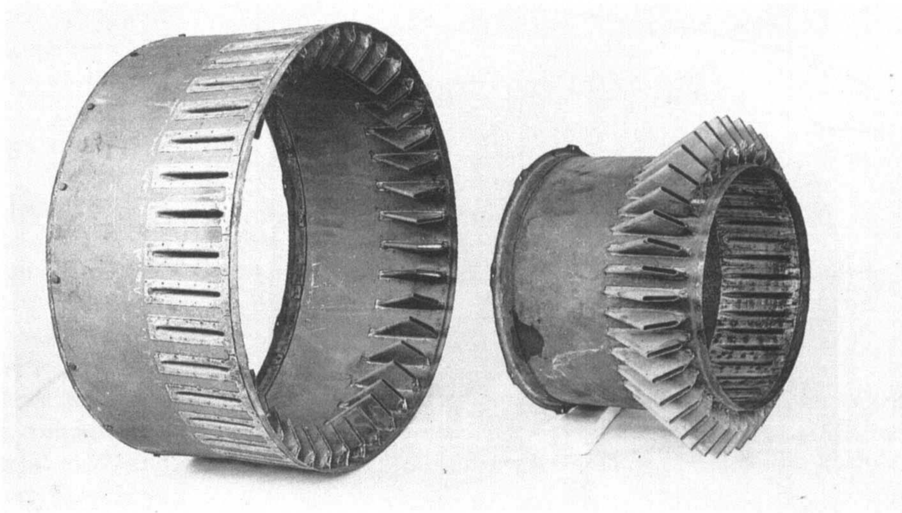
The restored BMW 803, photographed before the injection pumps and ignition harness were added. It is now in the Deutsches Museum, Munich.

injection. Wartime 132T output was assigned to French companies. Most models differed only in propeller and supercharger gear ratios. The take-off powers varied from 725 hp for the A to 970 hp for the wartime K and M.

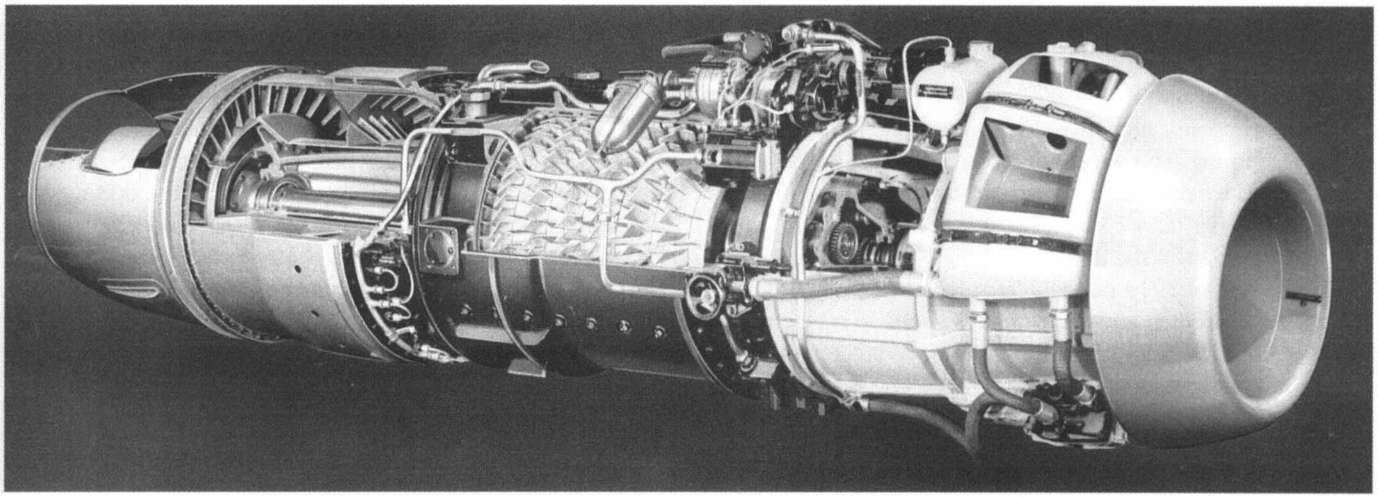
Prototypes only were made of the BMW 116 of 1932, a neat inverted V-12 with cylinders 130.2 mm square (capacity 20.6 litres), rated at 600 hp. More important was the decision of Hitler's RLM (Air Ministry) in 1935 to fund two high-power radials, one from BMW and a competitor engine from Siemens (Bramo). The latter company was taken over by BMW in 1939, bringing in valuable engineering talent, but it was under Sachse's direction that the 1935 engine went ahead as the BMW 139. This was two BMW 132s on a single crankcase, giving an 18-cylinder engine of 55.44 litres, which ran in 1938 at the design power of 1,550 hp. The 139 powered the prototypes of the Fw 190 and Do 217, but never entered production because of the promise shown by the more compact and fundamentally newer BMW 801, first run a few months after the 139. With only 14 smaller cylinders (156 mm square, 41.8 litres) the 801 was designed to the same power as the 139. All production versions had a Deckel 14-plunger injection pump and a *Kommandogerät* (control unit) which gave the pilot automatic single-lever control of the entire engine, all variables being governed to their optimum settings.

Most 801s were built as a complete engine-change unit which, for the first time, reduced installed drag below that of

Inner and outer combustor flame tubes of a BMW 003A. Design, materials and quality control were just adequate to put large numbers of jets into the sky.



When the BMW 109-003 was an active programme there was no time to make a sectioned display exhibit. This 003E-1 was constructed in the late 1950s. The E was the final production version for the He 162, similar to the A-1 but with a 30-second boost rating of 2,028 lb.

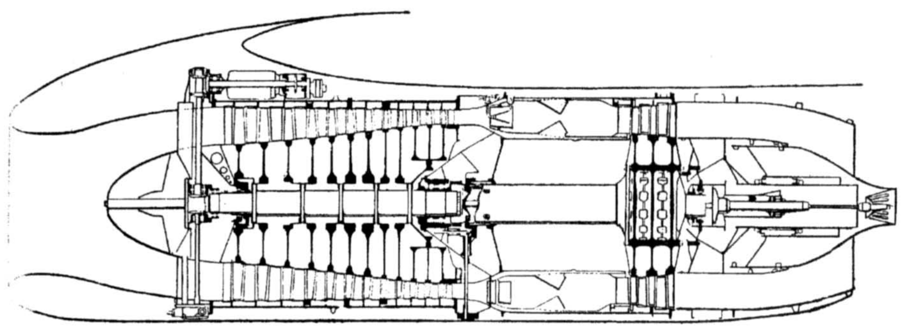


an equivalent liquid-cooled engine. The cowl fitted very tightly, and was pressurised by a front fan driven at roughly three times propeller speed, the air escaping to the rear through a peripheral slit around which, in most installations, the exhaust pipes were grouped to give ejector thrust. The oil cooler was inside a reverse-flow armoured ring round the front of the cowl. The 801A went into production in 1940 at 1,600 hp for a total powerplant weight of 2,669 lb, and later models included the highly boosted E of 2,000 hp and various turbocharged variants culminating in the 801TQ rated 1,715 hp at 12 km height. Total production exceeded 61,000 engines.

First run in 1940, the BMW 802 was broadly an 18-cylinder 801, with advanced and novel features. Prototype rating was 2,400 hp, but development was abandoned in 1942. By this time design was well advanced on one of the most powerful aviation piston engines, the BMW 803. This had 801-size cylinders arranged in two 14-cylinder radial units back-to-back to give a 28-cylinder four-bank radial; moreover, the cylinders were liquid-cooled and arranged in in-line pairs, each pair with a common head and camshaft. The front 14-cylinder unit drove the front coaxial propeller, while the drive from the rear unit to the rear propeller was via seven shafts passing between the forward banks of cylinders. Weight of the prototype was 2,950 kg and rating 4,000 hp, or a continuous output of 2,550 hp at 39,370 ft. Amazingly, in 1976 a complete 803 was at last recognised abandoned in California in a terrible condition. After 12 years of negotiation it was returned to BMW, where it has been lovingly restored.

Gas turbines

BMW claimed to have 'begun work on jet propulsion' in 1934. The substance of this claim may refer to the start of research on turbosuperchargers for piston engines under Kurt Loehner. This provided a valuable basis of experience, mostly adverse, on high-temperature turbines. In September 1938 Hans Mauch, of the RLM, visited BMW, Bramo, Daimler-Benz and Junkers to attempt to interest them in gas turbines and jet propulsion. The first two showed interest, BMW because of its turbine experience and Bramo because Ernst Udet was



The BMW 109-018 turbojet was just being assembled as the Allied troops reached Munich-Allach. This was an ancestor of the French Atar.

threatening them with closure. Bramo's engineering manager Bruno Bruckmann, and head of research Hermann Oestrich, doubted their ability to produce a powerful and efficient gas turbine. Instead they studied the prospects for increasing aircraft flight Mach number by using a piston engine to drive a multi-blade ducted fan similar to recent ducted fans such as Dowty-Rotol's. A small pattern was flown on an Fw 44 in October 1938, with encouraging results, and in early 1938 an ambitious power unit was tested at DVL Göttingen comprising a Bramo Twin Fafnir driving a large variable-pitch ducted fan with afterburning. This gave results far below calculation, and was dropped when DVL predicted ordinary propeller efficiencies better than 75 per cent at 900 km/h (which were just about being realised 60 years later).

By the start of 1939 Bramo's team reluctantly decided to go flat-out on a turbojet, and Bruckmann's efforts to merge with BMW (to avoid total shutdown) bore fruit, collaboration at the technical level from October 1938 being followed by the acquisition of Bramo in July 1939 with the name BMW Flugmotorenwerke. The original BMW team at Munich-Allach had already launched itself on a two-stage centrifugal turbojet, while the former Bramo team at Berlin-Spandau opted for what seemed the optimum engine, an axial counter-rotating unit smaller and lighter for a given thrust than any axial or centrifugal. In December 1938 this was placed under RLM contract as the 109-002 (all jet/rocket engines were prefaced by 109). To provide experimental data quickly a simpler axial turbojet was also ordered as the 109-003, using Loehner's turbine from the centrifugal engine.

The first BMW 003 ran at Spandau in August 1940, using a six-stage compressor designed by Encke of the AVA with a pr of 2.77, an annular combustor which held overall diameter to 670 mm, and Loehner's turbine with hollow blades to operate in a gas temperature of 900°C. It was soon realised that this temperature was very optimistic, and that almost every part of the 003 was full of problems. From September 1940 a new seven-stage compressor was designed with NACA blading and 30 per cent greater airflow, as well as a different turbine and fuel burner, of which there were 16. The revised engine, the 003A, reached 550 kg thrust on test in December 1942, compared with the previous 260 kg. Meanwhile, even the original 003 had been coaxed to 440 kg, and two of these were cleared for flight in November 1941 and sent to Augsburg to be installed in the Me 262 V1. Still with its Jumo 210 in the nose (a wise precaution) this aircraft flew on 25 March 1942, both BMW turbojets quickly flaming out.

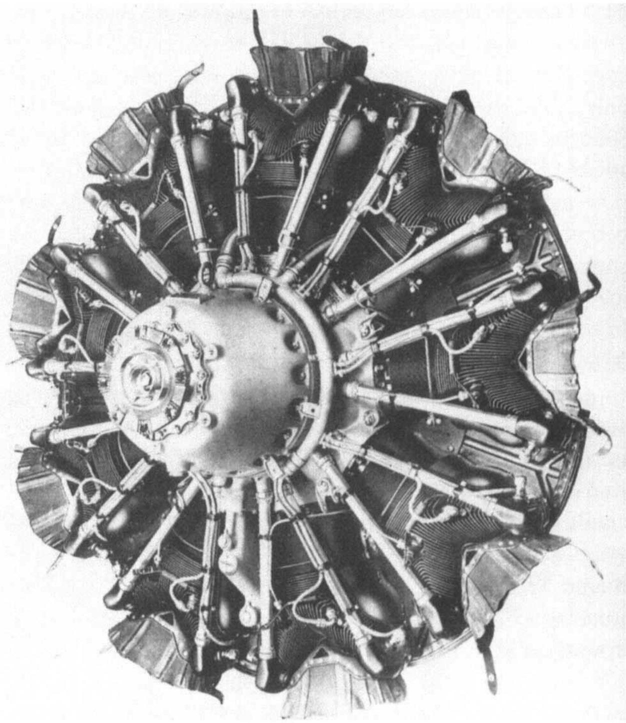
Hans Rosskopf, chief designer at Spandau, completed the drawings for the pre-production 003A-0 in September 1942, and most of the more serious faults were cured in the first half of 1943, though an A-0 did not fly until 17 October of that year, under the nose of a Ju 88A-5. By late 1943 the 003A was lifed at 50 h, giving a take-off thrust of 800 kg (1,760 lb); in the longer term the RLM believed it could equal the thrust of the bigger and more complex Jumo 004B. As it offered greater promise the RLM put enormous effort behind the 003A, deliveries reaching 100 by August 1944 and 1,000 by 27 September. About 3,500 had been produced by the end of 1944, most of them never reaching airframe plants (He 162A production alone was to reach 2,000 per month).

The 003C with a high-efficiency Brown-Boveri compressor ran just once, in May 1945; it was then taken over the border into Austria and hidden in a haystack. A month later Bruckmann visited the spot with Sir Roy Fedden, and the 003C was flown to Northolt, dismantled without metric tools and taken up in the lift to Fedden's office in Thomas Cook's building in Berkeley Street. As for the redesigned 003D with eight-stage 4.9 pr compressor and two-stage turbine, this was even less developed. The 003R, an 003A packaged with a BMW 718 rocket engine with sea-level thrust of 1,225 kg, did reach the flight-test stage in the Me 262C-2b. The bi-propellant 718 was dangerously temperamental, but on the one flight test in March 1945 the pilot was afraid the flaps and gear would be torn off before he could complete retraction; the 262 went steeply to 6 km in 50 s, the rocket propellants then being exhausted, and coasted on up to 8 km.

The BMW 109-028 was launched in February 1941 as a turboprop to give 8,000 ehp at 800 km/h at 7.2 km, with 12-stage compressor, 24-burner chamber and four-stage turbine. For the Ju 287 the corresponding turbojet, the 018, with a three-stage turbine and rated at 3,400 kg static thrust, was initiated in 1943. The 028 was never completed; the 018 was almost ready for test by December 1944 but was never run because it could be seen to have no influence on the war.

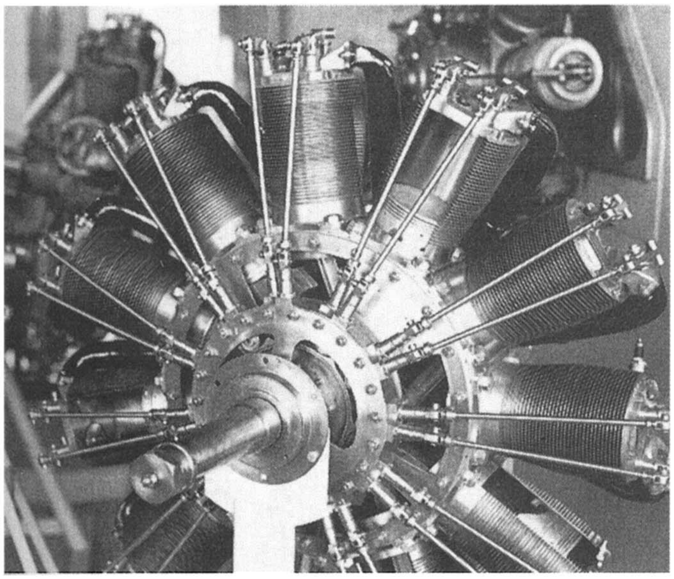
In 1957 BMW began making Lycoming piston engines, while designing a small turboshaft engine, the 6012. Rated at 100 hp, this led to the 250-shp 6022 turboshaft and 8026 turbojet of 121 lb thrust. In 1990 a 50/50 company named BMW Rolls-Royce was established. Further details are given under Rolls-Royce Deutschland.

Boeing (USA) This famous company set up a propulsion department to do gas turbine research in 1943. Soon it was designing hardware, the company assigning type numbers 500–600 for the results. The numbers did not get beyond 502, but No. 502 sustained a useful programme which was so diverse the company formed an Industrial Products (later Turbine) division. First to run, in 1946, was the Model 500 turbojet, with a single-sided centrifugal compressor outstanding for its day, with pr of 4.25 at 36,000 rpm, thrust being 180 (later 210) lb, there being two combustors and a ine-stage turbine. By adding a free power turbine the Model 502 turboshaft/turboprop was born, initially with an output of 270 hp. This found many customers and developed in power to 300 and later 365 hp in major drone-helicopter applications, with Army/Navy designation T50, other models going up to 500 hp. Output reached 500 by 1956 and about 1,600 at completion in April 1968. Rights were then sold to Steward-Davis Inc. Basically the same engine powers the Swedish S-type tank.



Bramo's Fafnir was taken over by BMW and eventually ousted the parent firm's own Type 132. This is a Fafnir 323AQ of 1,000 hp.

Bramo (GERMANY) The Siemens-Schuckert Werke, part of the giant Siemens electrical group, produced airships, combat aircraft and numerous rotary engines before and during the First World War. After building licensed Gnome engines in 1911 the Siemens und Halske subsidiary developed the Sh 1 contra-rotating rotary in 1914, the crankshaft rotating one way and the cylinders the other, both being geared to the engine mount and the propeller being on the crankshaft. The Sh 1 had nine Monosoupape-type cylinders 124 × 140 mm, each half of the engine rotating at 800 rpm, the output being 100 hp. About 180 Sh ls were built in 1916–17, followed by larger numbers of the Sh 3 and 3a. These had 11 similar cylinders and thus capacity of 18.6 litres. The Sh 3 was rated at 160 hp, each half turning at 900 rpm, and the 3a delivered 240 hp.



Visitors to London's Science Museum can gently rotate this Siemens Sh 3 (see Bramo) and will eventually fathom out how the 11 cylinders go one way and the crankshaft the other.

By 1921 Siemens had completed prototypes of two sizes of static radial with sound but pedestrian features, using seven aluminium cylinders with screwed-on heads and steel liners and the two valves in line, exhaust at the rear. The most important production engines were the Sh 5 of 1921, with 100 × 120 mm cylinders and rated at 77 hp, the Sh 11 of the same 6.6-litres size but rated at 96 hp, and the Sh 14 of 1931 with bore increased to 105 mm (7.1 litres) and rated at 113 hp. These led to the Sh 14A of 1934 with bore of 108 mm (7.7 litres) and rpm raised from 1,720 to 2,200 to give 160 hp. This was still in full production when in 1936 the works at Spandau was reorganised as a separate company, Brandenburgische Motorenwerke GmbH, trading as Bramo. The Bramo Sh 14A powered such major types as the Bu 133, Fw 44 and He 72, output certainly exceeding 15,000.

In 1927 Siemens had purchased a licence for the Bristol Jupiter, and this continued in modest production until about 1935. This greatly influenced the first big Siemens engine, the Sh 20 of 1930, from which was developed the production Sh 20B with cylinders 154 × 188 mm, giving capacity of

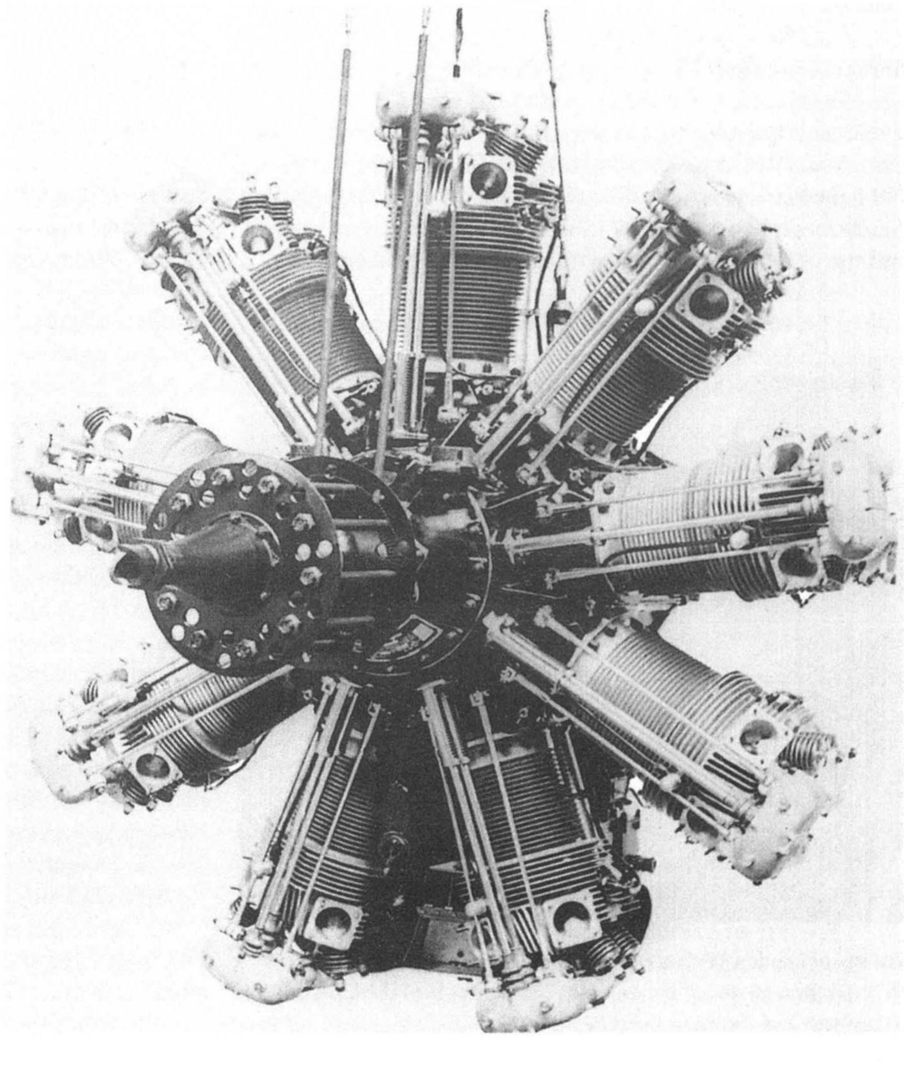
B

31.5 litres. This was larger than the Jupiter, because of the increased bore, yet even though stroke was reduced, the overall engine diameter was increased; and as maximum rpm were only 1,850 the take-off rating was only 540 hp. Undaunted, Siemens redesigned the Sh 20B to run at 2,500 rpm but with a stroke of 160 mm, reducing capacity to 26.82 litres, giving powers which started at 600 hp in 1933 and reached 760 hp two years later. A new numbering system was adopted, this engine being the SAM 22B, from 1935 called the 322B. It was made in many subtypes for early Luftwaffe use but was always troublesome and unpopular. Incidentally, in 1930 Siemens introduced sintered aluminium oxide spark plugs.

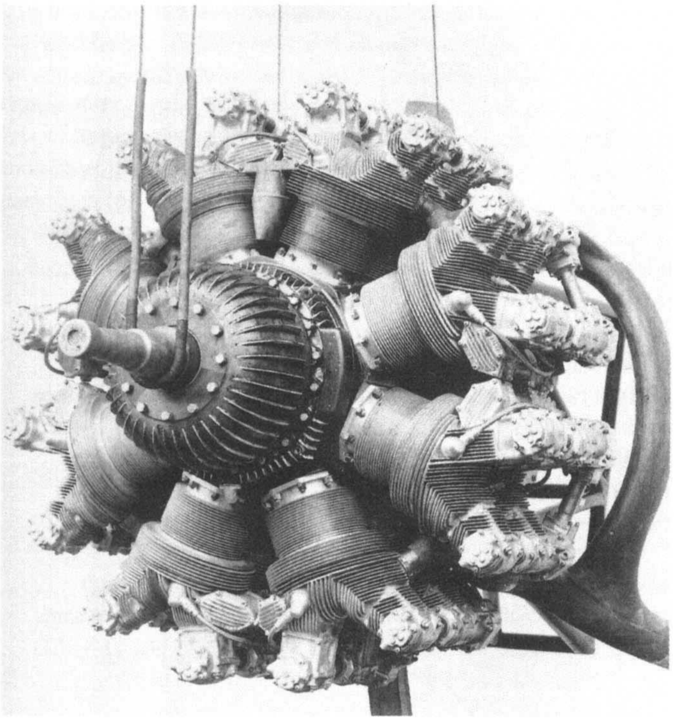
Continued refinement and the introduction of a two-speed supercharger and Bosch fuel injection resulted in the SAM 323, from 1936 called the Bramo 323 and named Fafnir. Cylinders were forged steel with valves at 35° in a head of Y-alloy, crankcase was aluminium and the rear cover and accessory gearbox, magnesium (Elektron). At least 14 sub-types of BMW Bramo 323 were produced in series, to a total of over 5,500, some types such as the Hs 126 and Fw 200C switching over from the BMW 132.

Nevertheless Udet told Bramo their output of about 100 Fafnirs a month did not justify official support, despite the fact that the RLM (Air Ministry) had previously been careful to maintain industrial competition. In 1935 it had ordered a new engine in the 2,000-hp class from Siemens, and when the company heard it might be closed it urgently rushed through prototype testing of this engine, the Twin Fafnir (but with only seven cylinders in each row), and was delighted to record 2,000 hp, in October 1938. BMW was still a long way from this power. The RLM did not relent, however, and merged Bramo into BMW, killing the Twin Fafnir. Production of the 323 Fafnir continued to 1944, the most powerful, the 323R2, being rated at 1,200 hp. Bramo's gas turbine history is dealt with under BMW (*qv*).

Bristol (UNITED KINGDOM) When Cosmos (*qv*) failed in January 1920 the Air Ministry was anxious to see the Jupiter continue, and applied pressure to the aloof and autocratic board of the Bristol Aeroplane Co. to buy the aero-engine assets. For £15,000 Bristol got Roy Fedden and his team of 31 engineers, five Jupiters and a mass of parts, drawings, patterns



One of the later Bristol Jupiters, with each cylinder equipped with a forged head with partially enclosed valve gear.

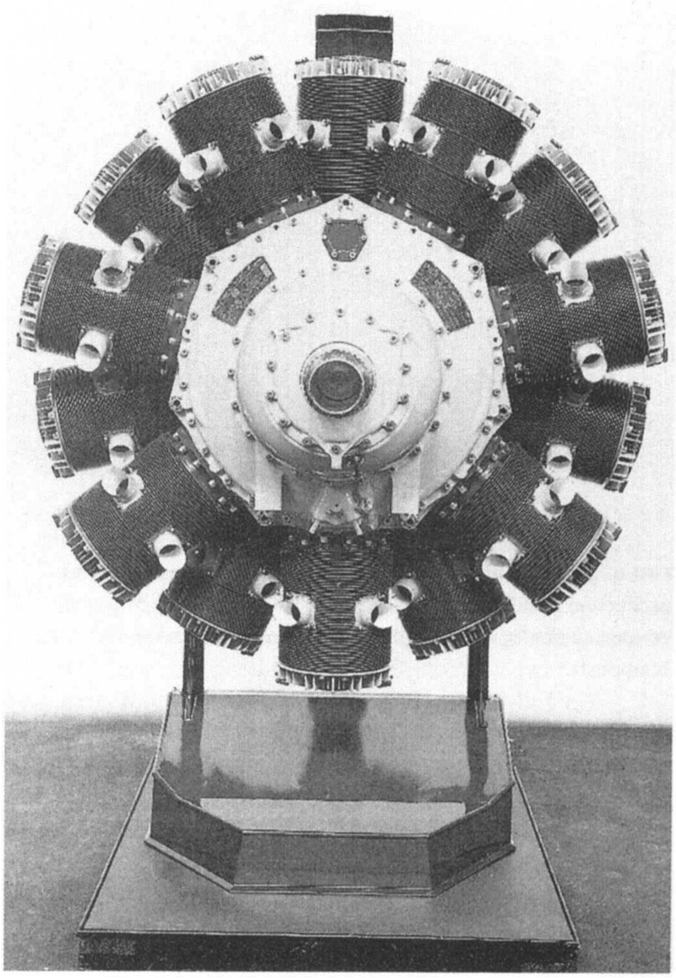


Bristol's 16-cylinder Hydra needed a centre bearing, despite its short and stiff crankshaft. Otherwise it was impressive.

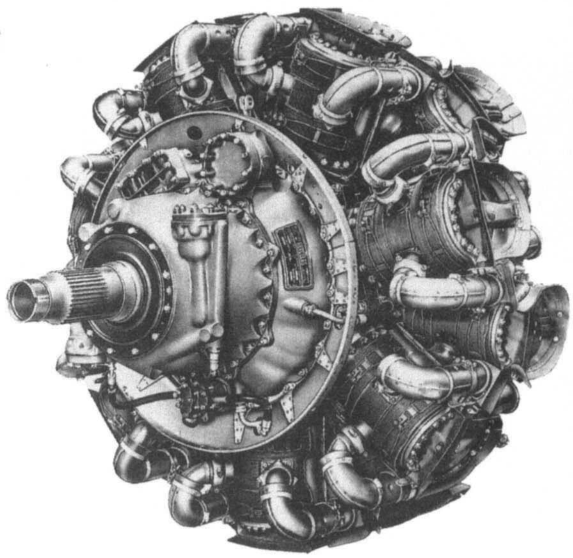
and tools, and a promised order for ten production engines. Fedden undertook to develop the engine in two years within a budget of £200,000. Sadly, the board did not include a single engineer and regarded Fedden as a mere employee; he, on his part, misunderstood their continued reluctance to put up money for his often optimistic schemes, and from the launch of the Engine Department on 29 July 1920 the lack of communication between Fedden and the board sowed the seeds of serious difficulty 20 years later.

After one year the total outgoings stood at £197,000 and the board decided at its next meeting it would close down the 'cuckoo in the nest' at the end of the year. But in September 1921 the Jupiter II, with auto-compensation for cylinder expansion on the valve pushrods, became the first engine to pass the severe new Air Ministry type-test, reaching 400 hp at 1,625 rpm, and Fedden obtained permission as a last straw to exhibit the Jupiter at the Paris airshow in October 1921. Here it created intense interest, as the only postwar high-power engine, and the famed Gnome-Rhône company purchased a licence. In December the Air Ministry began formal consideration of the Jupiter as its first new postwar engine for the RAF, and the vital order for 81 engines was signed in September 1923. It was a close-run thing.

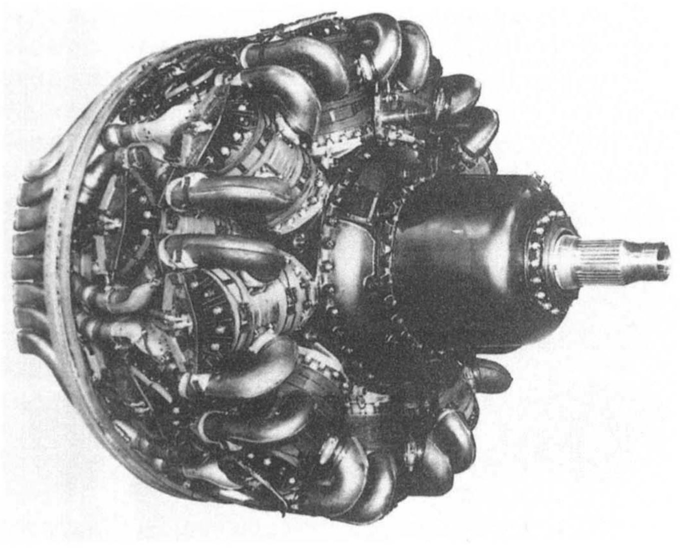
From then on, Fedden's insatiable drive forced the Jupiter to the very forefront, culminating after 10 years with 17 foreign licensees and a total of more than 7,100 Jupiters for at least 262 different types of aircraft. The Jupiter IV passed the British and French type-tests at 436 hp in March 1923. In November



The strangely clean appearance of the first Bristol sleeve-valve engines is evident from the Hercules of 1938. Rating was 1,375 hp.

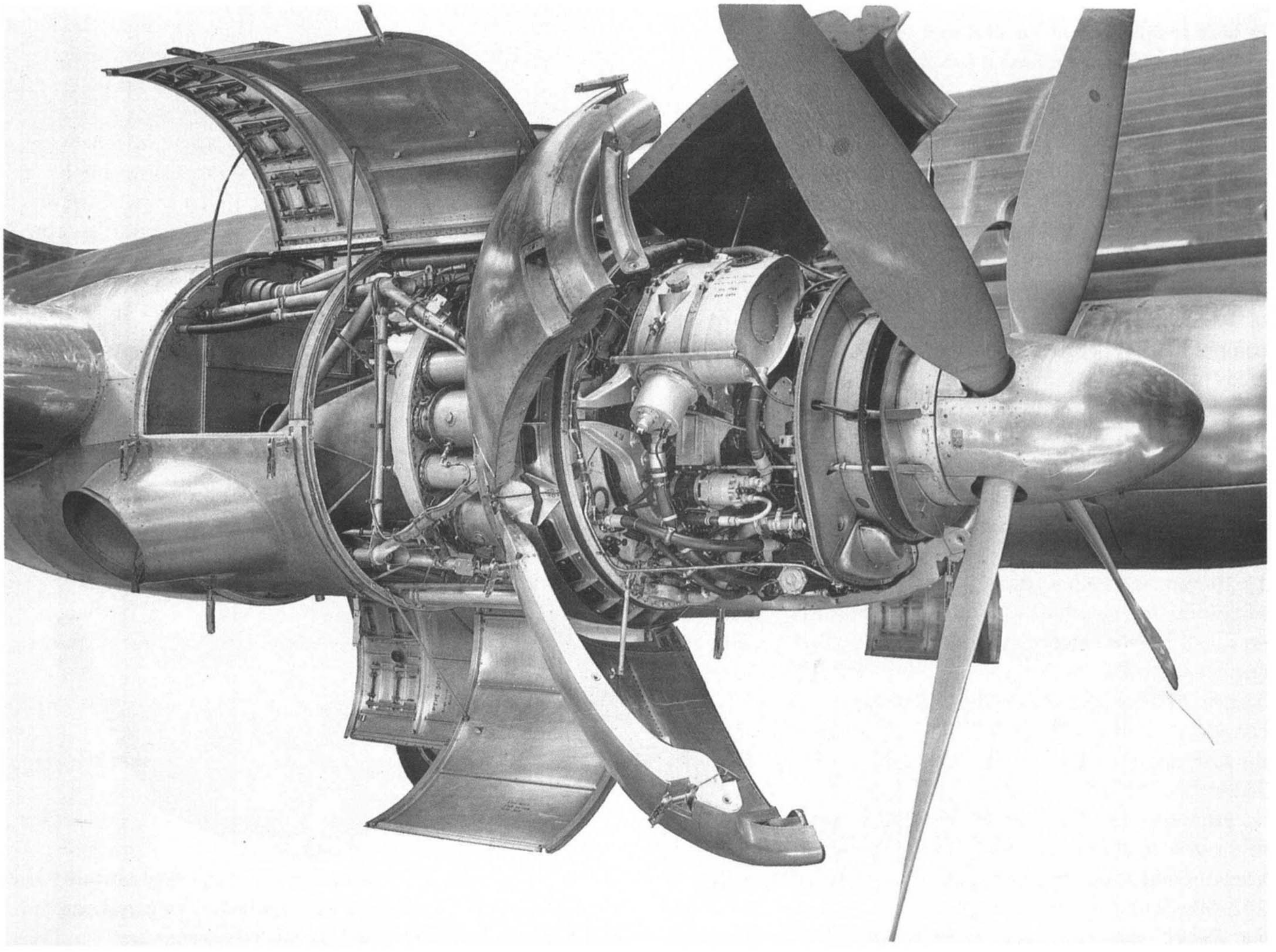


By 1945 the 'Herc' looked more cluttered; this is a 2,040-hp Mk 739 made under licence by SNECMA, mainly for the Noratlas.



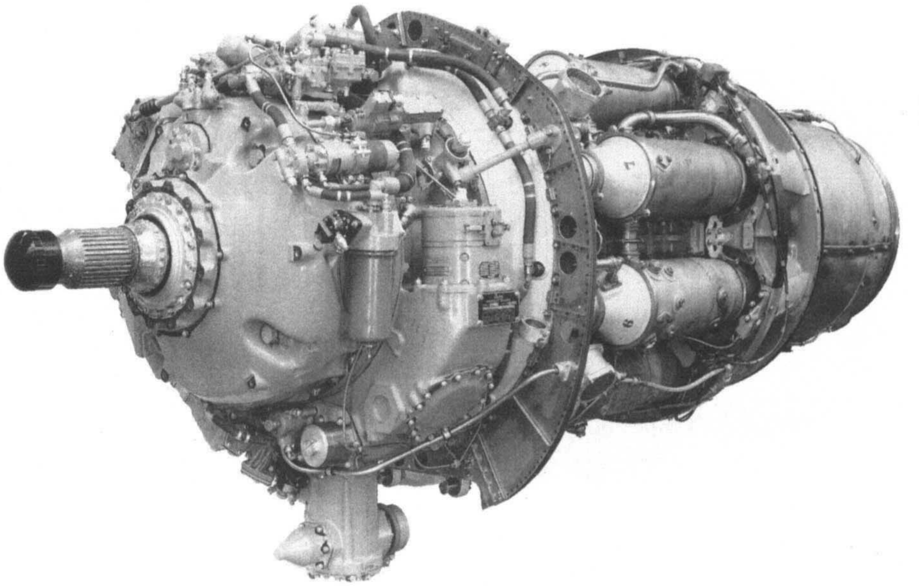
1923 the Mk V introduced a split crankshaft with maneton coupling and one-piece master rod with floating big-end. In June 1925 the Mk VI brought in a drop-forged duralumin crankcase and Bristol triplex carburettor, weighing 771 lb and rated at 480 hp. The VII added an outstanding geared supercharger, giving 460 hp. The VIII of 1928 introduced Farman reduction gearing, enabling the engine to run at 2,200 rpm with reduced vibration driving a larger propeller with higher efficiency. Forged screwed/shrunk heads replaced the old poultice head, such engines adding suffix letter F; the IX went to 525 hp at unchanged 5.3 compression ratio; and the supercharged and geared Jupiter X gave 530 hp at 16,000 ft, against some 220 hp at this height of the Cosmos Jupiter I. The HP.42 and other large airliners of 1929 used the Jupiter XFBM, with Bristol gas-starting operated from the cockpit.

Last of the great Bristol piston engines, the Centaurus went into production in this form in 1943 as the 2,520-hp Mk V, with rear exhaust stacks for close cowling and ejector thrust in the Tempest II.



The starboard outer Theseus turboprop of the Hermes 5, with everything opened. Britain was full of great technical achievements where 'the bottom line' was zero.

If only the Brabazon 2 and Princess had been cancelled earlier, 'Doc' Hooker would not have had to adhere to the reverse-flow layout in the Proteus turboprop. It was that very feature that delayed Britannia services from 1955 to 1957 and almost broke the Bristol company. This is a production Mk 765.



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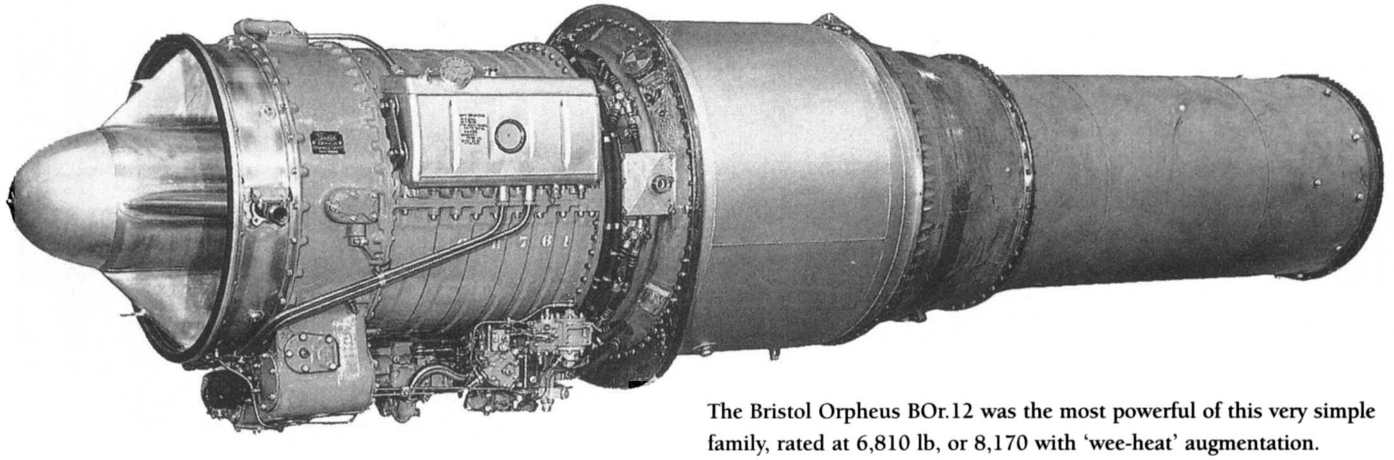
Other 1920s engines included the flat-twin Cherub of 1924 of 61 cu in capacity with ball and roller bearings for the crankshaft and big ends, increased in capacity to 74.9 cu in in 1926, raising power from 32 to 36 hp. The Orion, a turbocharged Jupiter VI, of 1926, was rated at 495 hp at 20,000 ft. The Mercury of 1926 was initially a short-stroke (6.5 in) Jupiter designed for Schneider racing, and giving 960 hp for a weight of 682 lb with diameter reduced from 53 to 47.5 in. The 200-hp Titan of 1927 had five Mercury-size cylinders, and the 300-hp Neptune of 1929 used seven similar cylinders. By 1929 the forged-head Titan was giving 240 hp, but most Titans were licence-built by Gnome-Rhône.

Originally called the Mercury V, the first Pegasus in 1932 restored Jupiter cylinder size (5.75 × 7.5 in) and capacity (1,753 cu in), but was mechanically improved throughout, with more and deeper cooling fins, enclosed valve gear driven by just two pushrods inside an oval tube, lighter reduction gear, and special automatic fuel and oil control systems, for rapid take-off from cold with enhanced power. The Draco of 1932, a Pegasus with direct injection, was soon dropped. By 1936 production Pegasus engines were rated at over 800 hp, and by 1939 this had risen to 1,065 hp on 100-PN fuel, for a weight of 1,110 lb. Pegasus production was completed in 1942 at about 17,000, 14,400 of these being delivered after October 1936. The shorter-stroke Mercury also came into production for fighters, the Mk IVA being cleared at 560 hp in 1931, in which year a IVS2 was tested at overspeed of 2,600 rpm giving 893 hp on 77-PN fuel. Fedden was the most important single driving force in the British industry for the variable-pitch propeller and 100-PN fuel, and the Mercury and Pegasus were the first British engines cleared for their use. The 1,520 cu in Mercury was rated in production at up to 995 hp at 2,750 rpm at 9,250 ft for a weight of 1,000 lb. Total production was 21,993, of which 20,700 came after 1936.

In 1931 a short-stroke (5 in) Mercury in a tight long-chord cowl increased the speed of a Bristol Bullpup 11 per cent compared with a Jupiter but remained a one-off. In 1927 Fedden planned a diesel of 1,000 hp, but this was not built; extensive flight testing was, however, done on the Phoenix, a version of the Pegasus which in 1934 set a diesel height record of 27,453 ft.

By 1926 Fedden was looking ahead to the next generation, and, unable to design an elegant twin-row engine with four valves per cylinder, picked the Burt-McCollum type of sleeve valve. The first research cylinder ran in 1927, and it was soon clear that sleeve valves would be such a stupendous task that an interim next-generation engine was designed. The Hydra, so named because it was double-headed, had 16 small (5 × 5 in) cylinders in eight pairs each with a common head with twin overhead camshafts. In 1933 it flew in a Hawker Harrier (biplane) giving 870 hp at a remarkable 3,620 rpm, but it needed a centre bearing and by this time 870 hp could be seen from the Pegasus and Mercury. Effort on sleeves was redoubled – mass-producing interchangeable sleeves proved a giant task which cost millions of pounds but it led to superb engines. With the benefit of hindsight the simpler answer might have been to fall back on just two poppet valves per cylinder and build big two-row engines, as did the firm's rivals.

The first complete sleeve-valve engine was the Perseus, the same size (5.75 × 6.5 in) as the Mercury. Run in July 1932, it was type-tested in the same year at up to 638 hp, flew services on Imperial Airways in June 1935, powered RAF No. 42 Squadron Vildebeeste IV torpedo bombers in 1937 and was subsequently delivered in quantity at 905 hp. The Aquila, with nine cylinders, 5 × 5.375 in, gave 500 hp in 1934 but did not go into production. The Hercules, with 14 Perseus cylinders giving capacity of 2,360 cu in, first ran in January 1936. The prototype gave 1,290 hp, and development continued on 87-PN fuel at 1,425 hp and 100-PN at 1,590 hp with



The Bristol Orpheus BOr.12 was the most powerful of this very simple family, rated at 6,810 lb, or 8,170 with 'wee-heat' augmentation.

improved oil-sludge centrifuges, closer-pitch cooling fins, fixed big-end bushes and crankshafts with Salomon vibration dampers. Neville Quinn transformed the previously poor supercharger inlet. Later marks had a steel head into which was shrunk a close-finned copper base for maximum heat emission. By 1945 Hercules production exceeded 57,400, most at 1,650 or 1,735 hp. Postwar military and civil marks gave 1,990 to 2,140 hp, many being licence-made by SNECMA, and the wartime HE.20SM was tested at over 2,500 hp on 125/165 fuel.

Planned as a successor to the Pegasus, the Taurus was run in November 1936. A compact engine with 14 cylinders, 5 × 5.625 in, capacity 1,550 cu in, and only 46 in diameter, the Taurus was type-tested in 1938 at 1,065 hp and produced in fair quantity for the Beaufort and Albacore at 1,130 hp. More important was the big Centaurus, with 18 cylinders, 5.75 × 7 in, giving capacity of 3,270 cu in. Planned for heavy aircraft, the first Centaurus ran in July 1938 and was type-tested in 1939 at 2,000 hp, but foolishly the importance of this engine was overlooked until 1943, despite the fact that the CE.4S prototype reached 421 mph in a Hawker Tornado in October 1941. In late 1942 the two-speed supercharged Centaurus was type-tested at 2,375 hp, and cleared for production – in an underground quarry at Corsham – as the Mk V and Mk XI at 2,520 hp. Many other versions followed for military and civil aircraft, most having a Bendix or Hobson/RAE injection carburettor and being rated at up to 2,810 hp with water/methanol injection. Post-war versions included the 2,625-hp Mk 661 for the Ambassador, 2,940-hp Mk 173 for the Beverley and 3,220-hp Mk 373 with direct injection into the cylinders. Before Fedden left the company in 1942 he had initiated construction of the Orion, with 18 cylinders, 6.25 × 7.5 in, capacity 4,142 cu in, to give 4,000 hp.

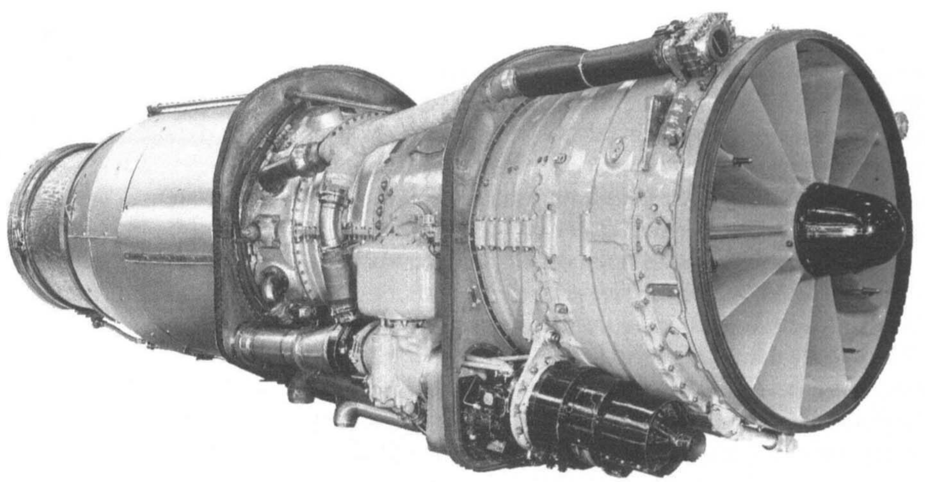
Gas turbines

Despite work on turbochargers from 1923, and a visit from Whittle in 1931, Bristol ignored gas turbines until December 1940 when Frank Owner began formal study of a turboprop in the 4,000-hp class to have fuel consumption at least as good as an equivalent piston engine, cruising at 300 mph at 20,000 ft (the lowest speed and height at which a turboprop was considered competitive). Soon this was thought too ambitious and the big engine was scaled down to become the Theseus, a 2,000-hp machine planned with a heat exchanger to increase thermal efficiency. This had a front annular inlet to an eight-stage axial compressor followed by a centrifugal stage delivering via eight axial pipes to the heat exchanger at the rear; here the flow was turned 180° to pass through eight combustion chambers arranged between the air pipes, the hot gas again being turned 180° to pass through the two-stage gas-generator turbine and independent single-stage power turbine driving the propeller gearbox, before going through the heat exchanger to the jetpipe. This complex arrangement resulted in a weight of 2,800 lb, 500 lb of this being the heat exchanger which took hot gas at 500°C through 1,700 stainless-steel tubes and delivered the incoming air at 300°C, saving a calculated 150 lb of fuel per hour.

The heat exchanger was not ready when the Theseus was first run on 18 July 1945; it gave persistent trouble when fitted five months later and was abandoned. In December 1946 the Theseus became the first turboprop to be type-tested, and eventually extensive flight development was done in Lincoln and Hermes aircraft, the Hermes 5 being powered by four fully engineered Theseus power units which impressed by their quiet running.

In September 1944 work began on a totally new 4,000-hp engine, named Proteus. It was planned for use in the Brabazon 2 and Princess, in each case in a coupled installation buried in the wing, fed from inlets in the leading edge. Thus the reverse-flow layout was deemed appropriate and retained, but in this case the air entered the engine towards the rear, passing between the combustion chamber delivery pipes and turning forward to enter the 12-stage axial compressor followed by two successive centrifugal stages, the intended pr being 9, with airflow 40 lb/s at 10,000 rpm. The high-pressure air then travelled back through the eight slim combustion chambers and out via

Bristol, then Bristol Siddeley and finally Rolls-Royce (but the same team throughout) took the Olympus from 9,140 to 40,000 lb thrust in 20 years. This is a 20,000-lb Mk 301 for a Vulcan B.2.



a two-stage compressor turbine and an independent single-stage power turbine driving the 11.4-ratio propeller gearbox.

To assist development the gas-generator section was built separately as a turbojet, named Phoebus, and this ran in May 1946 and flew in the bomb bay of a Lincoln. It did not even reach the design thrust of 2,540 lb and it was found that, far from raising pressure, the first centrifugal stage actually reduced it because of poor flow. It was therefore removed and replaced by a carefully profiled diffuser passage, though not before the first Proteus had begun testing on 25 January 1947. Results were very poor, and even after removal of the first centrifugal stage, giving a 5.35 pr, it seemed as if everything that could give trouble did so. Two Proteus 2s flew in a different Lincoln on 12 January 1950.

A year earlier Dr S.G. Hooker had joined the company and became chief engineer. His predecessor Frank Owner said to him 'I decided we should make the engine with the lowest fuel consumption in the world, regardless of weight and bulk. So far we have achieved the weight and bulk.' Hooker totally redesigned the Proteus, among other things using a two-stage power turbine of much higher efficiency, and the resulting Proteus 3, or 700-series, was 12 in shorter, 1,000 lb lighter, much more fuel-efficient and gave power increased from 2,500 to 3,780 shp. In production this was raised to 4,445 ehp.

To Hooker's relief the Brabazon and Princess were cancelled, but they left the engine with the reverse-flow layout which at the eleventh hour, as the Britannia was being delivered to BOAC, caused an irritating flame-extinction problem due to ice accretion. There was never any danger, and the problem could have been avoided by choosing a slightly different cruise height, but BOAC did all it could to magnify it, delayed acceptance two years, wrecked the Britannia sales prospects and very nearly broke Bristol financially. Subsequently the Proteus flew millions of trouble-free hours and pioneered the use of aero gas turbines for warships and electricity generation, respectively in 1958 and 1959. It also pioneered the use of precision-cast turbine blades, used on all subsequent Bristol engines.

Hooker designed a completely new turboprop, the BE.25 Orion, with a seven-stage LP and five-stage HP compressor, cannular combustor, single-stage HP turbine and three-stage LP turbine driving the LP spool and propeller. The Orion was flat-rated at 5,150 ehp to 15,000 ft, sea-level power being potentially about 10,000 hp. With specific fuel consumption of 0.39 it was a fine engine, but the market – mesmerised by jets – evaporated.

In 1946 Owner asked for studies of a high-compression turbojet for long-range bombers. The result was the first two-spool turbojet, with the HP turbine driving an HP compressor (Owner wanted a centrifugal but was persuaded to have an axial) via a hollow shaft through which passed the drive from the LP turbine to the LP compressor. The resulting BE.10 Olympus ran on 16 May 1950 at a design thrust of 9,140 lb; in fact on its first run Hooker took the throttle himself and deliberately banged it wide open to record a full 10,000 lb. From the start the Olympus was a superb engine, the antithesis of the Proteus, and the Olympus-Canberra testbed soon reached the record height of 63,668 ft, followed by 65,876 ft. The Mk 101 for the Vulcan B.1 had a six-stage LP spool, eight-stage HP, cannular combustor with 10 burners and single-stage HP and LP turbines. It entered production at 11,000 lb in 1955. The Mk 102 added a zero-stage on the LP spool to increase overall pressure ratio from 10.2 to 12, raising thrust to 12,000 lb. The Mk 104 introduced improved blade material which enabled temperature and rpm to be increased, giving 13,500 lb. All Vulcan engines were brought to this standard at overhaul.

In 1956 Hooker authorised a redesign of the Olympus with much greater airflow (roughly 240 instead of 180 lb/s), while maintaining the existing diameter and pr of 12 and yet using only five LP stages and seven HP. This Olympus 6, designed originally for 13,500 lb, began running in late 1956 at 16,000 lb, soon raised to 17,000. It was intended for the G.50 thin-wing Javelin, and competed for the Vulcan B.2, but the Ministry (in its wisdom) refused to support it and instructed Avro to redesign the B.2 for the rival Conway. Sir Reginald Verdon

Smith showed typical nerve in offering to develop the new Olympus at company expense and sell it in production at the same price as the Conway. It proved a massive success, entering service as the Mk 201 at 17,000 lb in July 1960, later becoming the Mk 202 with modified bleed systems. A zero-stage was then added to yield the Mk 301 rated at 20,000 lb, which replaced many 201s in Vulcans from May 1963. For later versions see Bristol Siddeley.

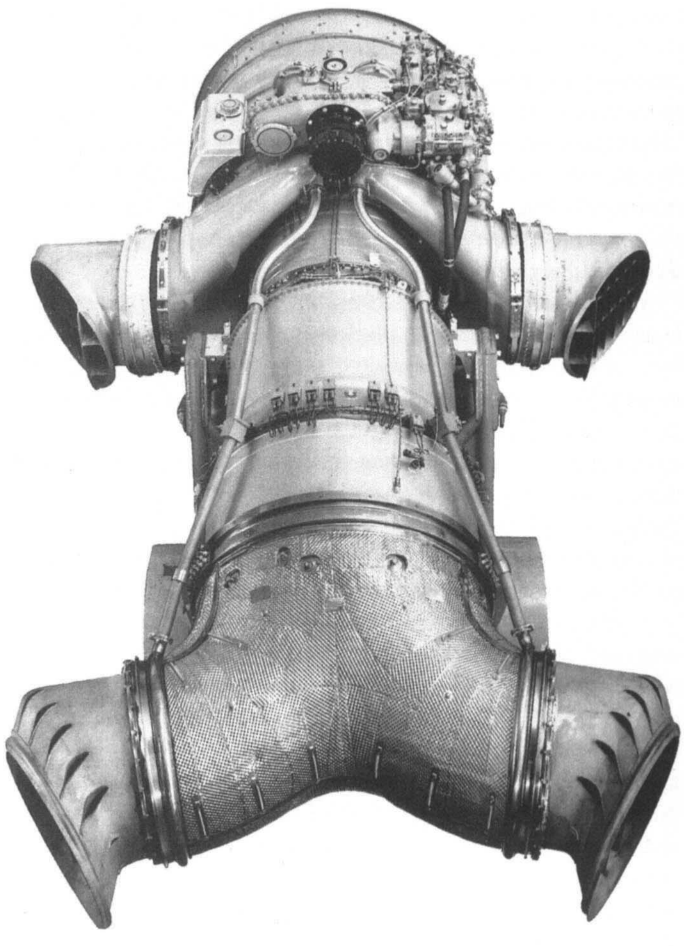
Among the prototypes were the Janus 500-hp turboprop of 1948, and the 3,000-lb BE.17 expendable turbojet for the Bristol 182 (Red Rapier) cruise missile. This in turn led to the 3,750-lb Be.22 Saturn designed for the Folland Gnat light supersonic fighter. The Ministry never supported these, but Bristol was convinced of the market for a small axial engine and put Bernard Massey – who had spent years working on Princess auxiliary plant – on the design of the BE.26 Orpheus. This had a seven-stage compressor (the same as the LP spool of the Orion) driven by a single-stage turbine via a shaft so large in diameter, with very thin walls, that no centre bearing was needed. Another novel feature was that each of the seven flame tubes in the cannular combustor incorporated one-seventh of the ring of turbine inlet vanes. The Orpheus ran at 3,000 lb on 17 December 1954 and was soon type-tested at 3,285 lb. It was selected for all contenders in a NATO light-fighter contest, won by the Fiat G91, so the Mutual Weapons Development Program (MWDP) paid for most of the development. Subsequently thousands of Orpheus were produced by Bristol Aero-Engines (the separate company formed in January 1956), Fiat, KHD, and Hindustan Aeronautics, mostly as the Mk 703 rated at 4,850 lb or Mk 803 rated at 5,000 lb.

Bristol Siddeley (UNITED KINGDOM) When the specification for the TSR.2 aircraft was issued in 1958 the Ministry of Supply used it as a 'carrot' to enforce mergers in the aircraft industry. The airframe companies did not join until 1960, and retained separate identities until 1964, but the engine suppliers carried out a complete merger (between Bristol Aero-Engines and Armstrong Siddeley Motors) in late 1959, the resulting company being BSEL (Bristol Siddeley Engines Ltd). From the start it was a good unified team, continuing existing programmes at Bristol and Coventry and developing new engines under technical director Dr Stanley Hooker. In 1961 it absorbed DH Engines and Blackburn Engines, whose airframe parents joined Hawker Siddeley.

The most important immediate development task was the TSR.2 engine, the Olympus 22R, planned for production as the Mk 320. This was basically a Mk 301 restressed for supersonic flight at sea level or over Mach 2 at height, with a large afterburner. An Olympus had run with a Solar afterburner in 1956, but the 320 was to have a more advanced type with a fully modulated nozzle. A high proportion of the new engine had to be titanium, Nimonic or other high-temperature alloys. Bench testing began in March 1961, followed by the definitive Mk 320 with an enlarged turbine section and 40.5 in diameter afterburner. Ratings were 19,610 lb dry and 30,610 lb with full afterburner, and 33,000 lb was soon demonstrated on test. The TSR.2 flew on 27 September 1964, and a production line was being set up when the whole programme was cancelled for political reasons on 6 April 1965.

Fortunately the Olympus was almost ideal as the basis of the propulsion system for the Concorde SST. At first a version known as Mk 591/2 was selected, based on the TSR.2 engine; then the bigger 593/3 followed with an improved cooled HP turbine; then the 593D raised dry thrust from 22,700 lb to 29,300 lb by adding a zero-stage to the LP spool and removing one from the HP to increase airflow; then the 593B raised thrust to a Stage-0 rating of 32,825 lb and Stage-1 of 35,080 lb; production Mk 602 engines were delivered at the latter figure, raised after two years of service in 1977 to the Mk 621 level of 39,940 lb. Airflow was 410 lb/s and static pr 15.5. French partner SNECMA was responsible for the afterburner, with integral variable nozzle, thrust reverser and noise attenuator. Each engine weighed 5,793 lb.

In 1958 Hooker's team began the design of the first vectored-thrust engine for vertical take-off, the BE.53.



Totally unlike anything seen before, this Bristol Siddeley BE.53/2 led to today's Pegasus. The two pipes conveyed 100°C bleed air to cool the 650°C rear nozzle bearings.

It stemmed from a very different conception put forward by former French aircraft designer Michel Wibault. As it involved a manned combat aircraft the British government was precluded from showing interest, because such aircraft had been officially pronounced obsolete. Boldly the board of the Hawker company decided to finance two P.1127 prototypes, while for the second time the MWDP put up 75 per cent of the money for the engine, Verdon Smith for BSEL again immediately agreeing to pay the rest. Thus was the Harrier allowed to happen. Take-off thrust was initially 8,000 lb, using an Orpheus as gas generator with shaft drive to the first three stages of an Olympus LP compressor delivering via curved left/right nozzles which could rotate 90° to give thrust or lift. In the BE.53/2, mirror-image blading enabled the LP and HP spools to contra-rotate to minimise gyroscopic torques. In the Pegasus 1 the spools were close-coupled, with a new two-stage fan overhung ahead of the front bearing with no inlet guide vanes (then a radical idea), and with the hot jet bifurcated to a second pair of left/right vectored nozzles. This engine ran at Bristol at 9,000 lb in September 1959.

By this time BSEL was being distracted by a giant NATO scheme for Mach-2 V/STOLs which resulted in the urgent development of the BS.100, an advanced vectored turbofan with PCB (plenum-chamber burning – in effect afterburning in the fan nozzles) giving take-off thrust up to 33,000 lb. This would have been a very important and useful engine, and both the RAF and Royal Navy were allowed to consider versions of the Hawker P.1154 to be powered by it, but like TSR.2 these aircraft, and the engine, were all cancelled in early 1965.

The Pegasus was allowed to continue, however, and progressed through various stages to 11,000 lb (P.1127 flight, October 1960), 15,500 lb (Pegasus 5, fitted to Kestrel), 19,000 lb (Pegasus 6) and 20,500 lb (Pegasus 10) to the 21,500 lb Pegasus 11 which powers the first generation of Harriers. These have a three-stage titanium fan with part-supersonic blades handling an airflow of 432 lb/s, eight-stage HP compressor, again of titanium, with overall pr 14, and an annular combustor with ASM-type low-pressure vaporising burners. The Pegasus 11 also has a two-stage HP turbine (both rotor stages air-cooled and with cast first-stage blades), a two-stage LP turbine, four nozzles (front steel, rear Nimonic) driven over an angular range of 98.5° by chains from a pair of air motors, and a packaged gas-turbine starter/APU (auxiliary power unit) mounted on top. Sea Harriers had the marinised Mk 104, the 11-21E in various sub-types was in production in partnership with Pratt & Whitney for the AV-8B/GR.7, and PCB research has once more been undertaken with a view to vectored engines of over 33,000 lb thrust for future applications such as the Joint Strike Fighter.

Much of the development of the Viper (see Armstrong Siddeley) took place under BSEL. For short-haul jets the BE.47, the jet derived from the Bristol Orion, was replaced by the all-new BS.75 of around 7,700 lb thrust, which was run in 1959. BSEL took over the Gnome, Gyron Junior and other engines from de Havilland (*qv*) and the Nimbus from Blackburn. The latter had purchased a licence from Turbomeca in 1953 and planned a range of inter-related engines initially based on the Palas/Turmo/Palouste all with redesigned inlet and accessory systems. In July 1958 Blackburn ran a turbojet based on the Artouste 600 with an added axial zero-stage, leading a month later to the 840-hp A.129 turboshaft from which was refined the Nimbus of 968 hp, flat-rated in helicopters at 710 hp and produced by BSEL.

A GE T64 licence was not taken up, nor were other planned marketing deals and a range of completely new small turboshafts and lift jets, other than the BS.360 which became the Gem (see Rolls-Royce). The BS.605 was an assisted-take-off rocket for South African Buccaneers; resting on extensive ASM and DH rocket experience, it was a 367-lb retractable package pump-fed on HTP (high-test peroxide) and kerosene to give 8,000 lb thrust. In October 1966 BSEL was purchased for £63.6 million by Rolls-Royce, which wished to stave off competition from a planned JT9D link between BSEL, Pratt & Whitney and SNECMA.

C

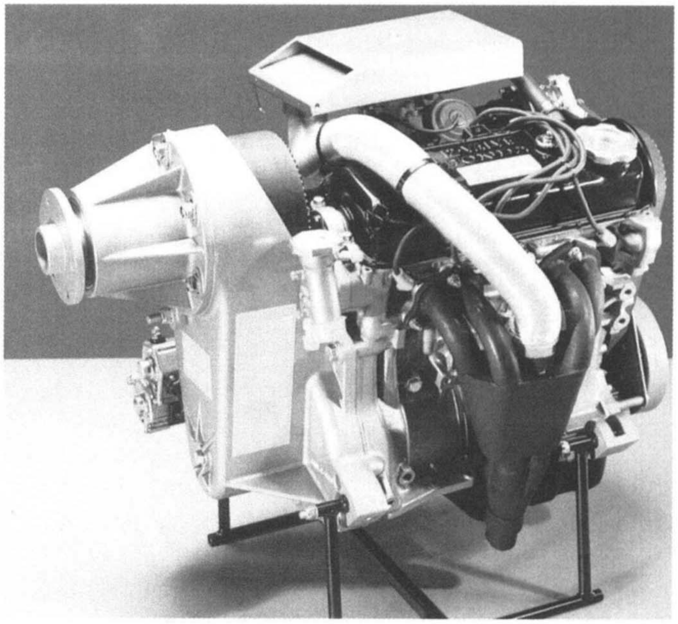
CAM (CANADA) Canadian Airmotive Inc. is marketing one of the best car-engine conversions. Based on the Honda Civic, the CAM 100 is a liquid-cooled four-in-line unit with a capacity of 1,488 cc (90.7 cu in); weight with cog-belt reduction drive is 202 lb and take-off power 100 hp.

Campini (ITALY) Secondo Campini was a pioneer of jet propulsion, but without the crucial adjunct of the gas turbine. He got Caproni to build an aircraft, the N.1, powered by an Isotta-Fraschini Asso piston engine of 900 hp. This drove a three-stage fan which blew air from the rear jet nozzle. To boost performance fuel could be burned in the jetpipe. First flight was on 27 August 1940. Performance was worse than if a normal propeller had been used.

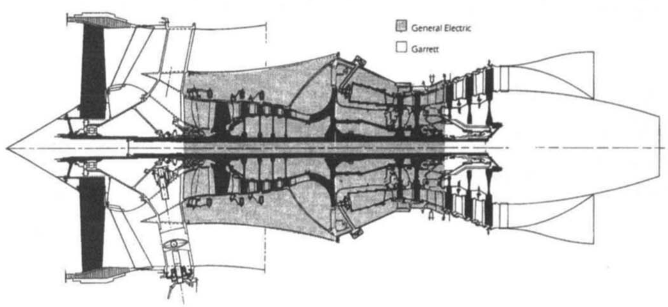
CEC (CHINA). From October 1958 this enormous establishment, with a 20,000 workforce, has made fighter engines to basically Russian design. Starting with the WP6 (derived from the RD-9BF) to power the J-6 and Q-5 families derived from the MiG-19, CEC next produced the WP13G, distantly derived from the R-13, to power later versions of F-7 derived from the MiG-21. CEC produces parts for the Pratt & Whitney JT8D and PW6000, and for $10 million purchased the software required to manufacture the Russian AL-31F.

CFE (USA) This company, based at Phoenix, Arizona, was formed in June 1987 as a 50/50 enterprise by Garrett and General Electric. Its purpose is to manage a turbofan aimed at future long-range business jets. As the diagram shows, the CFE738 is a two-shaft engine. It has a single-stage fan with titanium blades with part-span snubbers, a compressor with five axial stages and one centrifugal, an annular combustor (which, despite the centrifugal compressor, is not of the folded reverse-flow type), a two-stage HP turbine with cooled blades and a three-stage LP turbine. Bypass ratio is 5.3, overall pr 30, dry weight (which always tends to rise) 1,325 lb, take-off thrust 5,918 lb and cruise sfc 0.645. First deliveries were in 1991, but sales were disappointing.

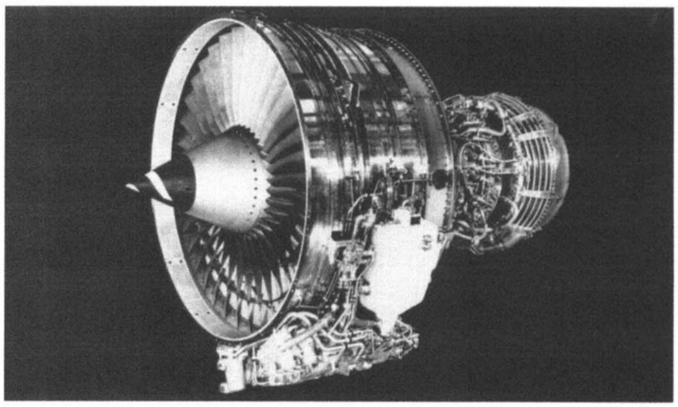
CFM International (FRANCE/USA) From 1968 General Electric and SNECMA independently concluded that a market existed for a modern commercial turbofan in the 10-tonne class; GE worked on the GE13 (the core of which is used in the F101) and SNECMA the M56. In 1971 SNECMA sought a partner and in December reached an agreement with GE. CFM as a joint company was formed in 1974 to manage the programme for the agreed engine, the CFM56. GE assumed responsibility for the core (derived from the F101 after State Department approval), main control system and design integration. SNECMA took on the LP system, reverser, gearbox, accessory integration and engine installation. Most models



The CAM 100 is claimed to have many outstanding features.



Longitudinal section of CFE738 showing the work-split.

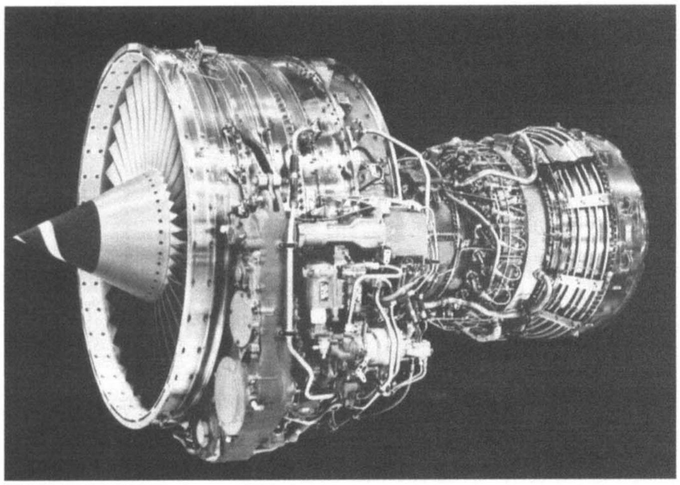


If you have a billion dollars to get through the first ten years, you can then start making money. CFM International is now enjoying a big income, initially from this CFM56-2 family of engines.

have a single-stage fan rotating with three-stage LP compressor driven by a four-stage turbine, nine-stage HP spool driven by a single-stage air-cooled turbine (about 1,260°C) and annular combustor. The first engine ran at GE on 20 June 1974, and the CFM56-2 was certificated on 8 November 1979.

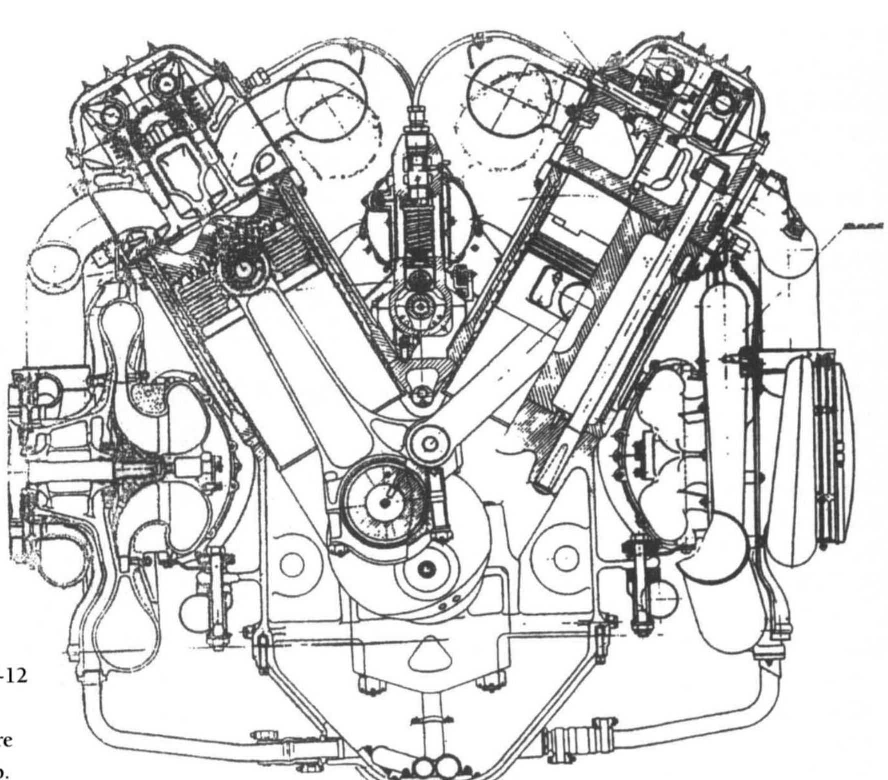
Large numbers power DC-8-70 series, E-3/KE-3 and E-6 aircraft and, as the USAF F108, KC-135R tankers; French C-135F tankers have the CFM56-2B1; the CFM56-2 family have thrusts of 22,000–24,000 lb. The CFM56-3 family were developed for the 737-300, -400, and -500; they have a fan reduced in diameter from 68.3 to 60.0 in, airflow being reduced from 817 to 688 lb/s, giving thrust from 18,500 to 23,500 lb. The CFM56-5 family was launched in 1984 for the A320, with an improved 68.3-in fan handling 956 lb/s and giving a thrust of 25,000–31,000 lb. For the A340 the CFM56-5C series introduced a five-stage LP turbine driving a 72.3-in fan handling 1,027 lb/s, giving thrust of 31,200–34,000 lb. In 1996 the 747 testbed began flying a CFM56-7, with a 61-in fan with only 24 wide-chord snubberless blades, active clearance control and Fadec control. Rated at 18,500–26,400 lb, these engines exclusively power the 737-600, -700, -800 and -900. Smallest version of all is the CFM56-9, with 24 broad blades of only 56-in diameter, driven by a three-stage LP turbine. Rated at 18,500–23,000 lb, this version is aimed at 100-seat aircraft.

For eight years from the first engine test in 1974 there were virtually no sales. Nobody then could have predicted that 20 years later the CFM56 would be selling faster than any previous civil jet engine. By 2006 nearly 16,000 engines had been delivered, with orders about to pass the 20,000 mark.



CFM spent over a billion dollars and for ten years sold virtually no engines; then customers came in a flood, over 125 airlines buying this CFM56-3 version alone.

Charomskii (SOVIET UNION) Aleksei Dmitriyevich Charomskii was one of the greatest exponents of the diesel aero engine. Beginning work in the 1920s, he was permitted to form a design collective at TsIAM (the national aero-engine institute) and in 1933 ran his first complete engine, the AN-1 (unrelated to the Fiat AN.1 diesel, the designation comes from



Charomskii's M-40F was one of a family of large V-12 diesel engines which powered the TB-7, Pe-8 and Yer-2 (also called the Er-2) bombers. This 61.04-litre engine was rated at 1,500 hp and weighed 2,645 lb. It more than made up for its ponderous weight by burning less fuel. Note turbochargers.

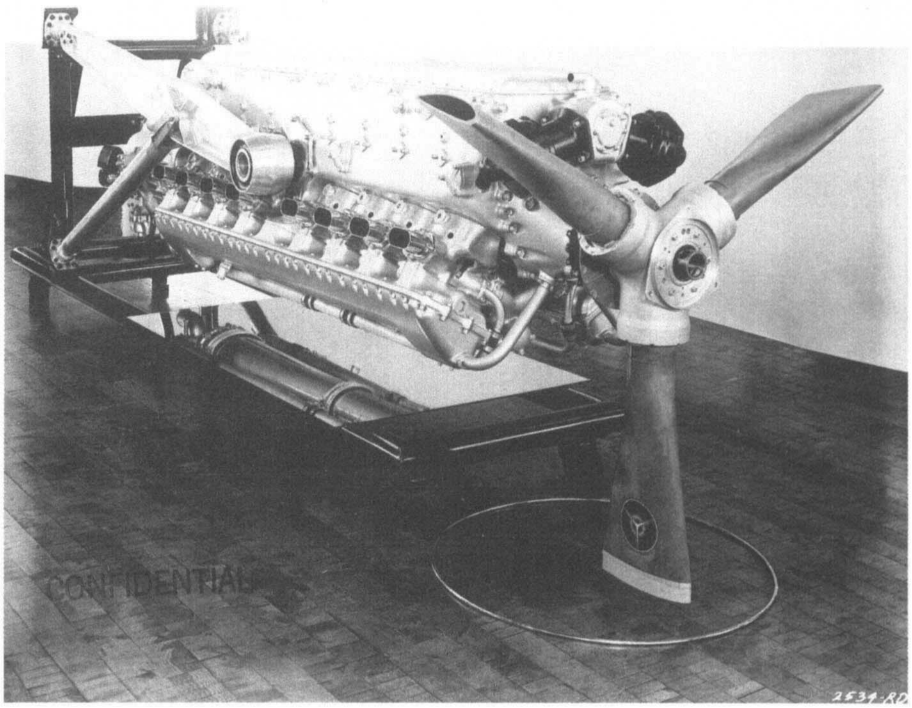
'Aviatsionnyi Nyeftyarnoi', 'aviation/oil'). A two-stroke water-cooled V-12, it had cylinders of the same size as the later engines, and was rated at 850 (later 900) hp at 2,000 rpm. From this Charomskii developed the M-30 and M-40, the latter being ahead in timing, running in 1939 and being flight tested in the following year (it is believed, in a TB-3).

Stalin was not interested in strategic bombers but was impressed by the diesel's long-range capabilities, and in October 1940 the M-40 was picked to re-engine the TB-7 (Pe-8). Because of its greater potential power the M-40 was then replaced by the M-30, also first run in 1939 but regarded by Charomskii as nowhere near ready for production. An advanced turbocharged V-12 with cylinders 180 × 200 mm, capacity 62.34 litres, it weighed typically 1,200 kg complete with integral pressure-glycol cooling system, and was rated at 1,400 hp. The production M-30B, from 1941 designated ACh-30B for its designer, was rated at 1,500 hp but caused the pilot problems, with the complex fuel controls. Later engines included the ACh-31 and 32 of 1,550 hp, the ACh-39 of 1,800 hp and 39BF of 1,900 hp.

Chernyshev (RUSSIA) Built beside Moscow's Tushino airfield in 1932, as Aviation Factory No. 500, this plant began by making small radials and large diesels (see Charomskii). In 1947, directed by the man after whom it is now named, it produced the RD-500 (Rolls-Royce Derwent) and then the VK-1 (developed from the Rolls-Royce Nene). Considerably enlarged, it then made the R-27, R-29, R-35 and RD-33 fighter engines, and the TV7-117S turboprop.

China In the past 30 years the People's Republic of China has enormously expanded its aero-engine industry, mainly with licensed foreign designs. CEC (Chengdu Engine Co.) makes the WP6 and WP13 (see LMC), and parts of the Pratt & Whitney JT8D. CLXMW, at Changzhou, makes the WZ6 (Turbomeca Turmo). DEMC (Dongan Engine Mfg Co.), at Harbin, makes a family of WJ5 turboprops based on the Ivchyenko AI-24. LM (Liming Engine Mfg Corp.) makes the WP6 (Tumanskii RD-9BF), WP7 (Tumanskii R-11F), and a large fighter engine designated WS6. LMC (Liyang Machinery Corp.) makes the WP7B and WP13 derived from the Tumanskii/Gavrilov R-11 and R-13. SAMP (Shanghai Aero-Engine Mfg Plant) made the WS8 turbofan similar to the P&W JT3D; another indigenous engine was the WS6 afterburning turbofan by Shenyang Aviation Research Institute. SMPMC (South Motive Power and Machinery Complex) make a range of HS6 piston engines based on the Ivchyenko AI-14, the WJ6 turboprop based on the Ivchyenko AI-20M, the WZ8 based on the Turbomeca Arriel 1C, and the locally designed WP11 turbojet for reconnaissance drones. XAE, at Xian, made Rolls-Royce Speys. ZAC, at Zhuzhou, make the Arriel-based WJ9 turboprop.

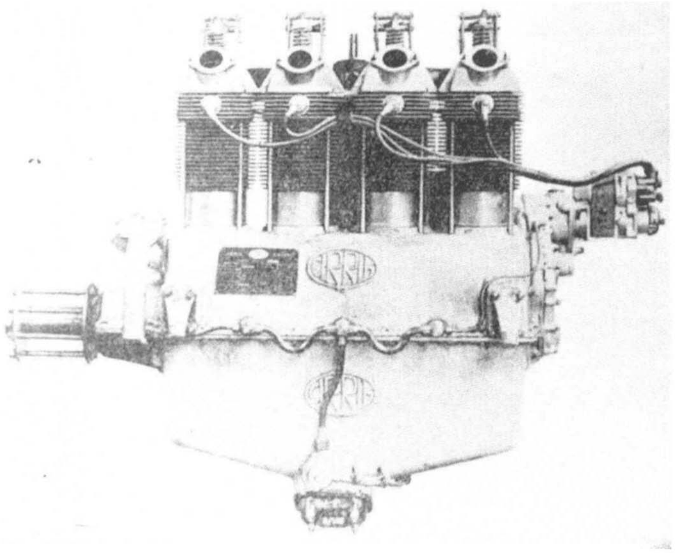
Chrysler (USA) During the time of violent expansion in June 1941, this famous car company pressured the US Army into giving it a contract for yet another liquid-cooled pursuit engine. The IV-2220 was essentially two inverted V-8s back-to-back with mid-drive to the front gearbox. The 138.75 cu in four-valve cylinders were highly blown by two-stage superchargers



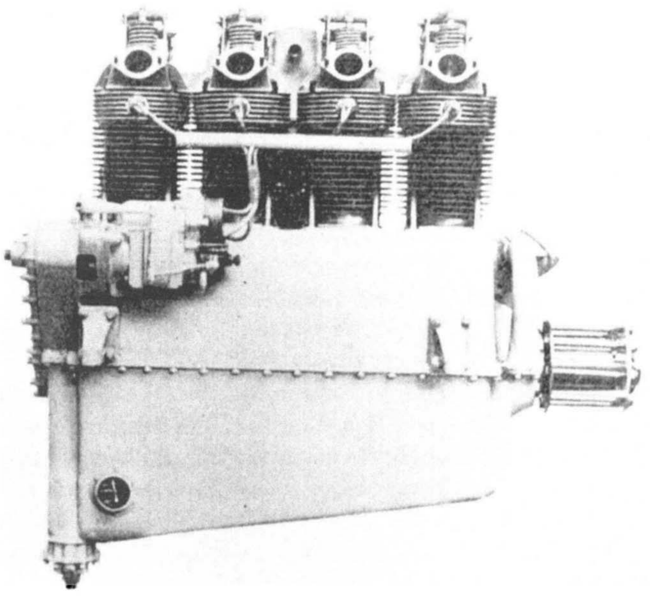
The first Chrysler IV-2220 display model, made in January 1942 (but, of course, not publicly exhibited). The propeller was one of the first to have forged hollow steel blades.

with a ventral intercooler, and the first run in December 1942 was encouraging. By this time the profusion of competing engines was obvious, and development was abandoned in June 1944 shortly after the XI-2220-11 (the designation had dropped the letter V) had been cleared for flight at 2,500 hp. It was on Chrysler's initiative that Republic completed the first of two planned XP-47H Thunderbolts, in which the engine was matched with a GE CH-5 turbo, and eventually flew it at Chrysler's expense on 26 July 1945.

Cirrus (UNITED KINGDOM) Major Frank B. Halford created the first Cirrus engine for Captain de Havilland in late 1924. He was working at Airdisco (the government Aircraft Disposal Company, where among other things were some 30,000 surplus engines). Halford used the cylinders and pistons from one-half of an Airdisco V-8, the air-cooled engine Halford had developed from the wartime Renault. In two months he had designed and built the new four-in-line, with a five-bearing crankshaft and deep aluminium crankcase. With cylinders 105 × 130 mm (the Renault was metric), capacity was 4.5 litres, weight 286 lb and maximum power 64 hp at 1,800 rpm, with 68 hp available for take-off at 2,000 rpm. De Havilland flew the engine in the prototype DH.60 Moth on 22 February 1925. Later that year Halford produced the Cirrus II with a bore of 110 mm, forged light-alloy conrods and bronze valve seats; this gave 85 hp for take-off, followed in 1926 by the Cirrus III with 114 × 140 mm cylinders, rated at 95 hp. Taken over by the Hermes Engine Company, this was marketed with refinements as the Cirrus Hermes I, rated at 105 hp. The 115-hp Hermes II was the first inverted model, all later Cirrus having this layout. The Hermes III and IV were rated at 120 to 140 hp depending on sub-type.



Frank Halford's Cirius III was the first of the four-in-lines to move significantly on from 1916 technology. Rated at 85/90 hp, it went into the 1928 Moths.



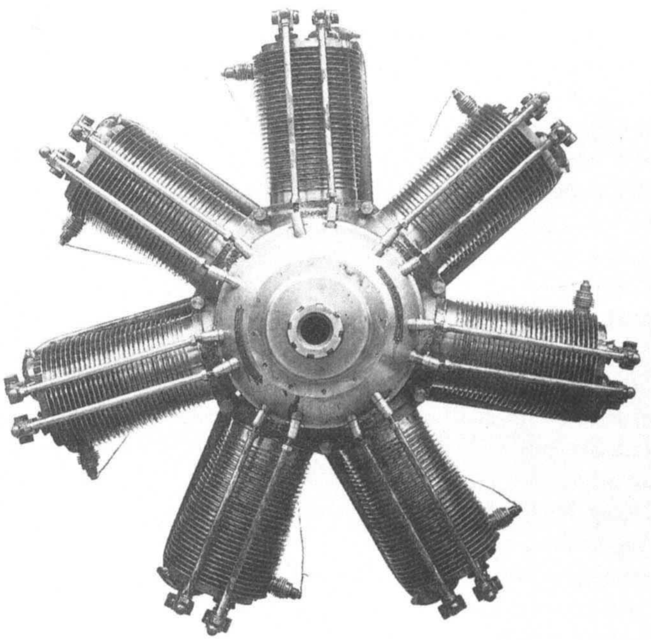
Differing mainly in crankcase, the Cirrus Hermes I was rated at 105 hp and powered such types as the Avian and Desoutter I.

In 1934 the business was bought by Blackburn Aircraft at Brough. Later the same year the prototype Cirrus Minor ran at 80 hp, later rated at 90 hp at 2,600 rpm, with cylinders 95 × 127 mm, capacity 3,605 litres. The wartime Minor II had 100 mm bore and gave 100 hp. The Cirrus Major of 1935 had 120 × 140 mm cylinders, 6.3 litres, and was developed from an initial 135 to 158 hp. After the Second World War Blackburn & General Aircraft produced a range of completely new inverted engines, the only one produced in quantity being the Bombardier four-in-line. This had a magnesium-alloy crankcase and direct injection into cylinders 122 × 140 mm, 6.5 litres, and was rated at 180 hp in fixed-wing installations and up to 200 hp in helicopters.

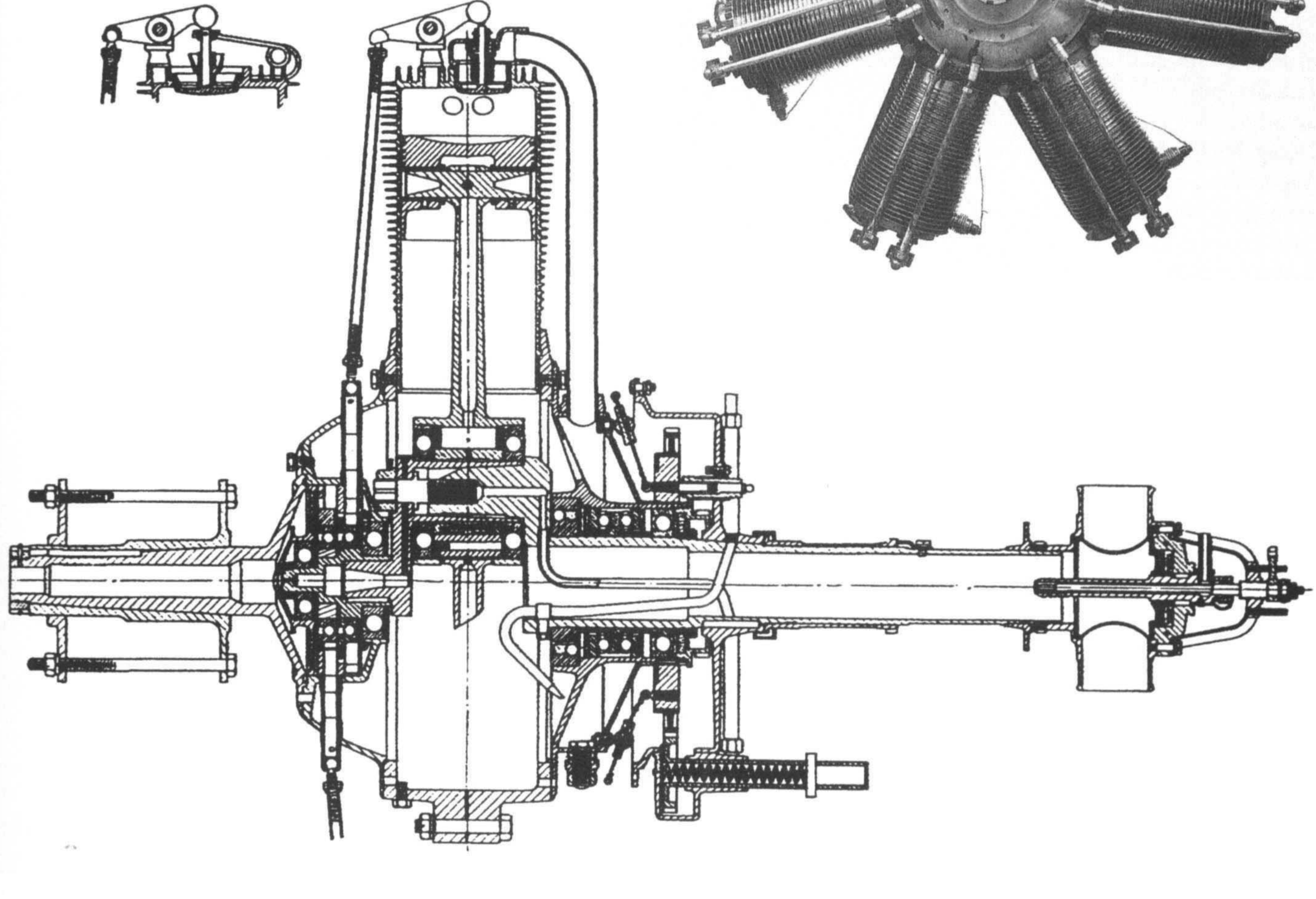
Clerget (FRANCE) Inspired by the Gnome, the Clerget precision-engineering firm produced what it claimed to be an improved rotary engine in 1911 with lower consumption of both fuel and castor-oil lubricant. The main difference was that the mixture was fed from the crankcase via normal external induction pipes to the cylinder heads. The latter were flat, instead of tapered, and housed inlet and exhaust valves both operated by pushrods. Unlike the Le Rhône, the pistons worked directly inside the steel cylinder, and in view of the piston-ring problem (see Gnome) the pistons had special obturator rings, failure of which caused severe cylinder overheating. Clergets were made by the thousand in Britain, as well as in France and other countries, and Bentley's first aero job was to seek a solution to this overheat difficulty.

The initial 1911 engine had seven cylinders, 120 × 150 mm, giving capacity of 11.88 litres, the rating being 80 hp at a nominal 1,200 rpm. By 1913 the Clerget 9 was in production; 15.3 litres, rated at 110 hp. In late 1915

The Clerget rotaries could be immediately distinguished from the Gnomes by their twin valve rods and side-mounted plugs. This is a 110 hp type of late 1915.



Cross-section through a typical 130-hp Clerget. Most British-made examples had a bore of 4.72 in and stroke of 6.3 in, and weighed about 380 lb. The inset shows the hairpin-type valve spring.



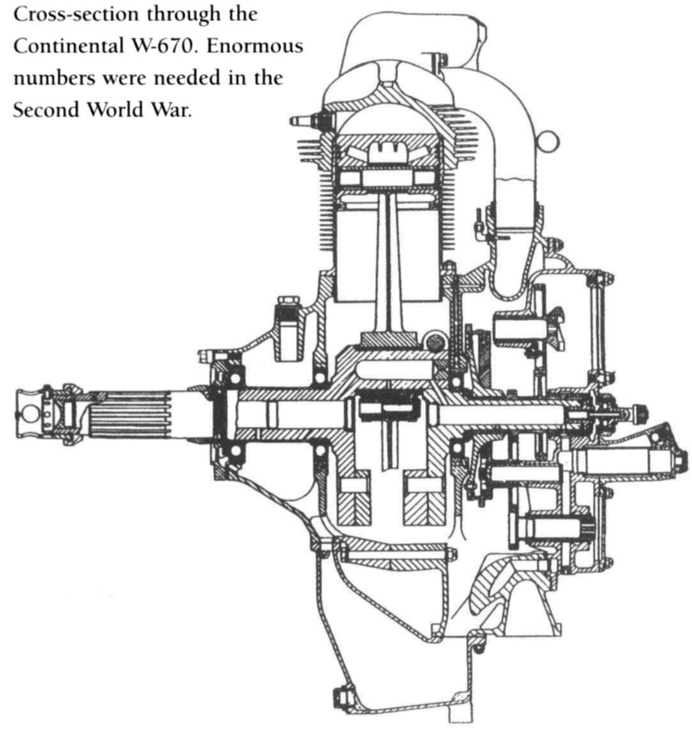
the 9B introduced the increased stroke of 160 mm, giving capacity of 16.29 litres, power rising to 130 hp at 1,250 rpm. The final production version was the big 11-cylinder 11EB, nominally of 200 hp. This was priced at £1,663, and even the mass-produced 9B was normally priced on English production at £907.50, considerably more expensive than other rotaries of similar power.

Pierre Clerget kept his company ticking over in Paris during the 1920s, switching to four-stroke diesels. Some of the first stemmed from the rotaries, though of course they were static radials; the 9A of 1929 gave 100 hp at 1,800 rpm. The two-row 14F-01, a big 14-cylinder unit developed with government funds, reached 7,665 m in a Potez 25 in 1937. His final fling was the 'Type Transatlantique', a water-cooled H-16 engine with four turbochargers designed to give 2,000 hp. Clerget had insufficient resources to test this engine.

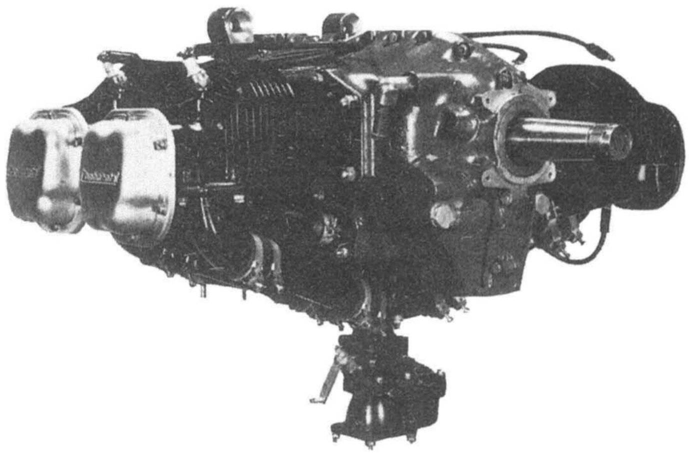
Continental (USA) In the 1920s Continental Motors was the world's largest maker of engines for use in cars and commercial vehicles built by others. In 1925 it purchased from British Argyll the patent rights to the Burt-McCollum monosleeve valve. It ran, but did not fly, an aero radial using the system in 1927, and subsequently produced a liquid-cooled poppet-valve engine for the Army and an air-cooled sleeve-valve radial for the Navy, neither being flown.

In 1928 the A-70 was run, and by 1929 tested in three different aircraft at 170 hp at 2,000 rpm. This high-quality seven-cylinder radial had bore and stroke both of 4.625 in and a capacity of 544 cu in. It had two poppet valves per cylinder, and the engine looked particularly clean because the valve gear was behind the cylinders. From it was derived the W-670 of 1934, with the bore increased to 5.125 in, giving capacity of 668 cu in. This began life rated at 210 hp at 2,000 rpm and during the Second World War was rated at up to 240 hp at 2,200 rpm (250 hp at 2,400 rpm in the equally mass-produced tank-engine version).

A few W-670s are still flying for a living in Ag-aircraft, but Continental's real business started with the emergence in 1931 of possibly the simplest piston aero engine ever built, the A40. This flat-four (four horizontally-opposed cylinders) had cylinders only 3.1 × 3.8 in, giving capacity of 115 cu in. Single L-type heads were bolted across each pair of cylinders, but the A40 still ran at 2,500 rpm to give 37 hp. It had the important advantage in the Depression of low price, and sold well enough to delay the much better A50 until 1938. The A50 had all the features of bigger aero engines, such as individual cast aluminium-alloy heads screwed and shrunk on to forged-steel barrels, three main bearings and dual ignition. Cylinders were 3.875 × 3.625 in, capacity 171 cu in, and rating 50 hp at the modest speed of 1,900 rpm. In early 1939 the A65 introduced different Marvel or Stromberg carburettors and various refinements, being rated at a useful 65 hp at 2,300 rpm. It was chiefly this engine that resulted in over 8,000 Continental sales by 7 December 1941; after this date a much greater number of O-170 military versions were built.



Cross-section through the Continental W-670. Enormous numbers were needed in the Second World War.

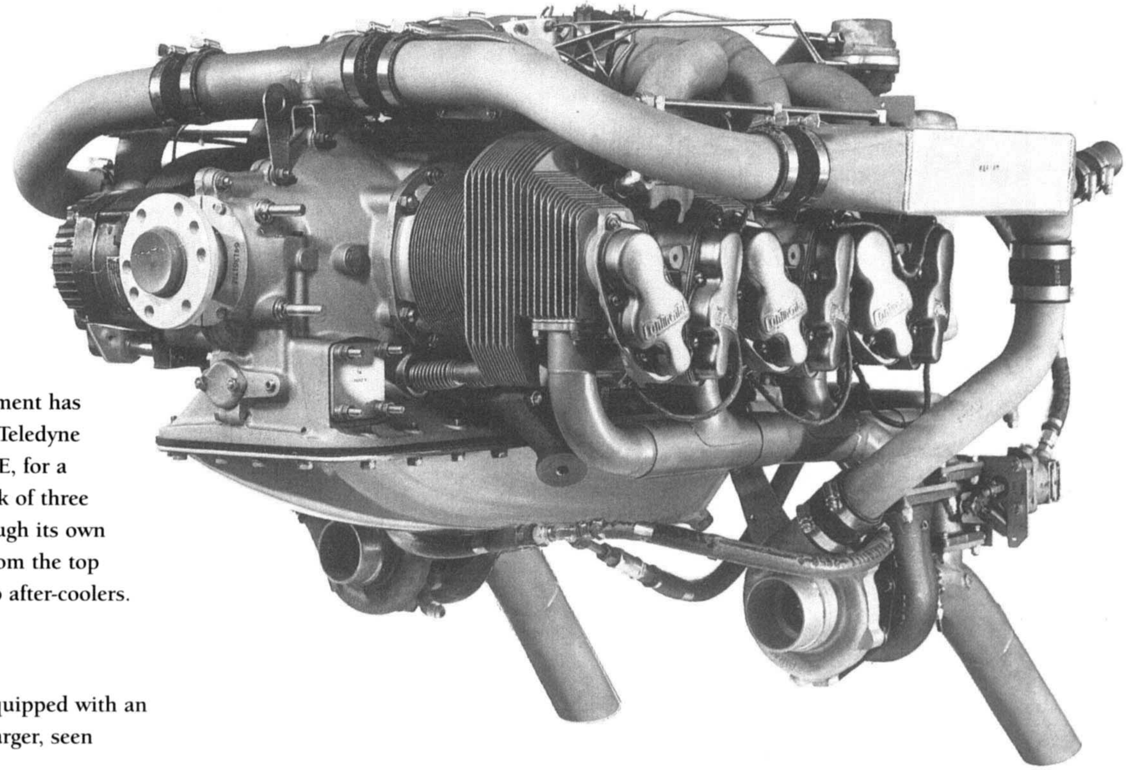


Continental's A65 did more than any other engine to establish the flat-four as almost the standard type for light aircraft.

After 1945 Continental poured forth refined engines with a standard cylinder 4.0625 × 3.625 in, the C75 and C85 being flat-fours (the number still denoting the horsepower) of 188 cu in and the C115, C125 and C140 being flat-sixes of 282 cu in. In 1947 the E165 and E185 hit the market as the first of the 470 cu in flat-sixes which had the military designation O-470. Over many years the old 'power' designations were gradually replaced by unified civil/military 'capacity' numbers based on cubic inches, prefaced by such letters as 'GTSIO' for 'geared, turbosupercharged, direct-injection, opposed'. Today Teledyne Continental is the world No. 2 builder of general-aviation engines, its most important family being the O-520 with six cylinders, 5.25 × 4 in, giving capacity of 520 cu in, with ratings from 285 to 435 hp. For 20 years to 1981 Rolls-Royce Motors of Crewe was a licensee. In 1965 Continental began development of a completely new 'Tiara' range of engines notable for advanced features and in particular for special control of torsional shaft vibration. Despite testing 46 prototypes, and start of production in 1971, the whole programme was eventually terminated, reminding one of the Ford Edsel, Corfam shoes and other classic marketing disasters.

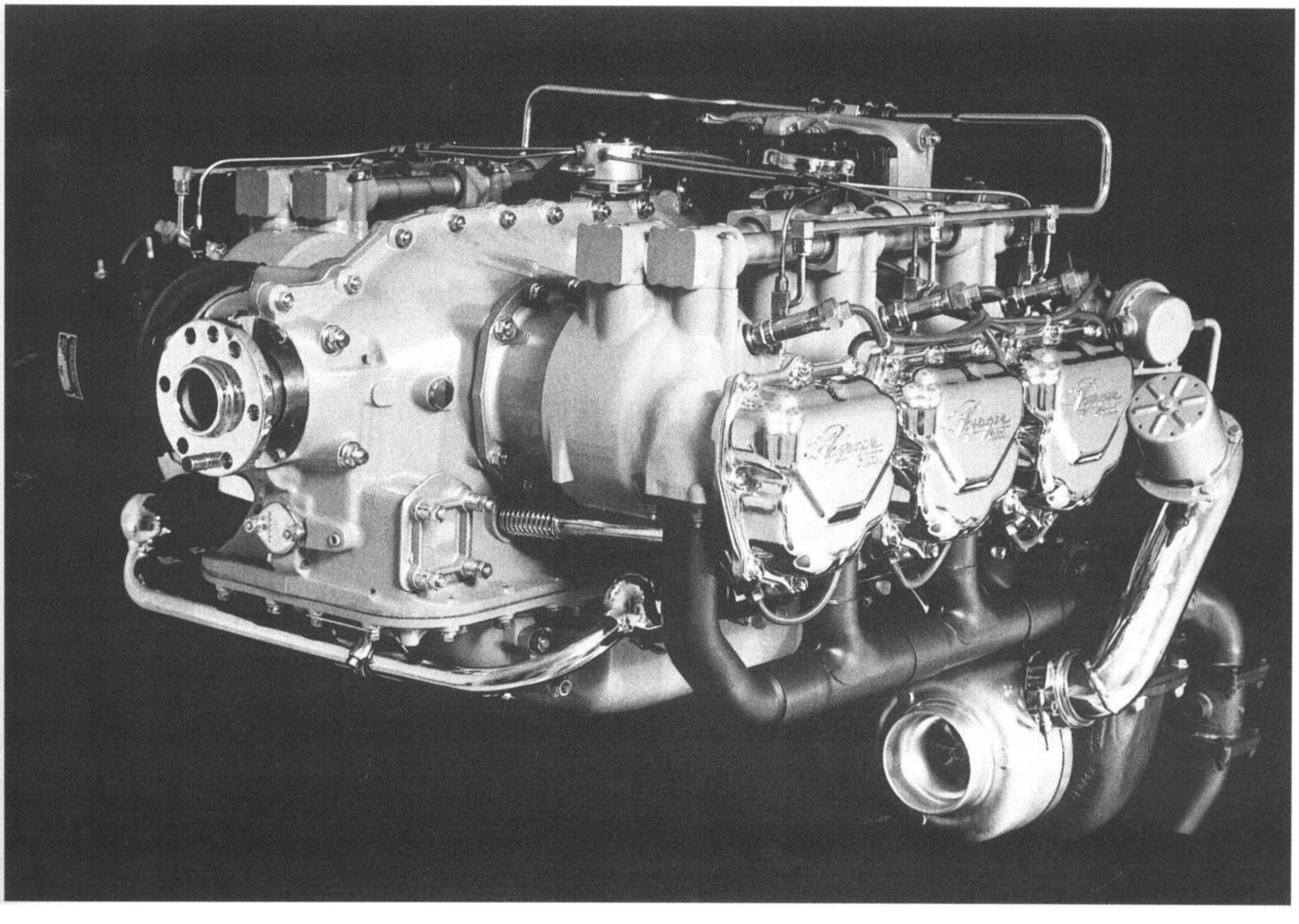
In 1985 TCM (Teledyne Continental Motors) began marketing alternatives to its established products. A range of RC (rotating-combustion) engines of basically Wankel type failed to find a market, as did a neat turboprop for general aviation. The only success has been to introduce engines with liquid cooling, using 60 per cent glycol. One drove the Voyager aircraft non-stop round the world, so they are known as Voyager engines, but even here production has continued on only one size, the 550 cu in, available at powers from 300 to 400 hp.

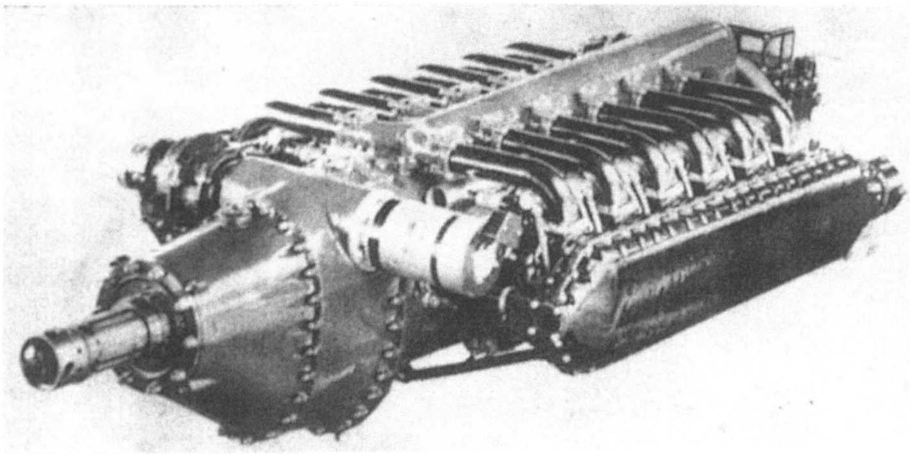
Less familiar is the story of the engine that was planned as the ultimate in piston aero engines but which was abandoned because it took so long to develop. In 1929 the US Army laboratory at McCook Field carried out research on cylinders



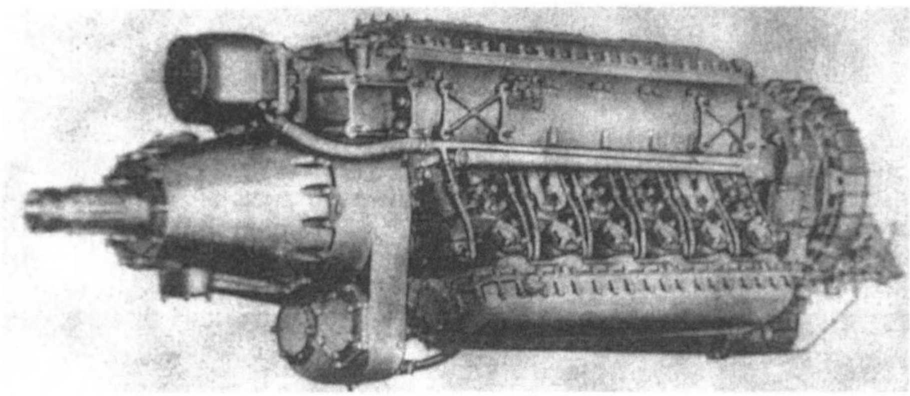
A half-century of refinement has now led to this 310-hp Teledyne Continental TSIO-520BE, for a Piper Malibu. Each bank of three cylinders exhausts through its own turbocharger, and air from the top intake goes through two after-coolers.

This Voyager T-550 is equipped with an exhaust-driven turbocharger, seen underneath.





A rare picture of the Continental 'Hyper' O-1430 flat-12 designed to fit inside the wings of Army aircraft. Project engineer was Harold Morehouse, who in 1937 went via Erco to Lycoming, Continental's chief rival.



When it was realised that the in-wing idea was a non-starter the O-1430 became this inverted V-12, the IV-1430. Output rotation could be reversed by a simple adjustment from outside the drive gearbox. Performance was fantastic, but too late.

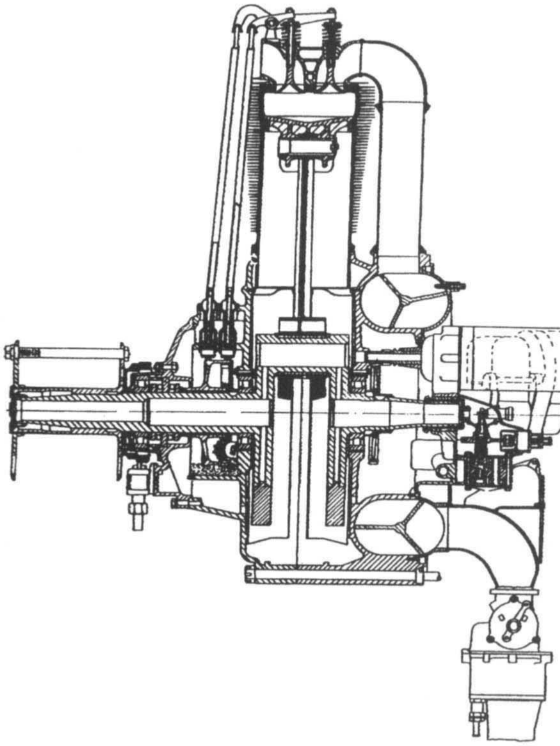
giving far greater power than any others of their size. By 1931 the 'Hyper' cylinder had been finalised with a hemispherical piston top and cylinder head, sodium-cooled valves and 4.625-in bore and 5-in stroke, so that a 12-cylinder engine would have capacity of only 1,008 cu in. The engine was to be an upright V-12 with cooling by Prestone (ethylene glycol) at no less than 149°C, so individual cylinders were used instead of monobloc banks. As the vital cylinder was regarded as already developed, Continental was given the job of producing the complete engine, which the Army fondly thought would take about two years. Harold Morehouse was project manager. In 1934 the Army ordered an increase in cylinder size to 118.8 cu in, or 1,425 cu in for the engine. In 1935 it was decided that future engines would be buried in the wings, for low drag and so the V-1430 was redesigned as a flat opposed unit, the O-1430.

The first O-1430 was tested at 1,000 hp in 1938; but it could never fit inside a fighter wing, and Colonel Lindbergh's report on the Bf 109, which he found most impressive, resulted in the O-1430 being replaced by the IV-1430, an inverted V-12. It was thought in 1939 that this would soon be ready for use with a turbocharger giving 1,600 hp at 3,000 rpm at 25,000 ft, and not only were the Lockheed XP-49 and McDonnell XP-67 designed around it but a giant new company-owned plant at Muskegon, Michigan, was equipped for IV-1430 production. Eventually it was realised the war would be over before production engines could appear, and the IV-1430 was reluctantly terminated – though not before a type-test in July 1944 gave 2,100 hp at 3,400 rpm at 87.8 in manifold pressure.

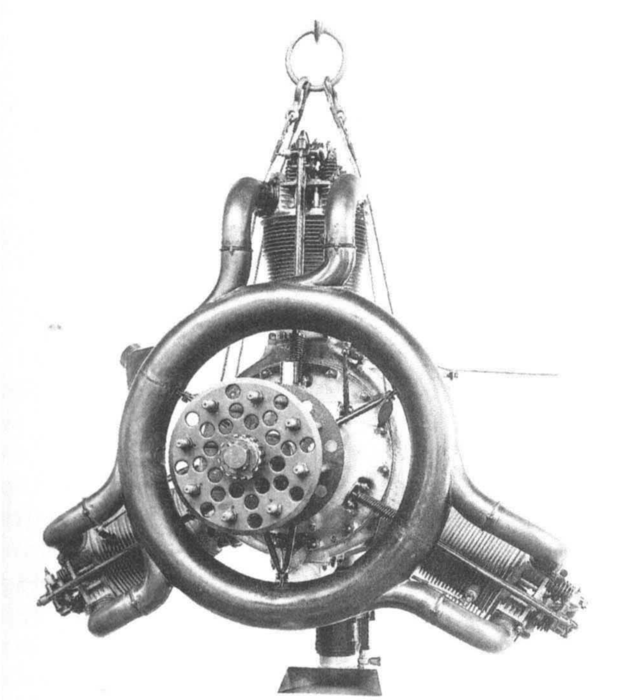
Cosmos (UNITED KINGDOM) Cosmos Engineering was the name given to Bristol's Brazil Straker works at Fishponds after it had been taken over by the giant Cosmos industrial empire in 1918. Brazil Straker's chief engineer, Roy Fedden, had, with L.F.G. Butler, designed two very good radials during the war. First came the Mercury, with 14 cylinders 4.375 × 5.8125 in arranged in helical form and seven thin conrods working side-by-side on each crankpin. Of 1,223 cu in capacity, it 'ran like a sewing machine' in July 1917 at 300 hp, and was immediately ordered by the Admiralty (but they were overruled by Lord Weir who was captivated by the ABC Dragonfly). In early 1918 came the Jupiter, with nine big cylinders, 5.75 × 7.5 in, 1,753 cu in, aiming at an eventual power of 500 hp. Run on 29 October 1918, the prototype gave about 395 hp for a weight of 662 lb in running order. Fedden put four valves in each cylinder for good breathing, but did not dare depart from the poultice type of head, the aluminium casting being added outside the closed top of the steel cylinder. A geared version followed, and direct-drive engines powered racers such as the Sopwith Schneider and Bristol Bullet. The Lucifer of 120 hp had three cylinders similar to the Jupiter but of only 6.25 in stroke, giving 130 hp at 1,700 rpm, with each firing stroke noticeable. The 1,000-hp Hercules, an 18-cylinder two-row Jupiter, was about to be built when in January 1920 the Cosmos empire crashed because of a wild financial gamble involving shiploads of household goods for Russia, all of which were of course seized by the Bolsheviks. *See* Bristol.

Curtiss (USA) Glenn Curtiss was America's, if not the world's, top racing motorcyclist in the first decade of the century, making his own engines. In 1903 T.S. Baldwin asked him to power a small dirigible, and this flew on 3 August 1904 with an air-cooled V-twin of 60 cu in, rated at 7 hp. In September 1907 he was a founder-member of the Aerial Experiment Association, and provided excellent air-cooled V-8 engines later known as B-8s, with cylinder dimensions reversed, to 3.625 in bore × 3.2 in stroke, 265 cu in, rated at 30–40 hp at 1,800 rpm. In 1908 he switched to cylinders of 5 in bore and stroke in the 50-hp E-4 and 100-hp E8, one of the latter carrying off top prize (Prix de la Vitesse) at the July 1909 Reims meeting. By this time Curtiss had also built several water-cooled aero engines, retaining the original cylinder construction with a steel barrel and integral head all held to the crankcase by four long tie-bolts and adding brazed water-jackets of either copper or non-corrosive Monel alloy.

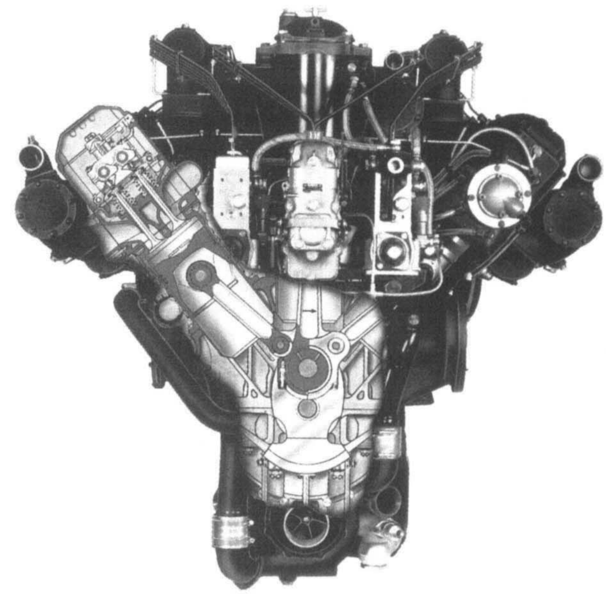
In 1910 the OX-5 appeared, with bore reduced to 4 in, giving 503 cu in capacity. It retained inclined overhead inlet and exhaust valves arranged in the transverse plane instead of the axial one, the inlet pushrods being inside the tubular



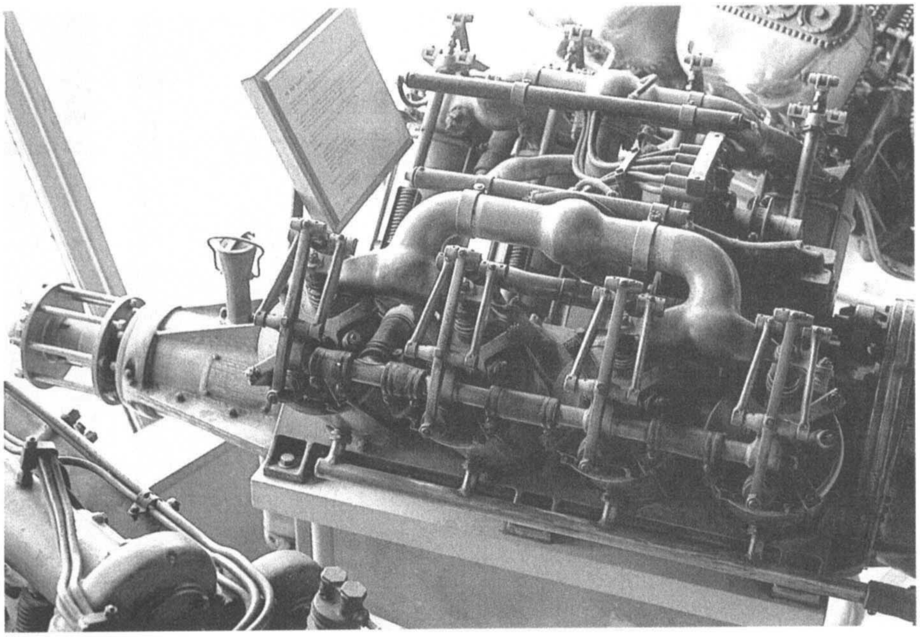
The Cosmos Jupiter I was the starting point for all the Bristol piston engines. By the time the last Pegasus was made the only thing unchanged was the cylinder size. Rated at 400 hp at 1,650 rpm, this classic engine weighed about 700 lb.



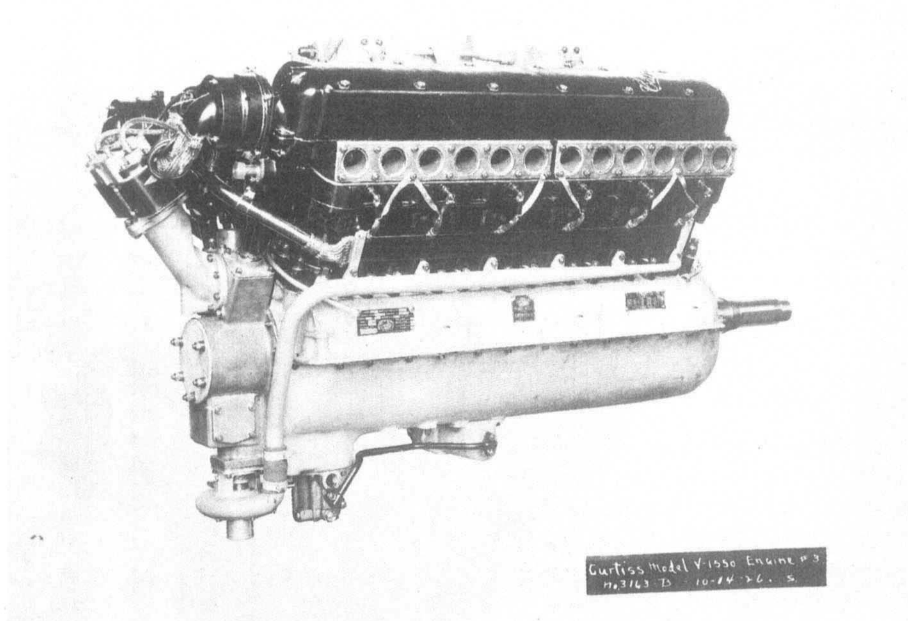
The Cosmos (later Bristol) Lucifer was one-third of a Jupiter. The exhaust systems were made laboriously by hand by a skilled one-man subcontractor who became Sir William Lyons, of Jaguar cars.



This cross-section shows the big Italian CRM 18D/SS diesel which was to have provided cruise propulsion for the US Navy's Westinghouse YEZ-2A Sentinel 5000 airships. Weighing 3,745 lb, these engines have three banks each of six water-cooled cylinders, and give a maximum of 1,850 hp at 2,100 rpm with economical use of oil fuel.



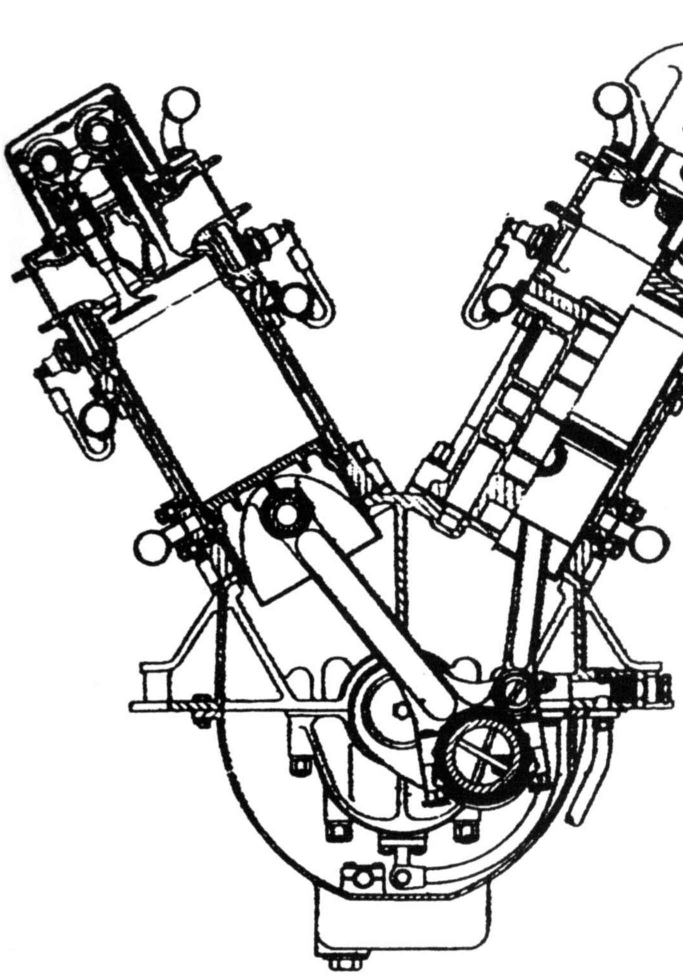
Designed in 1910, the Curtiss OX-5 was still in large-scale production in 1917. It weighed 320 lb, and gave an uncertain 90 hp. This is another London Science Museum exhibit.



The Curtiss V-1550 of 1926 was an enlarged D-12 which led directly to the V-1570 Conqueror. Note the rear drive to magnetos, camshafts and centrifugal water pump.

exhaust pushrods, and the camshaft driving the magneto and water and oil pumps. The OX-5 suffered from many unnecessary faults, was always unreliable and when made by numerous contractors in vast numbers in the First World War suffered from appalling quality control. Nominal power was 90 hp at 1,400 rpm, and two important OX-5 powered trainers were the Curtiss JN-4 and DH.6. Smaller numbers were made of V-12 engines of 100, 130 and 160 hp, with cylinders larger than the OX-5.

From early in the century Charles B. Kirkham's machine shop had been much patronised by Curtiss, and by 1912 Kirkham was itching to design an engine himself. Before he saw a Hispano he decided that using a single cast aluminium block for a whole row of cylinders would make an engine rigid as well as light, reduce water leaks and, if a wet liner was used – the water being in contact with the thin steel liner – give improved cooling. The upshot was a joint effort that put the Curtiss K-12 on test in October 1916. This V-12 was one of the truly significant milestones in aero engine development. It had cylinders 4.5 × 6 in, capacity 1,145 cu in, and gave 400 hp at 2,500 rpm. As a by-product, one of the banks of cylinders was used in the low-rated K-6 of 200 hp. The K-12



The Curtiss D-12 was possibly the best water-cooled engine in the early 1920s. It had a displacement of 1,145 cu in, dry weight of 693 lb and was rated at 375 hp at 1,850 rpm.

C

was in some ways the world's most advanced water-cooled engine of the war period, but the crankshaft needed seven bearings instead of four and the giant monobloc crankcase and the integral cylinder blocks were beyond the state of the casting art, and Curtiss and Kirkham failed to produce a good reduction gear. Moreover the US government decided to standardise on the technically older Liberty; finally, in a row centring on how much K-12 redesign was needed, Kirkham quit, Arthur Nutt taking over.

Curtiss made no attempt to use the C-6 (previously K-6) to compete with the prolific Wright-Hispano, and the few built were mostly derated to 1,700 rpm, giving 150 hp. All effort went into the K-12, which became the C-12 in 1919 (with separate blocks and crankcase but a troublesome reduction gear), the CD-12 (with seven-bearing crankshaft and direct drive) in 1920 and the definitive D-12 which passed its Navy type-test in 1922 at 400 hp. In the same year it began a brilliant career not only as an engine for fighters but also for racers, gaining world speed records and Schneider victories, the 1925 Schneider being won with the enlarged V-1400. Fairey attempted to licence-produce the D-12 in England as the Felix (*qv*).

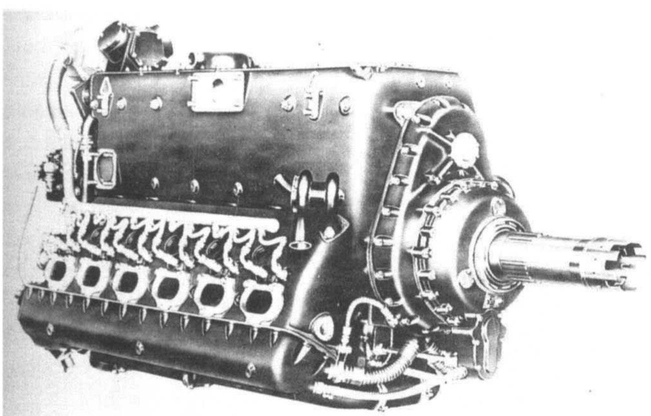
In 1924 Nutt began considering a next-generation military D-12 and in 1926 this entered production as the Conqueror, later also designated V-1570 from its capacity. Bore and stroke were increased to 5.125 × 6.25 in, and a major advance was use of modern open-ended cylinder liners. It was built in many versions with direct or geared drive, often with a supercharger (never used on a production D-12), with ratings of 575 hp in 1927, 600 in 1928 and 650 in 1932. Despite accounting for almost two-thirds of Army expenditure on large engines as late as 1932, Curtiss (merged with Wright in 1939) not only failed to push development but was faced by the Army's rapidly declining interest in liquid cooling. Tests at McCook Field in 1931 showed aluminium/steel leakage with high-temperature (149°C) pressurised glycol, and a year later all military funds for Conqueror development was cut off, replaced by long-term support for Continental and Allison.

Curtiss had no success getting airlines to persist with the Conqueror, TAT and Eastern flying water-cooled Condors for only one year. In 1926 Curtiss decided to try to beat the rival Wasp with a totally new air-cooled radial, the H-1640 Chieftain. This had two rows each with six cylinders, the front and rear cylinders being directly behind each other and sharing a common head and overhead camshaft. Diameter was extremely small, and partly because of this it was not very successful. An air-cooled inverted V-12, the Army-funded V-1460, with 4.875 × 6.5 in cylinders, rated at 525 hp at 2,300 rpm, ran well in 1929 but gained no orders. In 1929 Nutt became vice-president (engineering) of the merged Wright Aeronautical division of Curtiss-Wright.

CZ (CZECHOSLOVAKIA) In 1930 Ceskoslovenska Zbrojovka's Dr Ostroil began development of the ZOD 260-B nine-cylinder radial two-stroke diesel. Each cylinder had two overhead pushrod valves, weight was 598 lb and rating on test in 1933 a reliable 260 hp at 1,560 rpm. Some dozens were made for training and club aircraft.

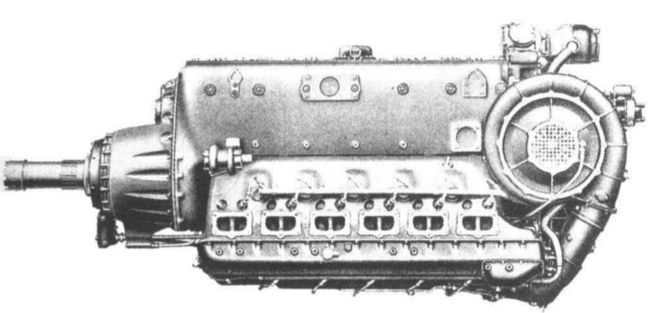
D

Daimler-Benz (GERMANY) This company was formed in 1926 by the merger of Daimler Motoren Gesellschaft, of Stuttgart, the parent company of Mercedes, with Benz. By this time the Allied Control Commission was relaxing its restrictions, and the wartime Mercedes D IIa was built in refined form as well as small numbers of a new 20-hp air-cooled engine derived from the Mercedes F 7502. In 1927 the big F 2 water-cooled V-12 appeared, with cylinders 165 × 210 mm of traditional separate form with welded jackets but with enclosed valve gear. From this Dr Berger's team derived a 750-hp diesel intended for long-distance aircraft. Tested in 1928, this in turn led to the massive LOF 6 airship engine. This was a V-16 more like a marine diesel, with four-stroke unsupercharged cylinders of F 2 size giving capacity of 54.1 litres. Output was initially 900 hp in 1933, but this rose to 1,200 at 1,600 rpm in the production DB 602 used in *LZ129 Hindenburg*; in *LZ130 Graf Zeppelin II* output rose to 1,320 hp at 1,650 rpm, for a weight of 1,976 kg.



All the Daimler-Benz inverted V-12 production engines were beautifully clean externally. This is a 1,350-hp DB 601E-1, powerplant of the Bf 109F-4.

The DB 603 was the largest of Germany's mass-produced liquid-cooled engines, with 44.5 litres against the 27 of the Merlin. Almost all the German inverted V-12s had the supercharger running on a transverse shaft.

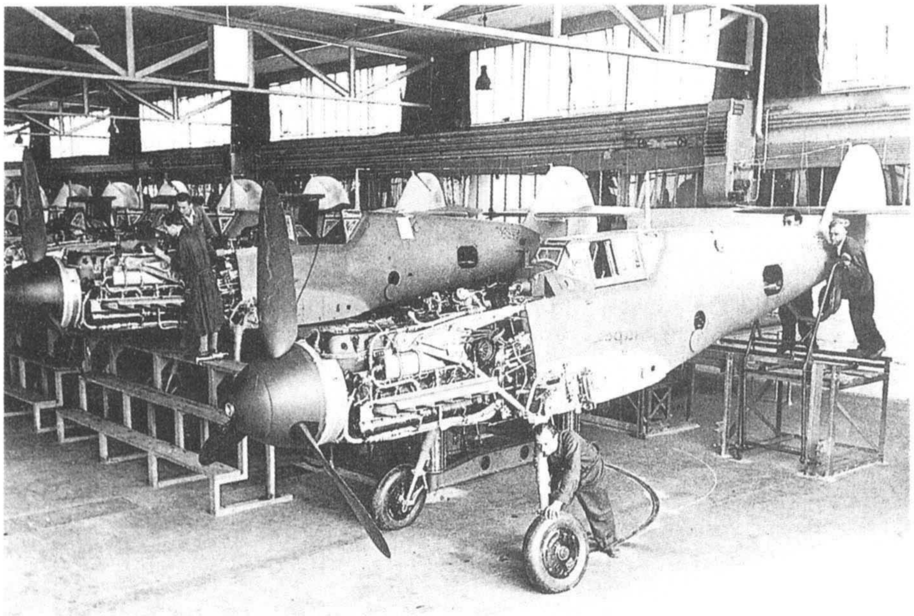


Throughout the first half of the 1930s the famous and properous firm studied the prospects for a new high-power aero engine, and in 1934 settled on the inverted V-12 layout with glycol cooling. The DB 600 had cylinders of 150 × 160 mm, capacity being 33.93 litres. Each cylinder block was a casting in Silumin (Si-Al alloy) with dry steel liners screwed (and, in pre-war engines, shrunk) into the block. The liner skirt projected and was threaded so that the block could be pulled down rigidly against the internally ribbed dural crankcase, the bottom cover finally being secured by studs and dowel-pins. The supercharged and geared DB 600A weighed 679–87 kg and was rated at 986 hp for take-off and 910 hp at 13,120 ft.

Delivery of prototype engines began in December 1935, the first flight being in the He 118 V2. The He 111 V5 followed in late January 1936 and the Bf 110 Vl flew on 12 May 1936. Luftwaffe expansion resulted in demand far exceeding the capacity of the Stuttgart-Unterturkheim works, and DB production was organised increasingly widely, by 1944 embracing eight major plants run by the company and six run by other organisations. The DB 600 was earmarked for bombers, the He 111B, D and J taking almost all available engines.

The DB 601 was thus eagerly awaited for fighters, notably the Bf 109 and 110, but though the new engine was running in 1935 there was a major bottle-neck in production, partly due to poor reliability by both it and the DB 600. The 601 differed in having Bosch direct injection, which in the Battle of Britain embarrassed the RAF by being unaffected by negative-g; other advantages were immunity to choke-tube icing, better behaviour on inferior fuel (87-PN maximum) and claimed lower fuel consumption. The 601 also introduced a fluid clutch drive to the supercharger, which in most DB engines was arranged on the left side and driven by a transverse shaft. Like the long-established Daimler Fluid Flywheel, the oil-coupled drive turned the blower slowly at sea level but slip was progressively reduced almost to zero at rated height. The 601A was rated at 1,100 hp at 3,700 m, take-off power being 1,050 hp. The 10th prototype 601 was prepared as the 601ARJ for the speed-record Me 209 V1, rated at 2,300 hp at 3,500 rpm with methanol boost for 1 minute. The 601E was cleared to run at 2,700 rpm and also had an improved supercharger, while the 601N introduced flat-top pistons to increase compression from 6.9 to 8.2, requiring 96-PN fuel, with rating 1,270 hp at 5 km.

This brings the story forward to mid-1940, where the new projects became so unbelievably prolific, under technical director Dipl-Ing Fritz Nallinger, that they are listed in numerical order: DB 602, already listed; DB 603, enlarged engine with cylinders 162 × 180 mm, capacity 44.5 litres, rated 1,750 hp at 2,700 rpm and produced from May 1942 (initially in small numbers because Nallinger had not obtained



Pushing one of 23,000 Bf 109Gs off a Messerschmitt line in 1942. The DB 605A engine was hung from forged Elektron (magnesium alloy) bearers, behind which can be seen the inlet to the supercharger.

RLM permission and the 603 was officially viewed with disfavour). Subsequently 8,758 were built with powers varying up to 2,830 hp at 3,000 rpm (603N); 604, X-24 with cylinders 135 mm square, 46.5 litres, weight 1,080 kg, tested 1940 at 2,660 hp at 3,000 rpm, abandoned 1942; 605, major successor to 601 with blocks redesigned to permit bore of 154 mm, capacity 35.7 litres, selected for Bf 109G early 1942 at 1,475 hp at 2,800 rpm, subsequently 14 production and numerous experimental models including 605AM series with DB 603 supercharger; 606, coupled engine comprising two 601s side-by-side with inner blocks almost vertical with common reduction gear to single propeller, first flown mid-1937 in He 119, rating 2,700 hp, weight 1,565 kg; DB 607, diesel DB 603, 1,750 hp; DB 609, 16-cylinder DB 603, 61.8 litres, 2,660 hp, 1,400 kg; DB 610, coupled DB 605s as DB 606, 2,950 hp, 1,580 kg, several production models; DB 612, DB 601 with rotary valves, 1,350 hp; DB 613, coupled DB 603Gs, 3,800 hp, 1,993 kg; DB 614, advanced DB 603, 2,000 hp; DB 615, two DB 614 in tandem with contraprop; DB 616, DB 605 development; DB 617, developed DB 607; DB 618, coupled DB 617; DB 619, coupled DB 609, 123.6 litres; DB 620, coupled DB 628; DB 621, DB 605D with two-stage superchargers; DB 622, DB 603 with two-stage superchargers followed by turbosupercharger; DB 623, DB 603G with twin turbosuperchargers; DB 624, DB 603G with totally different series of two shaft-drives plus one turbo-supercharger plus intercooler; DB 625, DB 605D with turbo; DB 626, DB 603G with twin turbos and intercooler; DB 627, DB 603G with two-stage superchargers and aftercooler – survived until March 1944; DB 628, DB 605A with large super-charger added around reduction gear with intercooler before original supercharger entry; DB 629, DB 609 versions with two-stage superchargers followed by turbo; DB 630, base engine for new series, W-36 configuration with cylinders 142 × 155 mm, 89 litres, 4,100 hp; DB 631, DB 603G with three-stage superchargers; HZ Anlage, power installation comprising two DB 603S or T on wings supercharged from giant Roots blower in fuselage driven by DB 605T, rated height 13.8 km.

Gas Turbines

With such a programme brewing it is small wonder that in October 1938 Nallinger refused to enter the field of gas turbines. In 1939, however, he decided he might be at a competitive disadvantage with no such experience, and he reluctantly agreed to get started. The company rejected Mauch's government scheme that it should take over Heinkel's programme, and instead agreed to develop a very advanced ducted fan, the 109-007. Work was started in September 1939 under Prof Karl Leist, who had joined in January after heading turbosuperchargers at DVL. The 007 was an engine that looks impressive even today. It had two contra-rotating spools, the inner spool having nine stages of compressor blading and the outer having eight interleaved stages of compressor blading internally and three stages of fan blading externally, the fan being in a full-length duct. There were four tubular combustion chambers whose gas was fed to 70 per cent of the periphery of the turbine. Design thrust was 1,400 kg at 900 km/h at sea level.

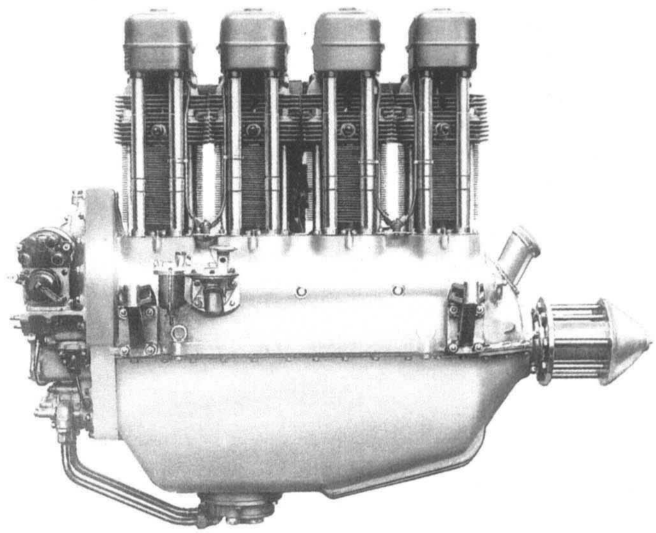
The prototype ran in June 1943 and soon gave a static thrust corresponding to 610 kg at 900 km/h at 7,200 m. It was cancelled in autumn 1943 because of its long-term nature; in its place DB was told to develop urgently the 109-021 turboprop, using the gas generator of the Heinkel-Hirth 109-011 (*qv*). Intended for a long-range Ar 234, it was to give 3,300 hp at 900 km/hr (height unstated).

In 1956 the resurrected company began designing a family of gas turbines, starting with the DB 720 turboshaft of 1,330 shp. This led to the DB 730 aft-fan turbofan of 1,433 lb thrust, 730F of high bypass ratio rated at 2,205 lb thrust, 730H gas-bleed engine for driving a remote-drive helicopter and the 721 turboprop of 2,180 shp. No customers were found.

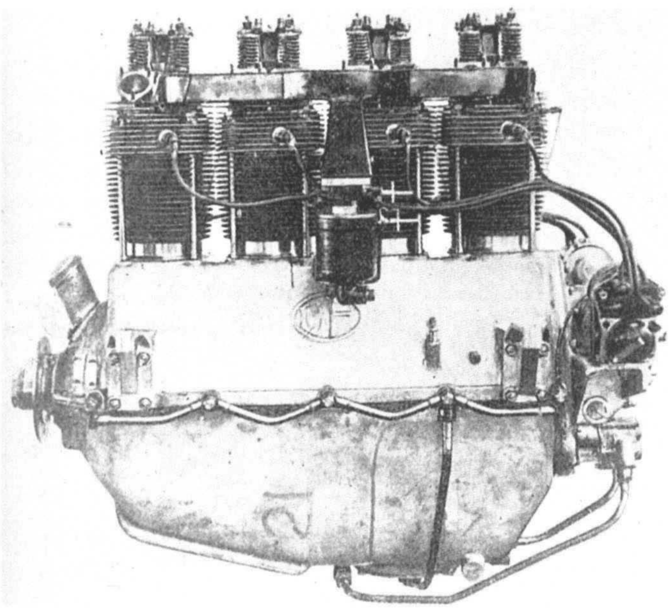
Dassault (FRANCE) In 1953 this aircraft company obtained a licence for the Armstrong Siddeley Viper turbojet in its 'longlife' version, rated at 1,640 lb, and developed handed versions for mounting on the wingtips of the SO.9000 Trident, flown on these engines in March 1955. Different installations were used in the twin-Viper MD.550 Mirage I, for which Dassault later developed the afterburning Viper MD.30R. By 1957 the company's own R.7 was on test, this being a Viper scaled up to 25 kg/s airflow and rated at 1,450 kg at 11,800 rpm (compared with 13,400 rpm for the Viper). The afterburning R.7R was never tested.

de Havilland (UNITED KINGDOM) In late 1926 Halford (*qv*) and de Havilland agreed that the Cirrus (derived from the old Renault) should be followed by a 'clean sheet of paper' engine, and the result was the Gipsy air-cooled four-in-line, run before the end of June 1927. Halford continued to use metric units, cylinders being 114 × 128 mm, and capacity 5.23 litres. The prototype was, in fact, built as a special racing engine tuned to 135 hp at 2,650 rpm on 80-PN fuel, fitted to the DH.71 Tiger Moth monoplane. In 1928 series production began of the Gipsy I, with take-off rating of 98 hp at 2,100 rpm. In the first nine months of 1929 an engine taken at random was sealed and flown in a Gipsy Moth for 600 hours; when stripped, the bill for repairs came to £7. In 1929 the Gipsy II had the longer stroke of 140 mm, giving take-off power of 120 hp at 2,300 rpm. The DH Ghost was a V-8 of 200 hp using Gipsy I cylinders. The Gipsy III was the first inverted model, as were all its successors; it was essentially a Gipsy II, but of course with dry-sump crankcase. In 1931 bore was increased to 118 mm without increasing weight (305 lb) and the result was the Gipsy Major I, which at 14,615 engines accounted for just over half the total for all Gipsy engines.

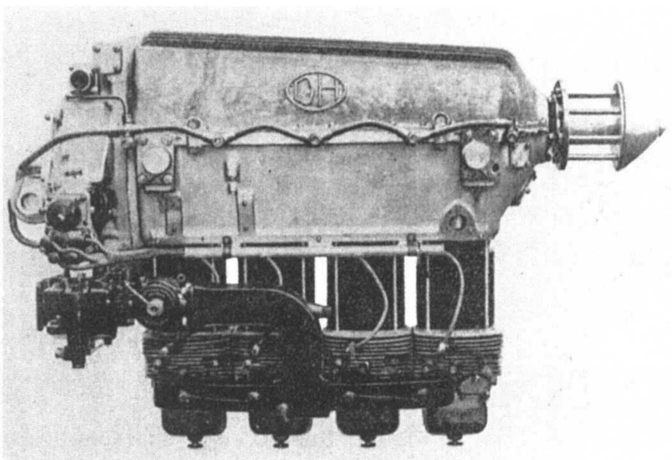
In 1932 a 200-hp engine was needed for the DH.86 and the answer selected was a six-in-line, the Gipsy Six. This always suffered from torsional vibration, and after its first run – when it vibrated so much it became a blur – had the odd firing order of 1-2-4-6-5-3. The Six was type-tested just in time to fly the first DH.86 on 14 January 1934. Nine months later the



The Gipsy II appeared in spring 1930, and not only gave up to 120 hp but introduced enclosed valve gear.

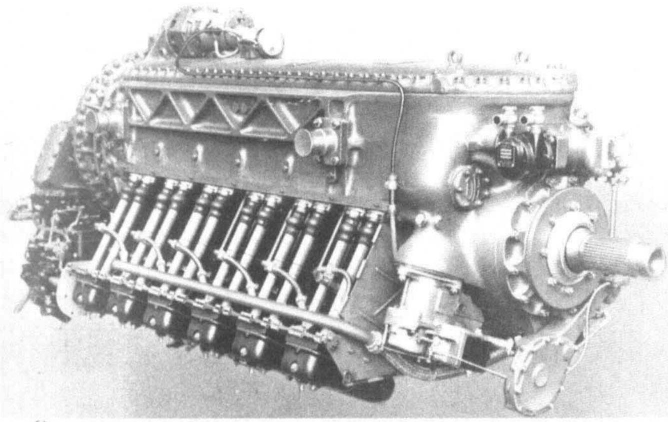


The first Gipsy I was a 135-hp racing engine hand-made to Halford's design by Stag Lane fitters Weedon and Mitchell. The production engine was derated to 85 hp.



Apart from the redesigned crankcase the Gipsy III of 1931 was virtually a Gipsy II turned upside-down. It was a great success and the IIIA went into production as the 130-hp Gipsy Major.

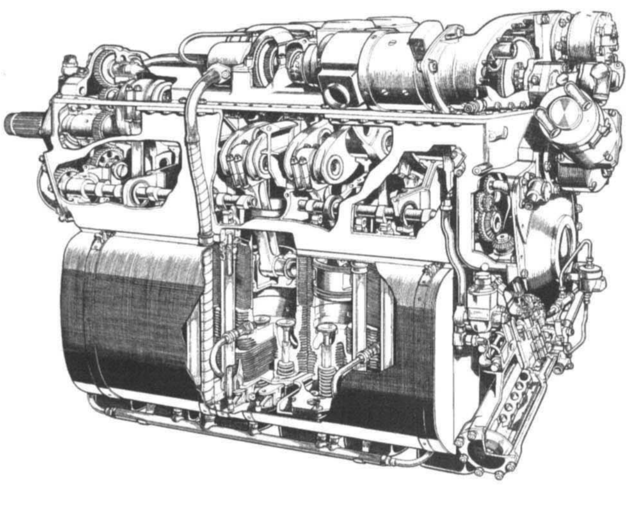
Flat discs on the spinners identify the French Ratier propellers on Comet *Grosvenor House*, winner of the 1934 MacRobertson race. They replaced the pilot-controlled Hamiltons fitted for initial test flying. The DH Gipsy Six R engines were also new.

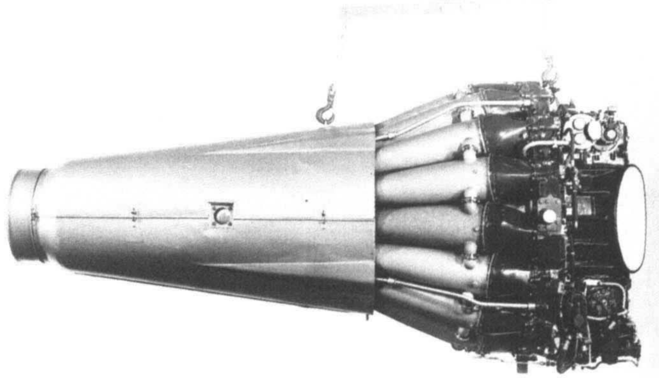


Left: Biggest de Havilland piston engine, the Gipsy Twelve (RAF Gipsy King) was made only in small numbers (about 95). Halford was distressed that it weighed over 1,000 lb.

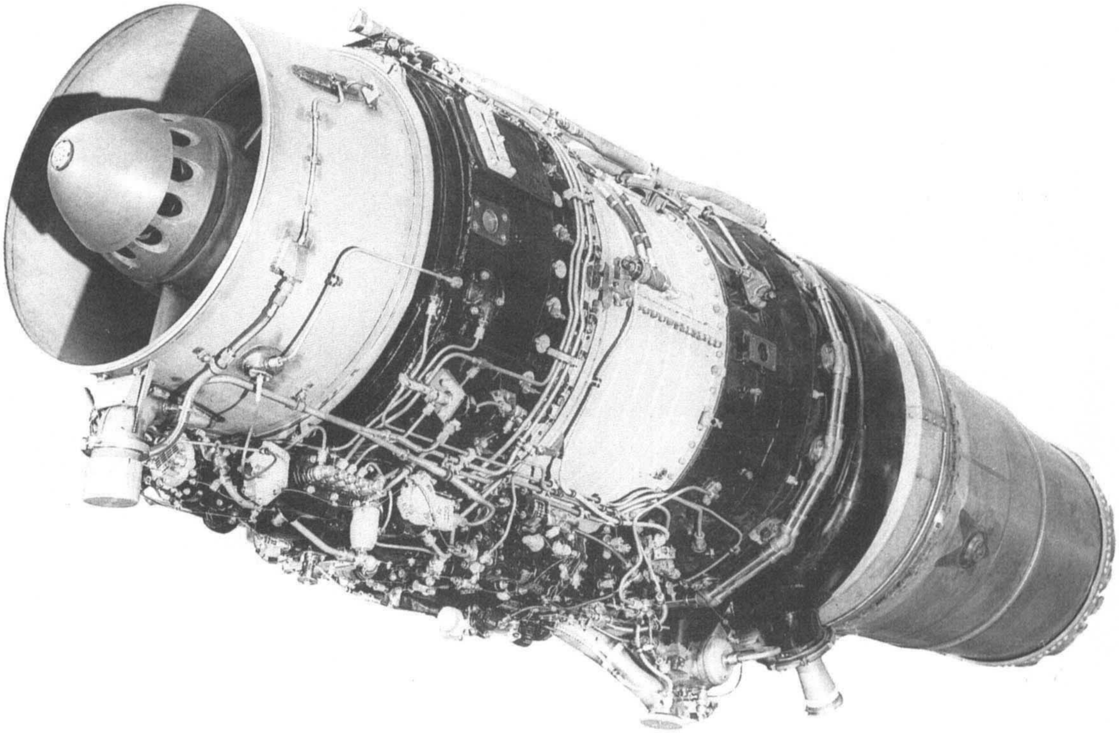
Below left: A de Havilland cutaway of the Gipsy Queen 30, the unsupercharged direct-drive member of the largely redesigned postwar family. It was rated at 250 bhp.

Below: The de Havilland Goblin was the first gas turbine to pass a British type-test, and by mid-1945 had completed a 500-hour test without change of 'any main component'. This picture dates from that time.





The first-generation de Havilland (Bristol Siddeley) Gyron Junior, the PS.43, was a neat 7,100 lb engine for the Buccaneer, with provision for an enormous boundary-layer-control bleed flow.



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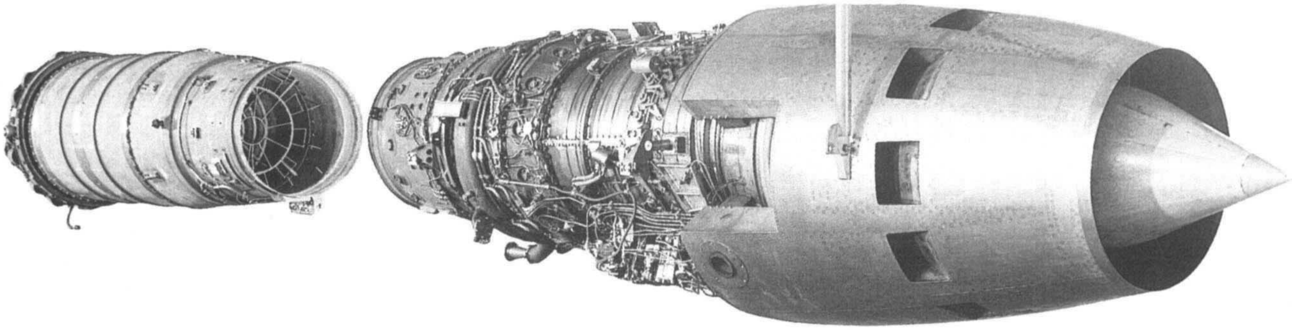
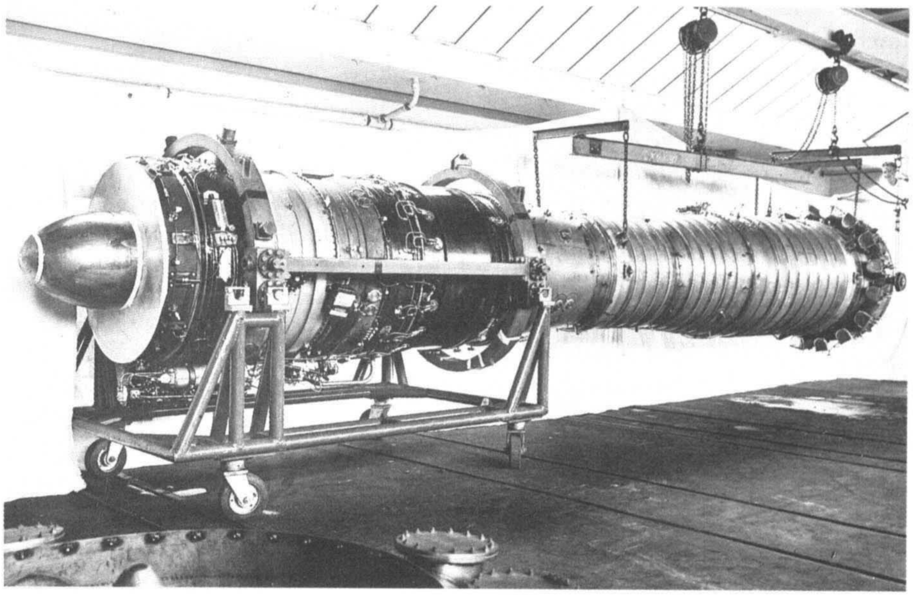
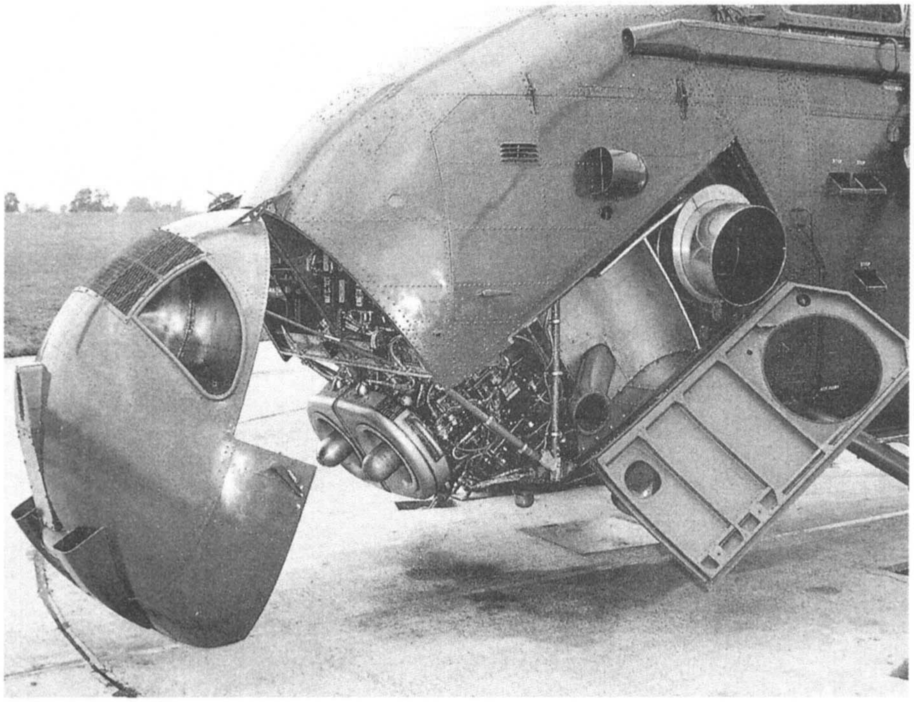


The de Havilland (later Bristol Siddeley) Gyron Junior PS.50 (DGJ.10) was very different from the original Junior. Engine of the all-steel Bristol 188, it is shown with its variable inlet at take-off setting and the 2,000K afterburner detached. The 188 did not carry enough fuel to reach the design Mach number of 2.5.



Bigger and heavier than the engine of Concorde, the de Havilland PS.26-6 Gyron with afterburner was tested in 1955 at 23,900 lb thrust at 6,400 rpm, and the PS.26-3 was to be rated at 27,000 lb. By 1957, when the Ministry halted further work, just over 28,000 lb had been recorded with a simulated P.1121 inlet system.



When Westland turned the S-58 helicopter into the Wessex they fitted the Napier Gazelle. Later most Wessex had the Bristol Siddeley Coupled Gnome, seen here, which provided a power reserve of 1000 hp.

MacRobertson race to Melbourne was won by a DH.88 Comet powered by two of the special Six R racing engines with 6.5 compression and high-lift valves, rated at 230 hp at 2,400 rpm. Regular production of the Six II began in 1935, with DH-Hamilton propeller and a rating of 205 hp at 2,400 rpm on77-PN leaded fuel. Small numbers were made of the Gipsy Minor, with 102 × 115 mm cylinders, capacity 3.759 litres and rated at 75 hp in 1931 and 90 hp at 2,600 rpm in 1938. The Minor tooling was shipped to Australia on the outbreak of war, but no production took place there. Curiously, DH Australia redesigned their Gipsy Majors for Tigers to have Imperial measures.

An oddball was the Gipsy Twelve, or Gipsy King, an inverted V-12 with regular 118 × 140 mm cylinders, capacity 18.37 litres. It was cleared to run at 2,600 rpm, giving 525 hp, and in the DH.91 and 93 was beautifully cowled with cooling air ducted in the reverse direction from leading-edge inlets. Halford designed the Twelve during his 1935–7 stay in an office in Golden Square, London. Still a freelance, he then agreed to head a design team of 52 at the de Havilland engine works at Stag Lane, where in 1938 he planned a complete new range of Gipsy engines with cylinders 120 × 150 mm, the Major 30 and supercharged 50 of 6.78 litres and the Gipsy Queen 30, supercharged Queen 50 and supercharged and geared Queen 70. Production had to wait until the end of the war, when these new engines, with much greater fin area, and new light-alloy heads and pistons giving 6.5 compression, went into production in fair numbers. The two Majors were rated at 160 and 207 hp, and the three Queens at 250, 295 and up to 400 hp. The last Gipsy of all was the 200-hp Major 200 and its methanol-boosted helicopter version, the Major 215, rated at 215 hp or 222 hp at altitude with turbocharger. Total Gipsy deliveries amounted to 27,654.

Gas turbines

In January 1941 Sir Henry Tizard invited de Havilland to design a jet fighter and the engine to go with it. No specification was issued, but Halford had access to Whittle's work. The decision was taken to use a single engine with the then very high thrust of 3,000 lb, fed from wing-root inlets to a single-sided centrifugal compressor. Another new feature was the use of straight-through combustion chambers, and because of the lack of high-power test facilities there were to be 16 of them. The Halford H.1 was on paper in April 1941, drawings went to the shops at Stonegrove and Stag Lane in August, and the first engine ran in April 1942, reaching 3,010 lb thrust two months later. No airframe existed for it, but eventually two were cleared for flight at 2,000 lb in a Gloster F.9/40 (*DG206*) and flown on 5 March 1943; this was the first flight of a British jet aircraft since the E.28/39 two years previously.

Named Goblin, the engine was flown in the prototype DH.100 at 2,300 lb on 26 September 1943. It was type-tested at 2,700 lb in January 1945 and, as the Goblin II with a new combustion chamber, at the design thrust of 3,000 lb in July 1945. In early 1943 the US Army and Navy were both anxious to have the H.1 built in the USA, and the choice fell on Allis-Chalmers. When Lockheed wrecked the first Goblin in the prototype XP-80 Shooting Star, de Havilland generously removed the engine from the second DH.100 Vampire (the only one available) and sent it by air. It powered the US fighter on its first flight on 9 January 1944. A month later the de Havilland Engine Company was formed, it having previously been a mere division, and Halford at last came on the payroll as chairman. He promptly planned the product line for 1944–5: the H.1 Goblin; an enlarged centrifugal turbojet, the H.2 Ghost; the H.3 centrifugal turboprop of 500 hp; the giant H.4 Gyron axial turbojet for eventual supersonic flight; the H.5, a developed and uprated H.2; the H.6 Gyron Junior; and the H.7 gas producer for helicopter tip drive.

The H.2 Ghost was designed to an airflow of 88.5 lb/s, compared with 63 for the Goblin. It had only 10 chambers, each fed by a pair of tangential elbows from the diffuser. The initial application was the company's own Comet airliner, and this called for a plain circular front inlet, as well as a large bleed manifold for cabin pressurisation, an air supply never before attempted on a passenger aircraft. The engine first ran on 2 September 1945, was cleared for flight at 4,000 lb in the outer positions of Lancastrian VM703, and later set a height record in a special Vampire. In the latter the Ghost had to have twin diagonal inlets, and in this form it was built in large numbers for most versions of the Venom. Svenska Flygmotor built various models as the RM2, the final RM2B having an afterburner and lateral clamshell nozzle. The H.3 was bench-run only.

The H.4 Gyron was designed to the modest pr of 6, with a seven-stage compressor, most of the compression being by ram from Mach numbers around 2. Airflow was 320 lb/s, there were 16 Duplex burners in the annular chamber, the turbine had two stages and it was planned to add an afterburner. The Gyron first ran on 5 January 1953. It passed a type-test at 15,000 lb in the same year, was flown in a Sperrin on 7 July 1955 at ratings up to 20,000 lb and was picked by Camm at 27,000 lb with afterburner (PS.26-3 version) for the Hawker P.1121 built at company expense, and finally abandoned after the government minister had insisted the RAF would never need any more fighters. The H.5 was not built, but the Gyron Junior was picked to power the Blackburn NA.39 low-level bomber which became the Buccaneer.

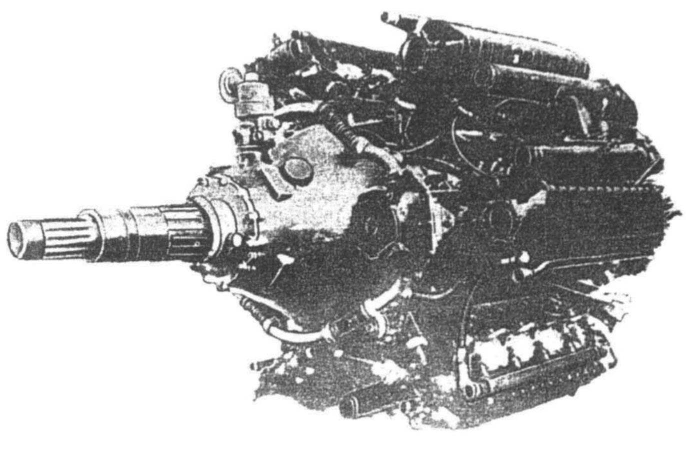
First run in August 1955, the Junior was a 0.45 scale of the Gyron, with 13 spill-type burners and cast blades in the first-stage turbine operating at up to 1,200°C. Take-off rating was 7,100 lb in the PS.43 version produced as the Gyron Junior 101 for the Buccaneer, with a large air-bleed flow for aircraft BLC (boundary-layer control) purposes. The supersonic afterburning PS.50 for the steel Bristol 188 was rated at 14,000 lb.

The H.7 study was the basis of the Napier Oryx, but the DH Engine Company had a very important additional business based on the technology of HTP (high-test peroxide). The first HTP unit was the Sprite ATO (assisted take-off) rocket for the Comet 1. Next came the much larger jettisonable ATO rocket pod attached under the wings of the Valiant, the engine being the Super Sprite using HTP/kerosene. Finally the Spectre was a big rocket engine of 8,000 or 10,000 lb thrust, using HTP/kerosene, and produced as an ATO pack for the Victor bomber and as a fully controllable powerplant for the SR.53 and 177 mixed-power interceptors. An advantage of rocket power is that output increases as the aircraft climbs, the reverse of normal, and this was an appreciated feature of a wide range of HTP devices produced for advanced combat aircraft including starters and APUs (auxiliary power units). The company took a licence for the General Electric T58 and ran the first de Havilland Gnome on 5 June 1959, altered to have a Lucas fuel system with Hawker Siddeley Dynamics computer. The licence for GE's T64 was not put to use. In 1959 the firm merged into Bristol Siddeley.

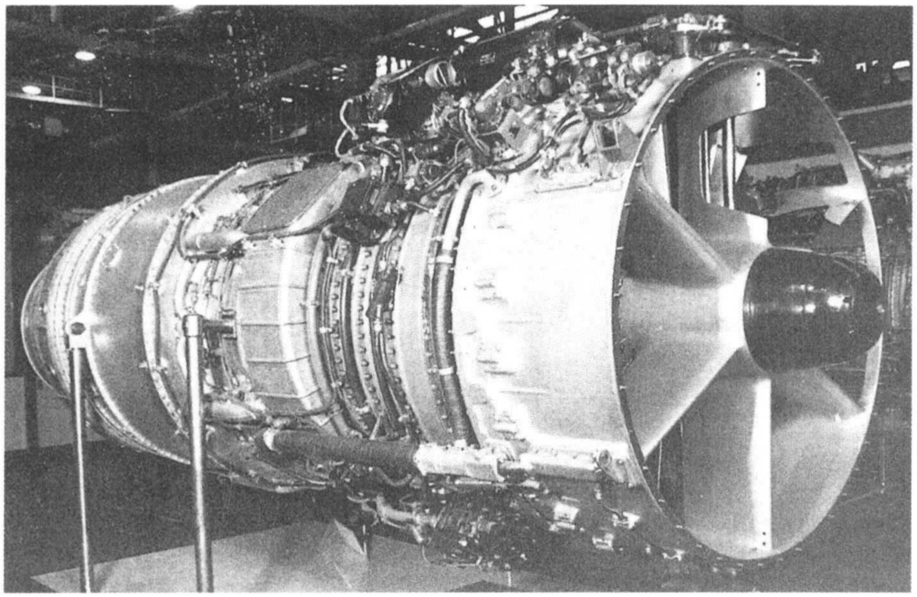
DEMC (CHINA) The Dongan Engine Manufacturing Company employs some 12,000 in Harbin, in what was formerly Manchuria. Founded in 1948, it produced the HS7, based on the Russian ASh-82V helicopter engine, and the derived HS8 for the fixed-wing Il-14, Tu-2 and (replacing the original Wright R-2600) Curtiss C-46. Since 1977 the main product has been the WJ5, a family of turboprops derived from the Ivchyenko AI-24A.

Dobrotvorskii (SOVIET UNION) Aleksei Mikhailovich Dobrotvorskii was permitted in about 1943 to develop a powerful engine using four Klimov VK-103 cylinder blocks in X-formation on a common crankcase, the two crankshafts being geared to a single large four-blade propeller. Designated MB-100, it gave 3,200 hp on test in January 1945. It was installed in a Yer-2 (after that KB (construction bureau) was taken over by Sukhoi), in a neat 1.95 m diameter cowl, but there is no record of flight. This designer was probably also responsible for the MN-102 engine intended for the Myasishchev DVB-102DM, left incomplete in 1944.

Dobrynin (SOVIET UNION) Vladimir Alekseyevich Dobrynin was a designer and lecturer at Moscow Aviation Institute in the 1930s. In 1939 he collaborated with G.S. Skubachevsky on the M-250, with six banks of four water-cooled cylinders with bore 140 mm and stroke 138 mm, which in 1941 was tested at 2,500 hp at 3,100 rpm. Later he became a General Designer,



Dobrynin's M-250 was the predecessor of the VD-4K shown in the drawing on page 64.



The VD-7 was designed to power the 3M (ASCC name 'Bison').

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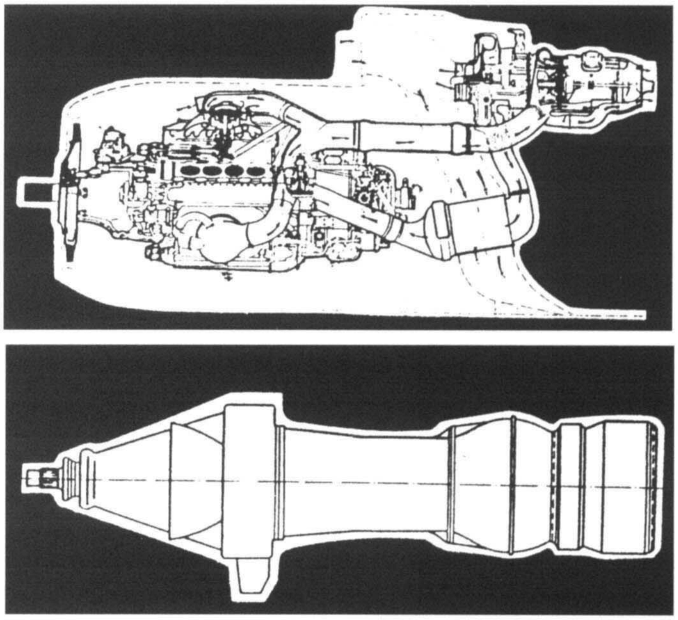


The most powerful piston engine ever to fly was Dobrynin's VD-4K, installed in the Tu-85 bombers with a giant exhaust-driven turbocharger. Tupolev wisely switched to the NK-12M turboprop (lower drawing, to the same scale) of almost four times the power.

the M-250 being redesignated VD-4 and developed into the VD-4K with blowdown turbines and a giant turbocharger to give 4,300 hp for the Tu-85. He also produced the 2,200-hp VD-251 liquid-cooled V-12 for the Alekseyev I-218.

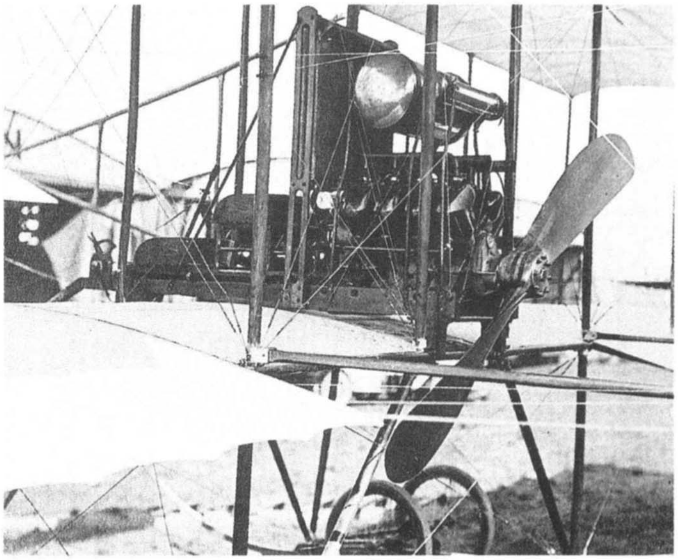
Dobrynin was entrusted with designing the turbojet to power the Myasishchev 3M heavy bomber. Large airflow meant high power, and high pressure ratio gave outstanding fuel economy, and the VD-7 rated at 24,250 lb thrust transformed the aircraft which had previously, as the M-4, been powered by the RD-3. Sadly, engine failures were frequent, and later 3M versions were powered by RD-3Ms or by Dobrynin's derated VD-7B of 20,943 lb. By 1959 reliability had improved, resulting in the VD-7F with afterburner giving 30,865 lb, VD-7P rated at 24,910 lb, VD-7M rated at 35,275 lb and without afterburner in the VM-T at 24,250 lb, and for the Tu-22 the VD-7M-2 (RD-7M-2) rated at 36,376 lb. The reduced-diameter VD-19 (22,480 lb with afterburner) was too late to power the Tu-128. Dobrynin's successor was Kolesov (*qv*).

E

Engine Alliance (USA) In May 1996 GE and Pratt & Whitney announced that, to meet the competition of the RR Trent 900, they would jointly develop an entirely new engine optimised to the propulsion of the stretched 747-500X/600X. In the event Boeing abandoned these projects, but the two engine partners have continued to develop the GP7000 family of engines. The most important is the GP7200 family, rated at 72,000 lb, which competes with the Trent 900 to power the A380. Features include a 116.7-in fan, with curvy blades, rotating with a five-stage LP compressor, and a nine-stage HP compressor. GE are responsible for the core (HP compressor, combustor and HP turbine), while P&W make the rest, and carry out assembly and test. The engine first ran in March 2004, six years behind schedule. A380 No. 009, the first with these engines, began flight testing in August 2006.

ENMA Elizalde (SPAIN) Elizalde SA, a major automotive firm, produced licensed Lorraine aero engines from 1925, but in 1929 began considering a range of locally designed engines. First came several variants of the Dragon five-cylinder radial, with the larger Super Dragons. Immediately after the civil war it re-equipped the Barcelona factory and began a series of Tigre inverted air-cooled in-line engines with cylinders 120 × 140 mm. The four-cylinder Tigre IVA and IVB, respectively with compression ratio 6 and 6.5 and rated at 125 and 120 hp, remained staple products for many years, but the planned six-, eight- and 12-cylinder models never materialised. In 1944 came the Sirio S-VII seven cylinder radial with cylinders 150 × 145 mm, initially rated at 450 hp, rising to 500 hp in the 1950s.

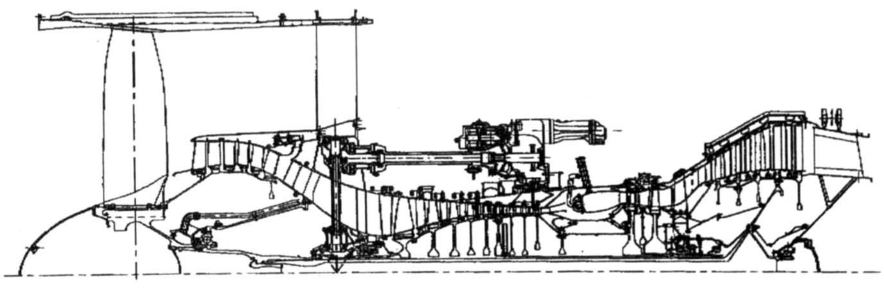
The old firm was taken over in 1952 by Enmasa or ENMA, Empresa Nacional de Motores de Aviaciòn SA. Work began on the Beta radial with nine cylinders, 155.5 × 174.6 mm, rated at 775 hp. In 1954 work began on the 275-hp Alciòn radial for horizontal and vertical installation, with seven cylinders 110-mm square, followed a year later by the 90-hp Flecha flat-four with cylinders 105 × 100 mm which ran in 1957. This was the high point. ENMA then began importing Turbomeca engines, and most of the piston engines faded from the scene. Marboré turbojets were made under licence, but for many years Spain has had no piston aero-engine manufacturing industry.



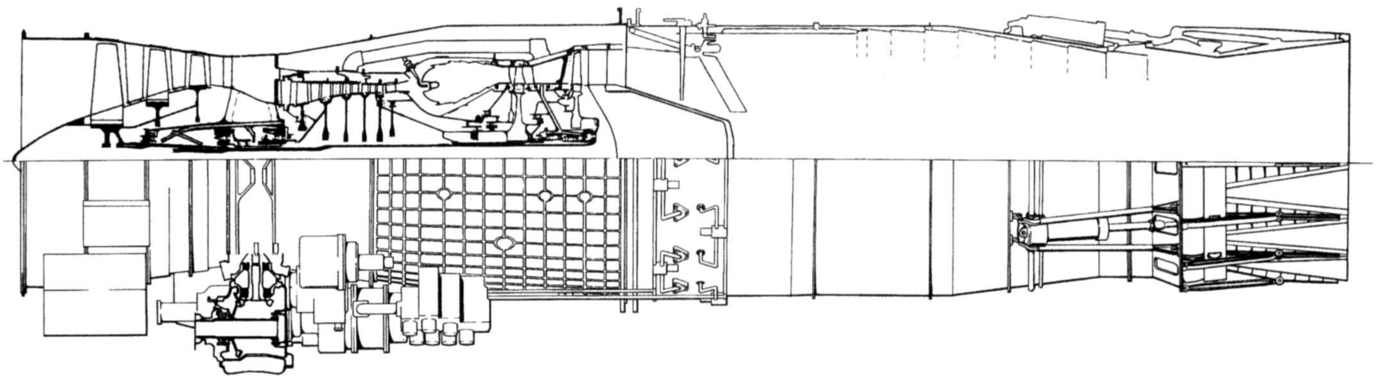
Seen installed in Bristol Boxkite No. 8 at the August 1910 Lanark meeting, the ENV eight-cylinder was in this machine called '50/60 hp'. Note the fuel tank and huge water radiator.

ENV (UNITED KINGDOM/FRANCE) The ENV, made in two sizes, was one of the best engines of 1909. It was designed in England but built at Courbevoie in France, and the name came from the fact it was *'en V'*, French for its configuration of a V-8. The water-cooled cylinders were 85 × 90 mm in the small 40-hp size, which sold for £350 in 1910, and 105 × 110 mm in the 60-hp engine, priced at £450. Its conservative and sound design gave fair reliability, features including electrodeposited copper water jackets on cast-iron cylinders, two valves per cylinder driven from a camshaft above the crankcase (sliding axially to vary ignition timing and valve lift), a Bosch magneto and coil and advanced forced lubrication.

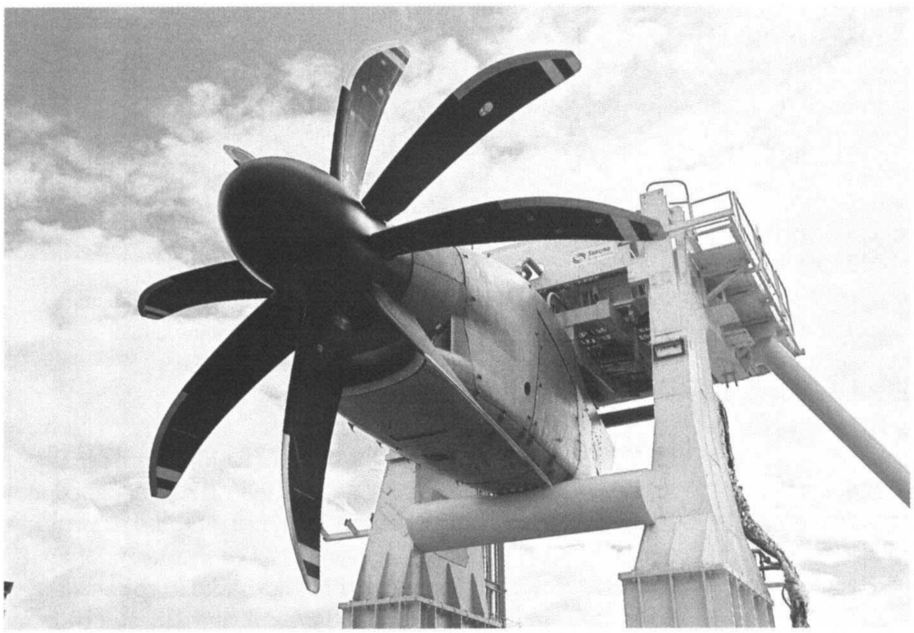
Eurojet (INTERNATIONAL) Eurojet Turbo GmbH was formed in August 1986 to manage the EJ200 engine programme for the Eurofighter Typhoon aircraft. Like the Eurofighter itself, this is a four-nation programme. Workshares have been allocated in



In late 1997 the design of the Engine Alliance GP7176 was essentially complete. This section through the upper half of the engine (transmitted by Fax) shows the main features, which include wide snubberless fan blades, three core booster stages and a single annular combustor.



Side elevation of the Eurojet EJ200, the upper half being sectioned. The basic engine is amazingly compact.



The eight-blade Ratier-Figeac propeller produced by Europrop International for the Airbus Military A400M transport, driven by the T400-D6 turboprop of 11,400 shp.

proportion to the expected aircraft requirements of the four nations, as follows: Fiat, now known as Avio, (Italy) 21 per cent, LP turbine and shaft, interstage support, reheat system, gearbox, oil system (with unique spinning oil tank to maintain artificial positive gravity in all combat manoeuvres), and participation in intermediate casing; MTU (West Germany) 33 per cent, LP and HP compressors, participation in HP turbine, and FADEC (full-authority digital electronic control) design responsibility; Rolls-Royce (UK) 33 per cent, combustion system, HP turbine, intermediate casing and participation in most other parts; and ITP (Spain) 13 per cent, bypass duct, exhaust diffuser, jetpipe and nozzle.

The EJ200 was derived from the Rolls-Royce XG40, and is an extremely compact two-shaft augmented turbofan. Despite having only three LP stages and five HP the overall pr is no less than 25. Dry and reheat ratings are about 13,500 lb and 20,000 lb. Weight is about 2,250 lb, but this might increase slightly with the introduction of a vectored-thrust nozzle, which in 1997 was at last being bench-tested by the Spanish partner. Service entry was achieved in 2002, nine years after the original target, the delays being due to indecision and politico-financial factors such as qualification for the Euro. The vectored nozzle might be introduced at a Eurofighter mid-life update. By 2006 over 300 engines had been delivered, and export sales achieved to Austria and Saudi Arabia, the latter taking over deliveries originally intended for the cash-strapped United Kingdom.

Europrop (INTERNATIONAL) In 1979 France, Germany and the UK began to plan a new airlift transport to replace the C-130, Transall and other aircraft. After 21 years of talk, documents were signed on 30 August 2000 launching the Airbus A400M, to be powered by four Europrop T400-D6 turboprop engines, driving eight-blade propellers of 17 ft 6 in diameter, the inboard and outboard engines turning in opposite directions. The partners are Avio of Italy, ITP of Spain, MTU and Rolls-Royce Deutschland of Germany, Rolls-Royce of the UK, and Snecma of France. Engine 001 ran, driving a dynamometer, at Rolls-Royce Deutschland in November 2005, and 002 drove its propeller at Snecma in March 2006.

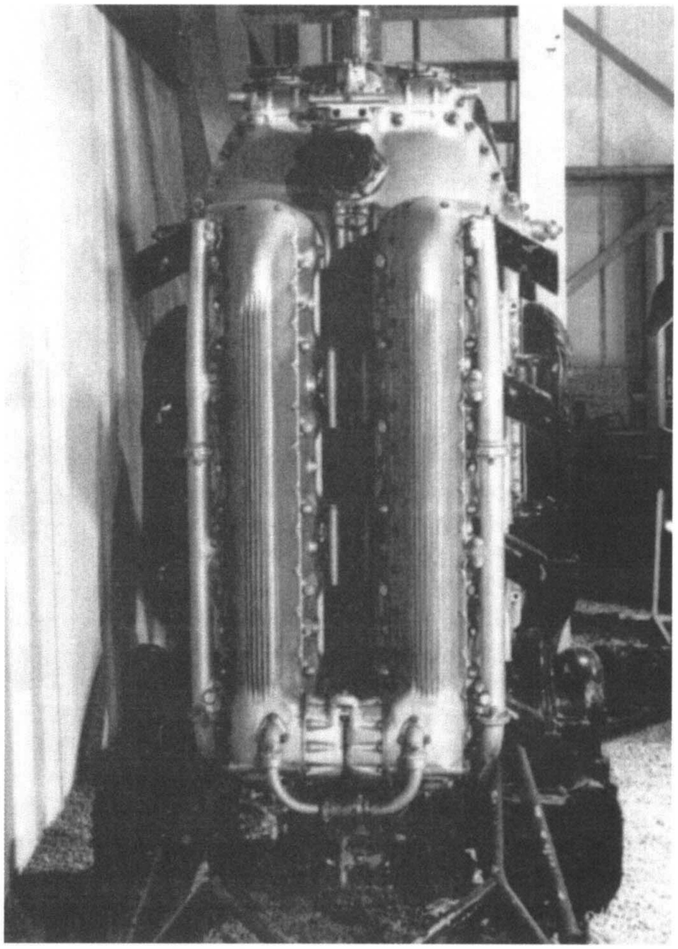
F

Fairchild (USA) After the Second World War this aircraft firm formed a guided missiles division, and also set up Fairchild-NEPA (Nuclear Energy for the Propulsion of Aircraft) at Oak Ridge, to undertake classified research. The missiles needed a small turbojet, and Ranger Engines division (*qv*) designed the J44, a simple engine of 24.3 in diameter in a monocoque casing serving structural and aerodynamic roles and often eliminating the need for a cowling. The diagonal (axial/centrifugal) compressor handled 25 lb/s at 15,780 rpm, thrust being 1,000 lb and weight 370 lb. Later a variant was used in booster pods for cargo aircraft. The 2,000-lb XJ83 did not go into production.

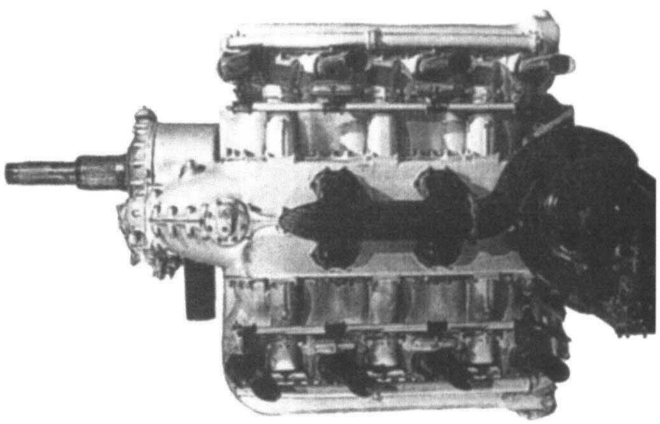
Fairey (UNITED KINGDOM) Fairey Aviation ran up against a political stone wall in its several attempts to build aero engines. The first occasion was 1924 when Richard Fairey was astonished at the technical advance of the Curtiss D-12 and Reed metal propeller. He bought licences for both, and planned a British D-12 as the Fairey Felix. The D-12 powered the Fox bomber which was so far ahead of official ideas that it was a grave embarrassment. Watching it fly in October 1925 Sir Hugh Trenchard agreed to order a squadron of Foxes, but he used the occasion as a stick with which to beat Napier and Rolls. The latter responded, and the Foxes of No. 12 Squadron were later re-engined with Kestrels.

Far from giving up, in 1931 Fairey hired Captain A.G. Forsyth as chief engine designer. Graham Forsyth had wide experience, and initially produced the P.12 Prince, a water-cooled V-12 of 1,559 cu in with a monobloc casting comprising both cylinder blocks and the upper crankcase. In complete secrecy, with Fairey's money, three prototypes were built and tested by 1933 at up to 710 hp or, in the case of the highly blown Super Prince, 835 hp. In 1934 a P.12 was flown in a Fox II, but Air Ministry policy was that there was no room for another engine company which 'could never acquire the strength needed to compete with Rolls-Royce and Bristol'.

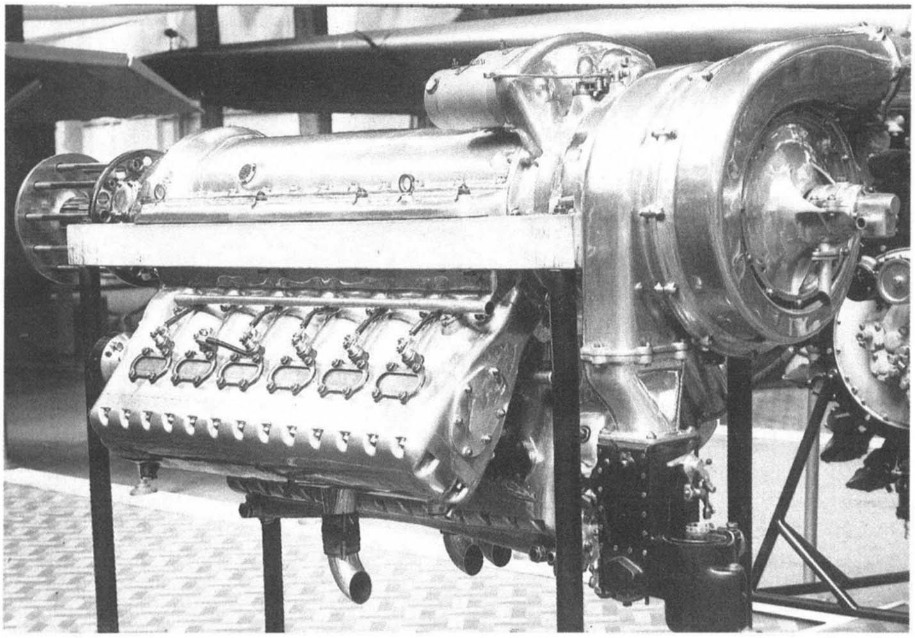
In January 1935 Fairey studied the P.16 Prince with eight-cylinder blocks and a rating of 900 hp at 2,500 rpm at 12,000 ft for 1,150 lb weight. Instead Forsyth went ahead in October 1935 with the totally new P.24, aimed at carrier-based aircraft. Twin-engine reliability was to be gained (for the first time in any engine) by having two halves each comprising a vertically opposed 12-cylinder unit with a side supercharger, with pressure-glycol cooling. Each crankshaft was geared to its own coaxial propeller, of Fairey constant-speed type. Each half-engine was tested throughout 1938 (the testbed could not handle the 2,200 total horsepower), and on 30 June 1939 the P.24 flew in Battle *K9370*. With a potential of 3,000 hp, the P.24 was considered for the Hawker Tornado and then the P-47 Thunderbolt, the Battle flying some 250 hours at Wright Field in 1942, but wartime pressures eventually forced termination of what was a very promising engine.



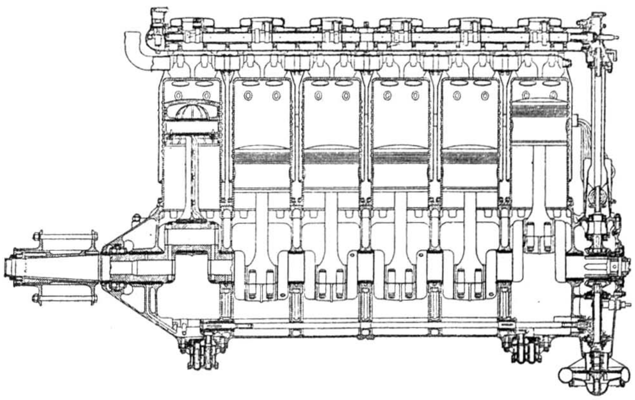
Forsyth's Fairey P.24 was simpler and much less troublesome than the Sabre, and also had the advantage that each 1,000-hp half, with associated propeller, could be shut down. It had carburettors, twin superchargers and poppet valves.



The Fairey P.24 gave three years of trouble-free flying in a Battle after it had been cancelled. (Fleet Air Arm Museum)



The Farman 18WI of 1929 had three cylinder blocks cast in Alpax silicon-aluminium alloy. Modest cylinder size permitted a crankshaft speed of 3,400 rpm, at which power was 730 hp. Dry weight with 0.407 Farman reduction gear and Rateau supercharger was 930 lb.



This longitudinal section shows the classic simplicity of the Fiat A.12bis, which delivered 328 hp from six cylinders, amazing for 1917. The secret lay in the almost-marine size of the cylinders: 160 mm bore and 180 mm stroke.

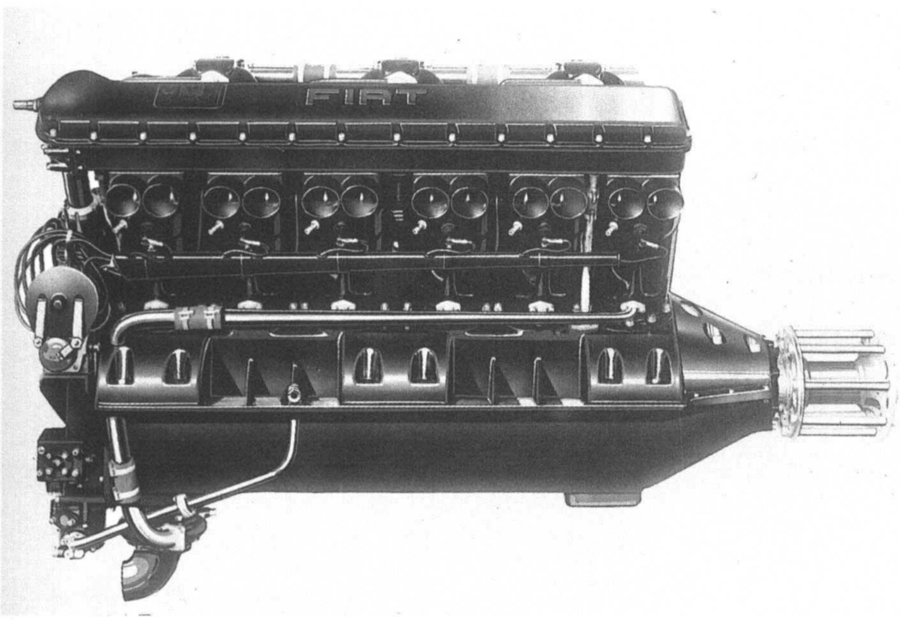
Farman (FRANCE) Between the wars France built so many types of aircraft and engine, most of them in ones or twos, that they defeat the efforts of the chronicler who has to contend with a limited size of book. Farman is an example on both counts. Avions Henry, Maurice et Dick Farman (who were originally British) had plenty of engineering talent in their vast works at Billancourt, and are credited with two of the chief inventions of the interwar period: the bevel epicyclic reduction gear, widely licensed to others, and the two-speed supercharger with clutch and gear-change.

Farman began building aero engines in 1915, and from the start concentrated on finely engineered high-power units running at high rpm, most of them water-cooled and with every conceivable geometric configuration and cylinder size. The only engine made in quantity was the 12WE, with three monobloc banks of four water-cooled cylinders, 130 × 160 mm, capacity 25.48 litres, rated at 500 hp at 2,150 rpm – very like a Lion but heavier at 470 kg and fitted with pushrods instead of overhead camshafts. This flew in an F.60 Goliath in October 1922, powered the Super Goliaths and various other Farman bombers, and kept going for 38 hours in 1924 to set a distance record in the giant single-engined F.62.

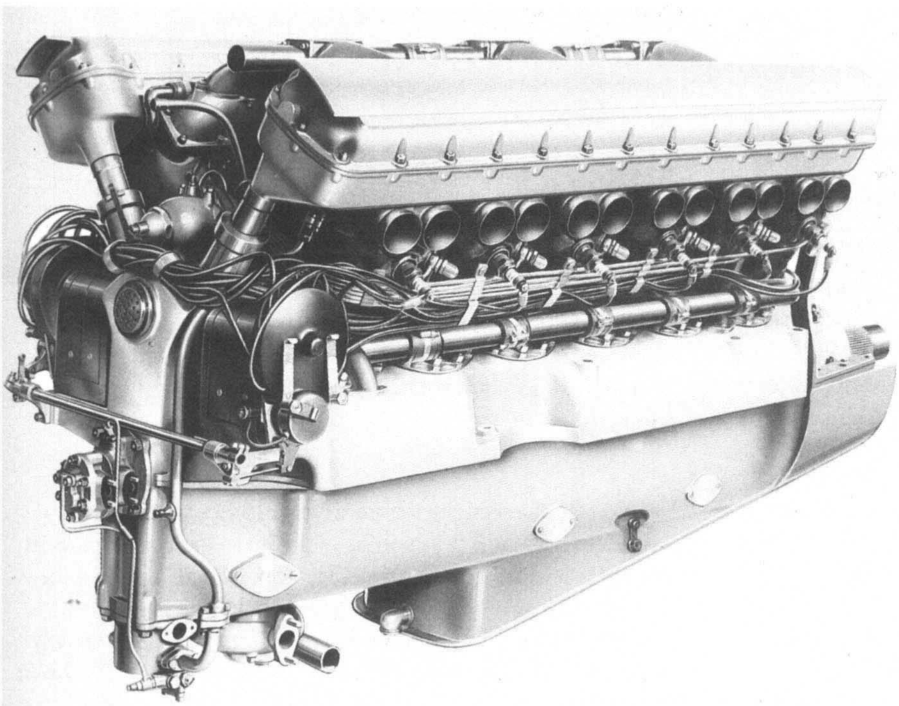
Other engines included the neat 8VI inverted V-8 (with added triple Rateau-Farman superchargers for a height record); the derived 400 hp racing version; another racing engine, the 470-hp 12Brs cleared to 4,020 rpm; the 12WI inverted V-12; and two remarkable 18-cylinder engines, the 18WI inverted engine with three banks of 110 × 125 mm cylinders, and the 18T with three banks of 120-mm square cylinders arranged in T formation. Both the 18-cylinder engines ran at 3,400 rpm.

Fiat (ITALY) This great company built its first aero engine in 1908. It drew on racing-car experience with the SA 8/75, an air-cooled V-8 rated at 50 hp with pushrods driving two overhead valves per cylinder. Many fresh designs followed, including the water-cooled S55 V-8 of 1912, but the preferred formula from 1913 was the upright water-cooled in-line with large cylinders. By far the most important of the early engines was the A 12, a hefty six-in-line with bore 160 mm and stroke 180 mm, giving capacity of 21.71 litres. On the left at the mid-length was the carburettor group which fed via different geometries of manifold in different versions, while at the back was the vertical shaft driving the overhead camshaft at the top and centrifugal water pump at the bottom. No fewer than 13,260 of these engines were delivered in 1916–19, with ratings from 248 to 300 hp. In 1917–19 Fiat also delivered 500 A 14s, at the time the world's most powerful production engine. A V-12 with cylinders 170 × 210 mm, its capacity was 57.2 litres, weight 791 kg and rated output 725 hp.

Only prototypes were built of the A 15 of 1923, a 430-hp engine with each six-cylinder block enclosed in a watertight cooling box, and with geared drive from a 2,415-rpm



The Fiat AS 2 was a racing derivative of the regular A 14 and A 22 V-12s. Ignition leads were enclosed in a metal conduit which can be seen above the water supply manifold. This was one of the first Fiats with enclosed valve gear.



In the 1920s Fiat fought Isotta-Fraschini for supremacy in powering Schneider racing seaplanes. The ultimate engine was the AS 5, which lost to Isotta in the Macchi M.67 of 1929, but in 1930–1 it was used as half the mighty AS 6, two being mounted in tandem.

crankshaft. From this was derived the monobloc A 20 of 1925, rated at the same power though with capacity reduced from 20.3 to 18.7 litres, and the A 22 of 1926 whose cylinders measured 135 × 160 mm, giving capacity of 27.48 litres and with output typically 750 hp. Several hundred A 22s were built, and they not only gained 13 distance/endurance records but also powered Balbo's transatlantic flying-boat formations. The 700–20-hp A 24 was similar. A much bigger engine was the A 25, with cylinders 170 × 200 mm (54.48 litres), rated at 1,000 hp. Last of the major V-12s was the A 30 RA family dating from 1930, typically rated at 600 hp; these powered Fiat's own biplane fighters, 2,679 engines being built. Inspired by the Gipsy, small numbers were made of the 135-hp A 60 series inverted aircooled four-in-line in 1931–4.

In addition, Schneider racing engines were created, the basis being the AS 2 for the 1926 and 1927 races, refined into the AS 5 for the 1929 race. Both were V-12s with 138 × 140 mm cylinders, 25.13 litres, the AS 5 being rated at 1,050 hp at 3,300 rpm. For the 1931 race two AS 5s were bolted together, with a vast carburettor group at the rear feeding into a giant supercharger delivering mixture along a large pipe along the top between the banks. The front engine drove the rear two-blade propeller, and the rear engine gearbox drove a shaft passing between the banks of the front engine to drive the contra-rotating front propeller. Weighing 932 kg this lengthy engine still had less capacity than the A 14, at 50.26 litres, but at 3,200 rpm it put out 3,100 hp to gain the world piston-engined seaplane speed record at 709.2 km/h (440.6 mph) which still stands. Sadly for Italy it did this three years too late for the 1931 Schneider Cup race, when it was still suffering massive and sometimes fatal backfires which were eventually cured by Britain's Rod Banks.

In 1930 the 220-hp AN.1 diesel was flown, a simple six-in-line water-cooled engine weighing 390 kg. By this time Fiat was firmly wedded to the air-cooled radial, with no more water-cooled projects apart from the RA 1050 RC58 Tifone, the German DB 605A built under licence in 1942. First important model was the A 50 of 1928, with seven 100 × 120 mm cylinders and rated at 95–105 hp. The A 53 of 1930 differed in having a bore of 105 mm and speed raised from 1,800 to 2,000 rpm, giving 120 hp. There were several other small radials, but the main business centred on high-power engines. Several of the early 1930s engines owed a little to Gnome-Rhône and Pratt & Whitney, but the first mass-production type was the 14-cylinder A 74 RC38 of 1936, rated at 840 hp. It led to a mass of 14 and 18-cylinder engines, the biggest with 140 × 165 mm cylinders, all made during the Second World War: the 770-hp A 74 RC42, 900-hp A 74 RC18, 1,000-hp A 76 RC40, 1,000-hp A 80 RC41, 1,100-hp A 80 RC20, 1.250-hp A 82 RC40 and 1,400-hp A 82 RC42.

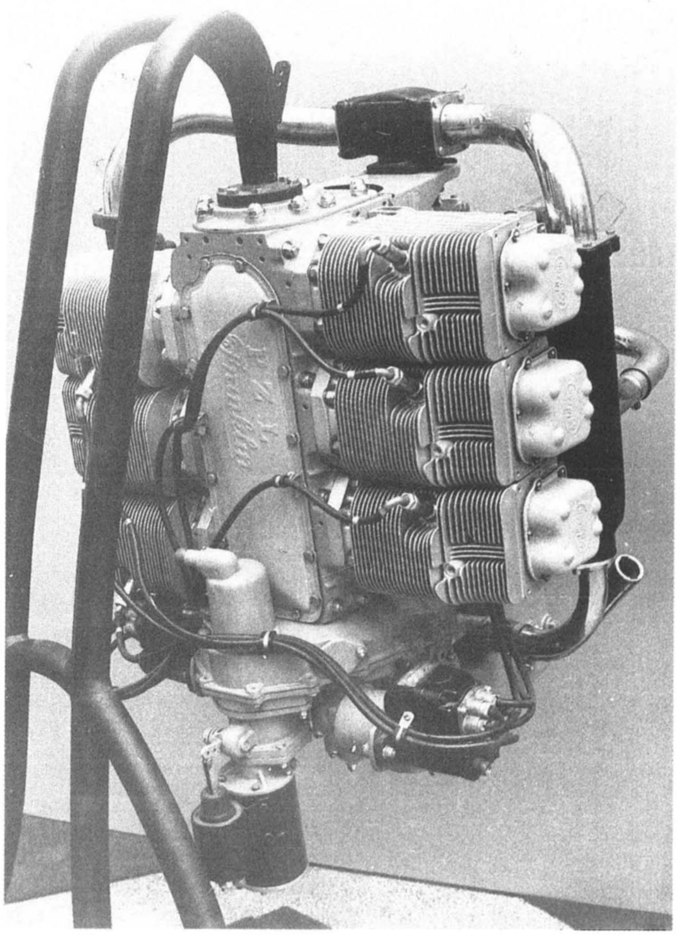
After the Second World War Fiat licence-built the de Havilland Ghost turbojet, and in 1955 produced its own Model 4002, a simple centrifugal turbojet with reverse-flow annular chamber, rated at 250 kg thrust at 26,000 rpm. This assisted design of the Model 4700 gas generator of 542 hp, which served as power unit of the Fiat 7002 tip-drive helicopter prototype of 1961.

Today a prosperous subsidiary called Avio makes no engines of its own design but has large production lines making parts for engines in which it is usually a risk-sharing partner, with considerable design and qualification responsibility. These engines are the Eurojet EJ200, General Electric CF6, GE90, GEnx,T64-P4D and T700/CT7, IAE V2500, Pratt & Whitney PW2000 and PW4000, Pratt & Whitney Canada PW308, Rolls-Royce Spey 807 and Turbo-Union RB.199. It is a partner in the Europrop company developing the TP400-D6 turboprop.

Flygmotor (SWEDEN) *See* Volvo.

Franklin (USA) Franklin automobile company failed in 1935 and the assets were bought by several former engineering staff, chief engineer being Carl T. Doman. By 1938 the new company, Aircooled Motors, had launched its range of light flat-four and flat-six aero engines, built to a very high standard. First was the 4AC-150, meaning four air-cooled cylinders of 150 cu in; it was rated at 50 hp. Subsequently the company concentrated on engines from 65 to 175 hp, with most cylinders 4.25 × 3.5 in and as many interchangeable parts as possible (and no geared drives, to reduce cost). In 1944 the 6ACV-405 introduced vertical fan-cooled units leading to massive sales to Bell and Hiller helicopters. The latter mainly used the 335 Vertical, a 335 cu in engine of 178 or 200 hp in which bore was increased to 4.5 in. The 225, with four cylinders of this size, was rated at 75 to 100 hp, and the biggest post-war unit was the 425, with six 4.75 × 4-in cylinders, rated at 245 hp.

Under chief engineer Cregan this range continued to fight for a diminishing market, with various horizontal and vertical engines of 235 cu in (not 225) with four cylinders or 335 or 350 cu in with six cylinders. In 1975 Franklin gave up and sold all rights to the government of Poland, since when PZL-Franklin engines, now called just PZL-F, have gone into production at Rzeszòw. A flat twin, the 2A-120C of 117 cu in and rated at 60 hp, now complements the 235 and 350 cu in range.



Mounted for display, this PZL 6V-350B is one of the last of the Franklins. It is a vertical helicopter engine of 235 hp, all Polish F engines having cylinders 4.625 in by 3.5 in.

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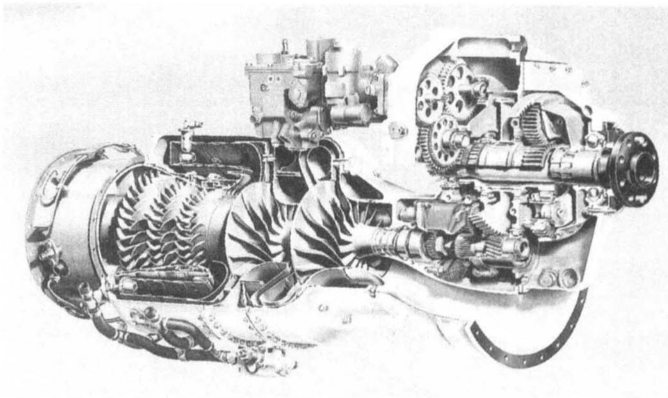
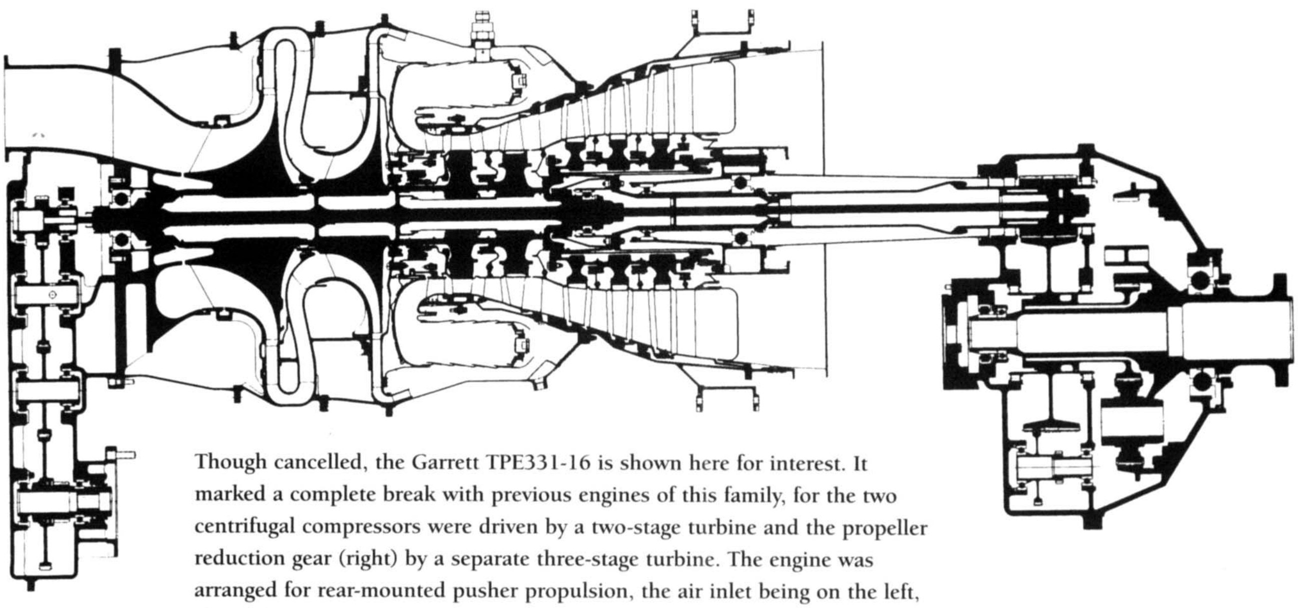
Galloway (UNITED KINGDOM) A subsidiary of Beardmore, Galloway Engineering itself took over the BHP engine and produced it in slightly modified form as the Adriatic. It had a compression ratio of 4.96, compared with 4.56 for the original Beardmore and 5.0 for the Puma, was heavier than either at 690 lb, and used a rotary oil pump instead of two gear pumps. More ambitious was the Galloway Atlantic V-12, the prototype of which comprised two BHP cylinder blocks on a common crankcase, running in about October 1917 at 500 hp. A month or two later the decision was taken to redesign it with Puma blocks, and in this form it was selected for immediate production as the most powerful British engine. Some dozens were made for the DH.15 and V/1500. It was planned to continue production as the Siddeley Pacific, but Siddeley-Deasy produced their own double-Puma as the Tiger.

Garrett (USA) For many years AiResearch Manufacturing claimed to have produced 80 per cent of all gas turbines of 60 to 2,500 hp made in the USA and Europe. In 1957 McDonnell took three of the mass-produced GTC85 turbocompressors and used these to power the Model 120 tip-drive helicopter (which in consequence set a record in lifting a payload double its own empty weight). Since then AiResearch has gradually carved out an ever-bigger niche in the general aviation and light military propulsion market. Since 1981 the AiResearch name has been dropped, though Garrett Turbine Engine Company (now Honeywell) continue to be based at Sky Harbor Airport, Phoenix, Arizona, where 15,000 aircraft propulsion engines have been delivered since 1965.

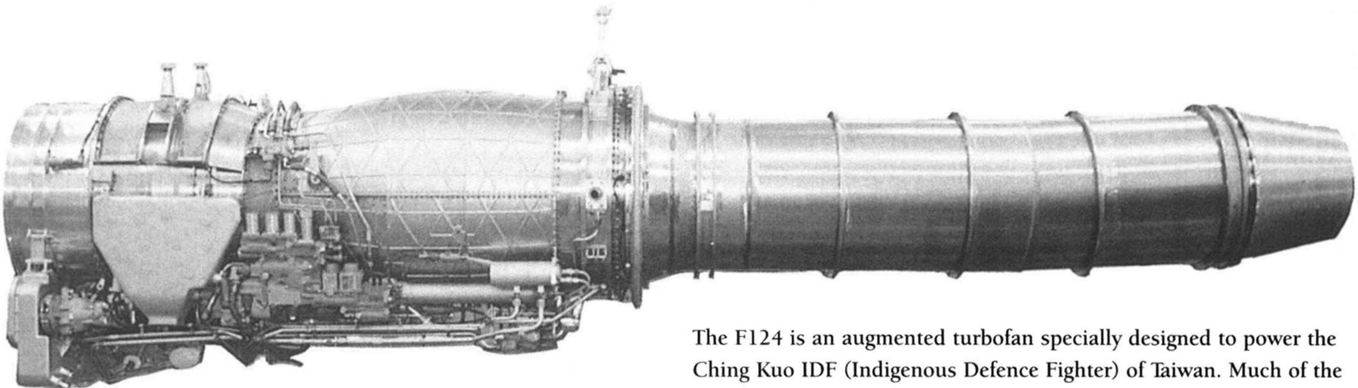
Throughout the 1950s the larger engine companies studied powerplants for ultra-high-altitude flight burning liquid oxygen and liquid hydrogen, but the company that got nearest to running a complete engine was Garrett AiResearch. As a result of a proposal by R.S. Rae, a British engineer at Summers Gyro, the USAF awarded Garrett a study contract in October 1955 for what became the Rex I, II and III, the first being a geared turboprop and the Rex III a highly supersonic turbojet with thrust *in vacuo* of 4,500 lb. This scheme was intended for an ancestor of the Lockheed Blackbird family.



A cutaway of the Garrett (now Honeywell) TPE 331 single-shaft turboprop showing the tandem centrifugal compressors, folded reverse-flow combustor and three-stage turbine. This is one of the versions with the inlet below the reduction gear.



Though cancelled, the Garrett TPE331-16 is shown here for interest. It marked a complete break with previous engines of this family, for the two centrifugal compressors were driven by a two-stage turbine and the propeller reduction gear (right) by a separate three-stage turbine. The engine was arranged for rear-mounted pusher propulsion, the air inlet being on the left, above the accessory drive gears.



The F124 is an augmented turbofan specially designed to power the Ching Kuo IDF (Indigenous Defence Fighter) of Taiwan. Much of the technology is based on the TFE731 bizjet engine, but the bypass ratio is only 0.3. Take-off rating is 6,025 lb.

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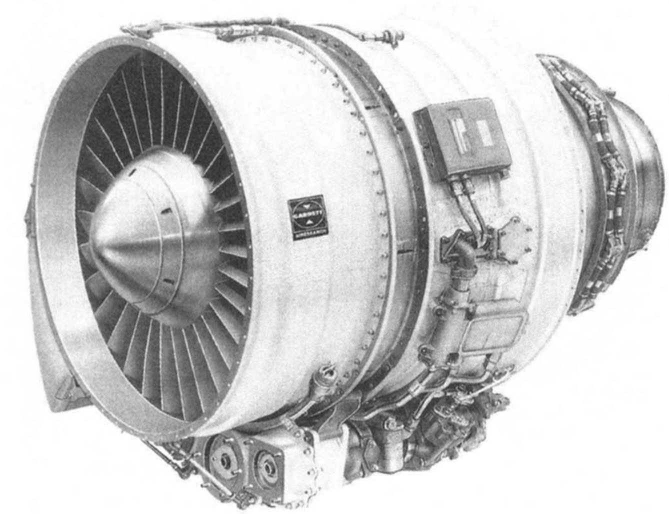
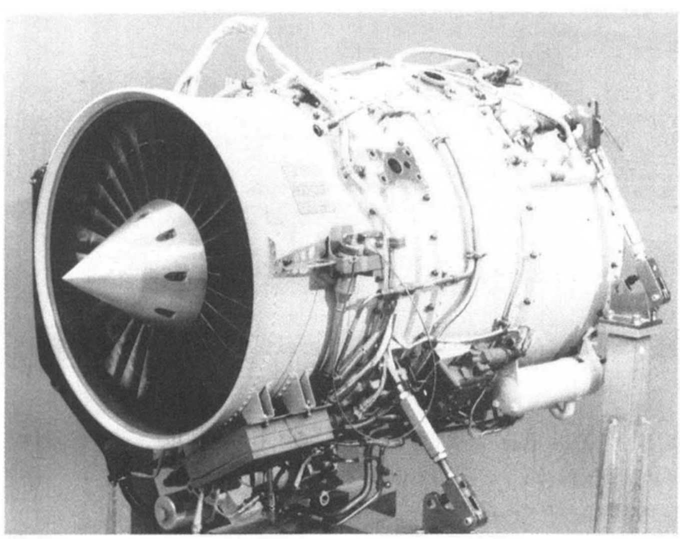


A Garrett TFE731-5 turbofan for business jets. The front fan is driven via a reduction gear.



Garrett's F109, designed for the cancelled Fairchild T-46A, was a very simple turbofan yet achieved remarkable fuel efficiency.

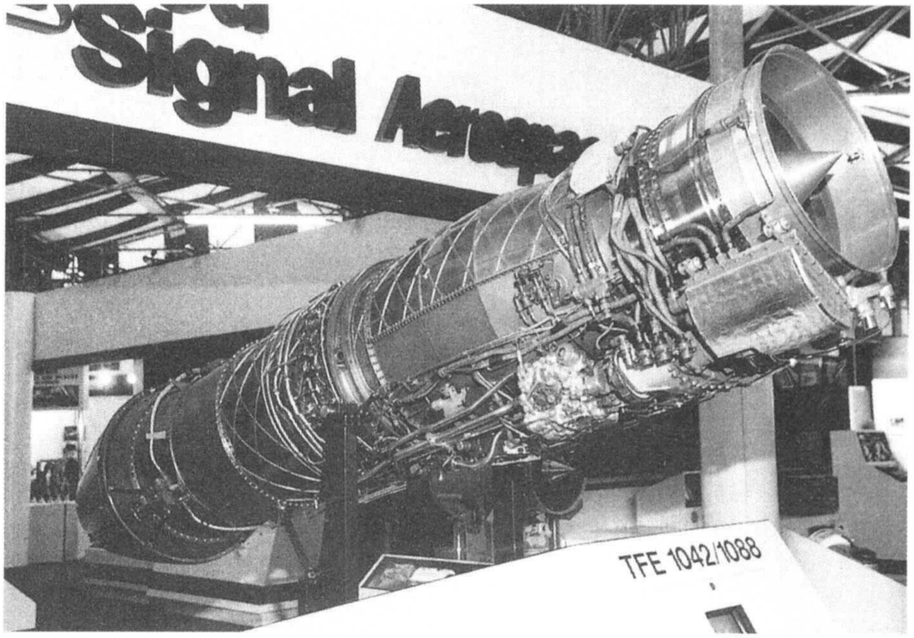
Design of the Model 331 began as a private venture in 1959. It was planned as the 500-shp TSE331 for helicopters and as the TPE331 turboprop. The former flew a Republic Lark (licensed Alouette II) on 12 October 1961, but did not go into production. In contrast almost 14,000 TPE331s have been sold, including a few T76 military versions. The latter have the inlet above the propeller, unlike the majority of commercial variants. All versions have two-stage titanium centrifugal compressors (airflow 5.8 to 11.6 lb/s), annular combustor and three-stage turbine with blades cast integral with the disc. The TPE331 is unusual in being a single-shaft engine, with no separate power turbine. Weights vary from 335 to 659 lb, indicative of the growth in mass flow and power in engines that look very similar. After becoming part of AlliedSignal a major redesign took place to produce the TPE331-16, with a separate power turbine driving a pusher propeller for the EMBRAER-FMA CBA-123, but this aircraft was cancelled and the engine along with it.

Garrett had a smash hit with the TFE731. One of a rare species, a geared turbofan, with a small high-speed turbine driving a relatively low-speed fan, this family of engines became a product of AlliedSignal, and today of Honeywell. So far 11,900 have logged over 62 million hours in 27 types of aircraft.

Announced in 1969, all versions so far have a three-stage LP turbine driving a single-stage titanium fan connected to a planetary ring gear and a four-stage LP compressor, a single-stage HP turbine driving the single-stage centrifugal HP compressor, and a folded annular combustor. HP turbine gas temperature is typically 1,010°C, fan airflow 113–43 lb/s, pr (overall) about 14–15 and thrust 3,500–4,500 lb. Bypass ratio is 2.6–2.8 in most engines, but the Dash-5 has a bigger fan raising the ratio to 3.48.

Third production engine is the unique ATF3 (funded initially by the USAF as the F104 for Compass Cope RPVs). It has a reversed three-spool layout: air enters at the front and passes through the single-stage titanium fan, driven by the three-stage IP turbine; fan airflow 162 lb/s, bypass ratio 2.8. The core flow of 40 lb/s then passes through the five-stage IP spool, driven by a two-stage LP turbine. It continues through

The ITEC TFE1042 is seen here in an afterburning version.



the single-stage centrifugal HP compressor (overall pr 25 at cruise), driven by a single-stage air-cooled HP turbine. The HP compressor faces aft at the rear of the engine and its eye is reached via a peripheral bypass duct. From the HP compressor the air passes forwards and then through two 180° bends in the annular combustor, and out via the three sets of turbines, being turned through two sets of 90° cascades in eight large struts in the mid-section to mix with the bypass flow in the full-length cowl. Accessories are on the circular rear cover. Weighing 1,125 lb, the ATF3-6A is rated at 5,440 lb and, despite its extreme unconventionality, has found a modest market in the Falcon 200.

In July 1982 Garrett's TFE76 turbofan was selected, as the F109, to power the T-46A trainer. This could hardly be simpler, with a 28-blade fan, tandem two-stage centrifugal compressors, annular reversed combustor and two-stage HP and LP turbines. Weight is 400 lb and thrust 1,330 lb. Such is the progress with high-rpm centrifugal compressors, and in component efficiency generally, that the sfc of this simple engine at take-off is 0.392, while that of the complex ATF3 is 0.506, but the T-46A and its engine were cancelled. The TSE 109 was a shaft version (see LHTEC).

Using a core based on that of the TFE731, Garrett teamed with Flygmotor of Sweden to produce the TFE1042 for light supersonic fighters. This effort was dropped, but later, in 1980, Garrett formed ITEC in partnership with the AIDC company of Taiwan. ITEC developed the TFE 1042-70 to power Taiwan's Ching Kuo twin-engined fighter, 134 of which were built, followed by a trainer version. This engine is rated at 9,250 lb in afterburner. Other versions failed to replace the Adour in the T-45 Goshawk, but were developed to power the Czech L 159, Aermacchi M 346 and various UAVs and projects.

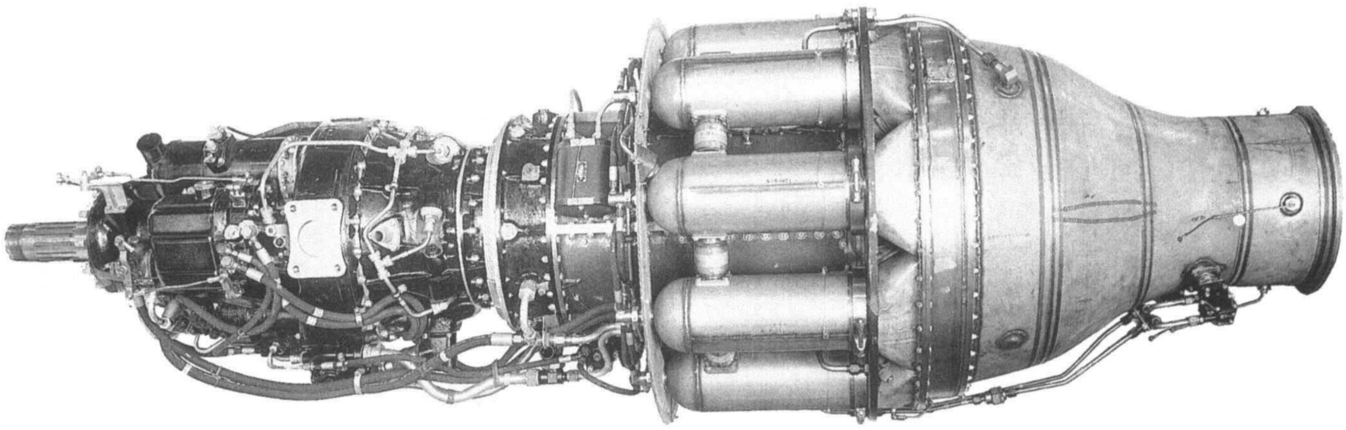
Later Garrett engines, *see* Honeywell.

Gavrilov *See* Motor.

General Electric (USA) It's a small world. When Sanford Moss was a PhD student at Cornell University his gas-turbine experiments offended Professor William F. Durand in the room above. In the First World War Durand headed the newly formed NACA (National Advisory Committee for Aeronautics), and one of his tasks was to push the development of the turbosupercharger. The world leader in this field was Moss, and this gave General Electric (GE) a valuable background of gas-turbine experience when General Arnold urged NACA to form a jet research group in February 1941. The resulting committee was headed by Durand.

The committee charged three existing steam-turbine firms with building aero gas turbines: Allis-Chalmers, a ducted fan; GE, a turboprop; and Westinghouse, a turbojet. GE had already begun work on a gas turbine for Navy PT boats, but scaled it down to suit the available air supply for testing. This happened by chance to be right for the TG-100 turboprop, and detail design began under Army contract on 7 July 1941. The company's steam-turbine division at Schenectady under Glenn Warren and Alan Howard used a 14-stage compressor in the TG-100, and multiple tubular combustion chambers. The gas generator ran on 15 May 1943, but a run with gearbox and propeller did not take place until May 1945. Redesignated T31 by the Army/Navy system, it flew in the nose of the Convair XP-81 on 21 December 1945; the XT31-GE-3 was designed for 2,200 shp plus 600 lb residual thrust, but actually gave about 1,650 shp. The T31 powered the Ryan XF2R-1 and a little work was done on the TG-100B, but the TG-110 and twinned TG-120 were never built.

In March 1941, 10 days after writing to the NACA, General Arnold was in England. He was aware of British jet patents, but



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General Electric began design of the TG-100 turboprop before they heard of Whittle. This T31, the outcome, weighed 2,180 lb and gave about 75 per cent of the planned 2,200 shp.

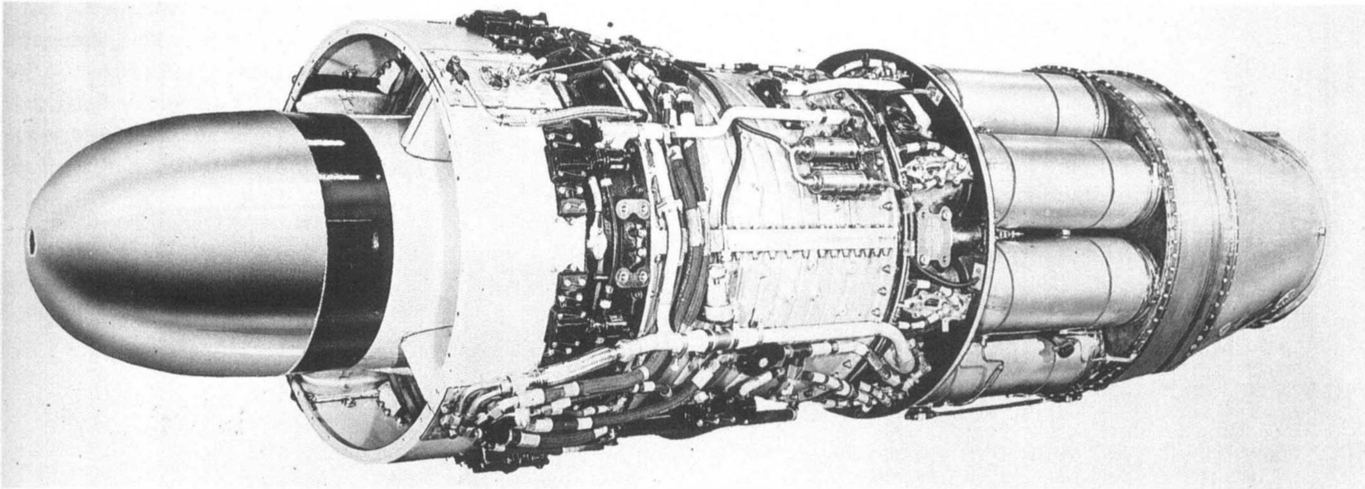
was surprised to find the Whittle engine about to fly. He quickly made arrangements to have the W.1 brought to the USA, and picked GE to build it under licence. In April he asked the company to send a good engineer to Britain to work with Colonel A.J. Lyon of the Army Air Corps in London. Such a man was already there: D. Roy Shoults, expert on turbochargers. In September contracts were signed with the GE turbocharger group at Lynn for a Whittle W.1 copy designated Type I (not 'one' but 'eye') Supercharger (as a cover), Donald F. 'Truly' Warner heading the team. On 1 October the W.1X (Power Jets' only bench engine) and a complete set of drawings for the W.2B were flown to Bolling Field, arriving at Lynn on the 4th. GE made many changes, added an automatic control system and used forged Hastelloy B for the turbine blades. The first Type I was mounted in its cell, called 'Fort Knox', and started on 18 April 1942 at 11.05 p.m. It ran hot, and on a visit in June Whittle suggested adding partitions in the blower casing to separate the flow to each chamber. This led to the I-A, two of which, rated at 1,250 lb, powered the Bell XP-59A on 2 October 1942.

Thus began GE in the field of aero gas turbines, starting with nothing but experience with turbochargers and steam turbines yet so motivated and well managed that many people consider it the world No. 1 aero-engine company. Even in its first perusal of the Power Jets' drawings it identified features that had proved troublesome, and in autumn 1942 work began on the I-14, of 1,400 lb thrust, with new blower casings, rectangular 90° diffuser passages, fewer but larger turbine blades (as in the W.2/500), a redesigned combustor liner and improved materials. The I-14 gave its design thrust soon after first running in February 1943. The I-16 design was begun in January 1943 and first run was in April; the 1,600 lb rating was soon guaranteed, at sfc of 1.24 and a weight of 849 lb. Altogether GE delivered 30 I-As and 241 I-16s to the Army, as well as a few I-16s for the Navy FR-1. Only prototypes were made of the I-14, of the 1,800-lb I-18 run in January 1944 and the 2,000-lb I-20, run in April 1944. This was because GE and the Army recognised that far more power was needed. The P-59A, with I-16s, was reclassified as a trainer, and in early 1943 the Army asked GE to study a turbojet of 4,000 lb rating. GE did better: it quickly produced two, a centrifugal at Lynn and an axial at Schenectady.

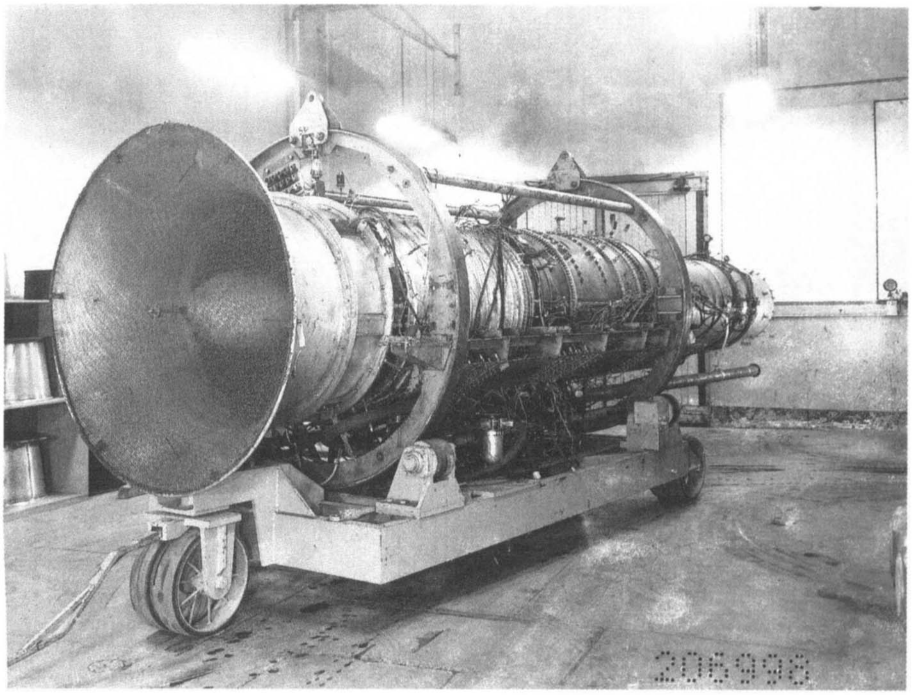
Naturally called the I-40, the Lynn engine was created very quickly in the second half of 1943 by a group under Dale Streid, who in 1939 had studied and reported in detail on the prospects for high-speed jet propulsion by gas turbine. Originally 3,000 lb had been the target for this engine, but in June 1943 GE decided to go ahead with both at 4,000 lb, the centrifugal because it could help win the war and the axial because of its greater future potential. Though designed for airflow of some 78 lb/s compared with barely half as much for the I-16, the I-40 used almost the same compressor and turbine, but with changed materials and manufacturing methods. The big change was the straight-through combustion system with 14 tubular chambers of wrapped Nimonic.

Important advances were also made towards casting turbine rotor blades. The I-40 went on test on 9 January 1944, hit 4,200 lb in February, and flew in the XP-80A on 10 June 1944. This slightly enlarged Shooting Star had been specially designed for the I-40 and the latter soon replaced the J36 (Goblin) as the production P-80 engine. Lynn built 'a few dozen' I-40s, and GE's Syracuse plant worked up close to the planned rate and delivered 300 production engines, designated as the J33, by the end of the war. In September 1945 complete responsibility for the J33 was passed to Allison (*qv*).

The challenging axial engine, the TG-180, drew on the TG-100 for compressor and turbine design and on Whittle for the eight separate tubular chambers, but its size and power posed major problems, and the manpower needed was at the expense of the less-important turboprop. An 11-stage compressor of constant tip diameter was chosen, with aluminium-alloy discs, steel blades, a magnesium-alloy casing (as in the I-40), airflow of 75 lb/s and a pr of 5. The first TG-180 was run on 23 April 1944 (or, according to recent GE publications, 21 April) at a weight of 2,300 lb, pr of 4 and thrust of



Few jet engines can equal the total of 36,500 General Electric J47s. The most numerous sub-family was the E-series, for the B-47E, this J47-27 being an example.

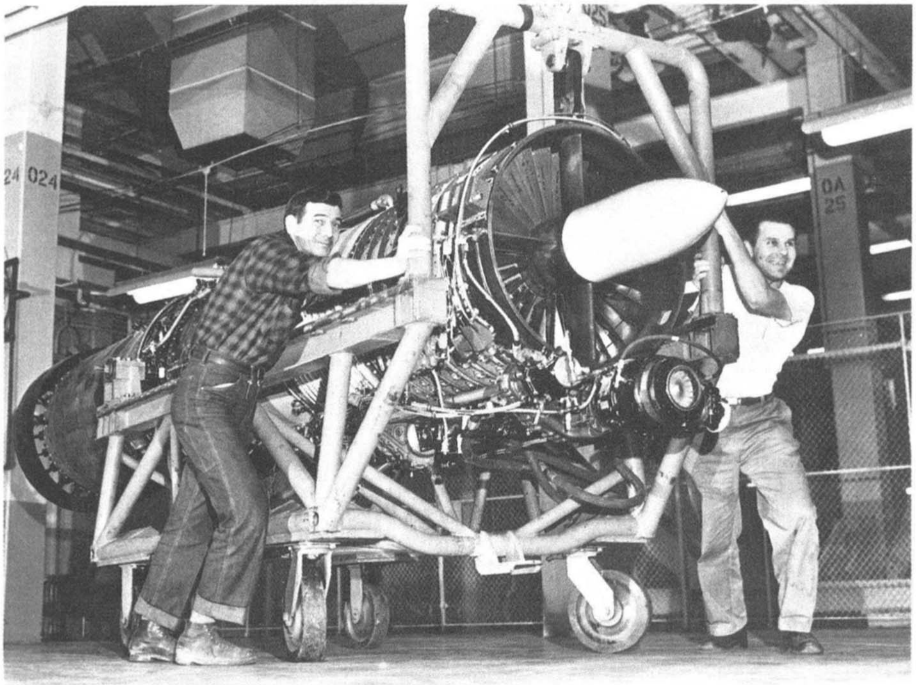


Festooned with instrumentation, a mighty XJ53 goes to the test cell in March 1951. It was simply too much engine for that era.

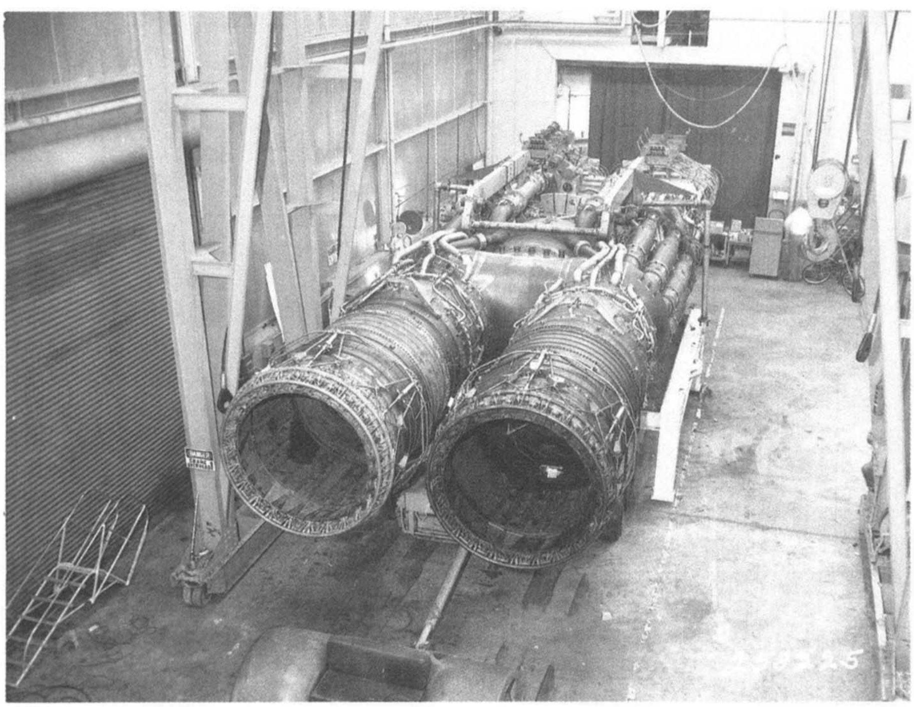
3,620 lb. No insuperable problems were met, and the engine flew at about 4,000 lb rating in the prototype XP-84 on 28 February 1946. Thus, rather surprisingly, both GE's 'own design' turbojets made their first flights in single-engined prototype fighters. By 1946 the TG-180 was beginning to come 'out of the wood' and as the J35 it was adopted for numerous new fighters and bombers. By this time GE had built 140 pre-production engines, and production J35s were beginning to flow from the Chevrolet Division of General Motors, but again Allison was selected for mass production. Complete responsibility for the J35 was handed over to that company in September 1946, Chevrolet withdrawing voluntarily.

Thus, soon after the war's end, GE had lost its two important new turbojets to a competitor. This was done to get Allison into gas turbines and provide competition, and because of that company's available capacity to build. GE now got started in earnest, and under Harold D. Kelsey built up a new AGT (Aircraft Gas Turbine) Division with development and production capacity concentrated at Lynn. Kelsey had to contend with extremely small budgets and with many who believed jet engines would bring only problems and financial losses. But at least the company's forecast was that by 1950 the division's business would total $35 million. To get that business GE decided to design a J35-type engine uprated to 5,000 lb and with better fuel economy.

Under Neil Burgess the TG-190 went ahead on 19 March 1946. It had the same frame size as the J35, and thus could easily replace the earlier engine, but the compressor and turbine were new, the former having 12 stages passing 92 lb/s at pr 5, and so was the lubrication system. There was severe



They may well smile as they hustle the first XJ79 to the test cell in June 1954; almost another 17,000 followed it.

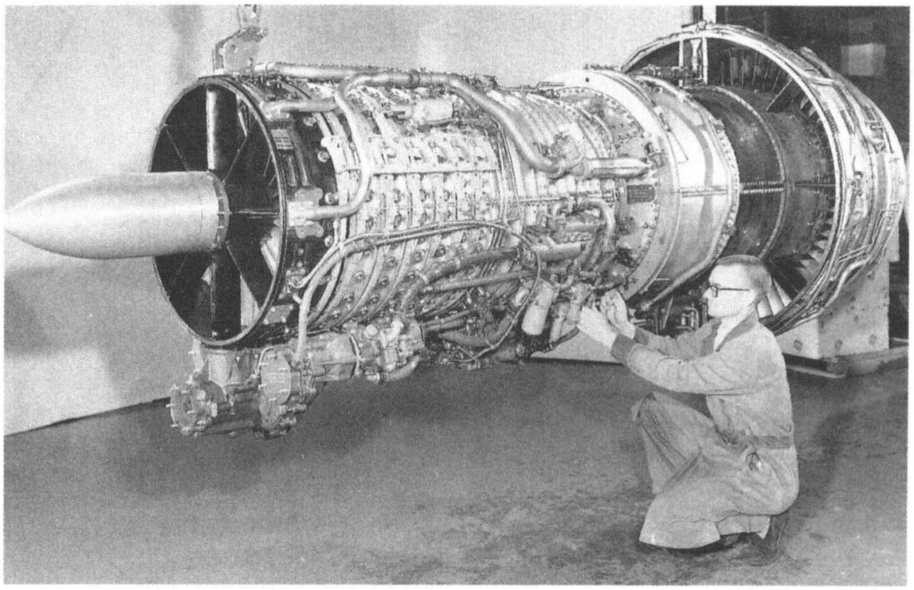


GE made about 17,000 fewer of the immense X-211 nuclear powerplant. The twin J87 turbojets had chemically fuelled afterburners but used a high-temperature reactor instead of the usual combustion chamber. Problems were awesome.

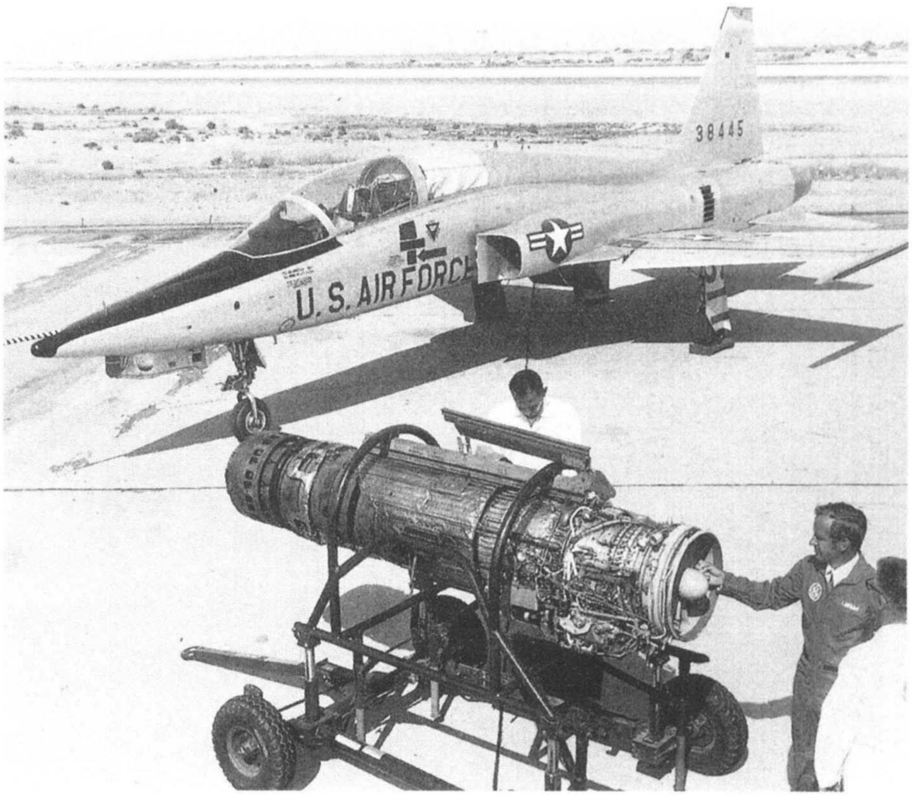
difficulty reducing the weight of major components, and the engine came out heavier than the J35, but it had great potential.

The USAAF accepted GE's proposal for the new engine and for production on a scale rivalling Allison, and began to fund development as the J47. The first engine went on test on 21 June 1947. By mid-1948 production J47s were coming off the line at Lynn, but by this time demand for it was so great that a second source had to be found. The choice fell on Lockland, near Cincinnati, Ohio, a wartime Wright engine plant which had been the world's biggest single building (in terms of volume under one roof). Marty Hemsworth inspected the 40 engine test cells and out of them produced 14 much more capable turbojet cells. An engineering staff of 150 moved in, and on 28 February 1949 Lockland reopened as a GE facility. At first the company needed only part of it, but it later was to be many times extended and today is the aero-engine headquarters.

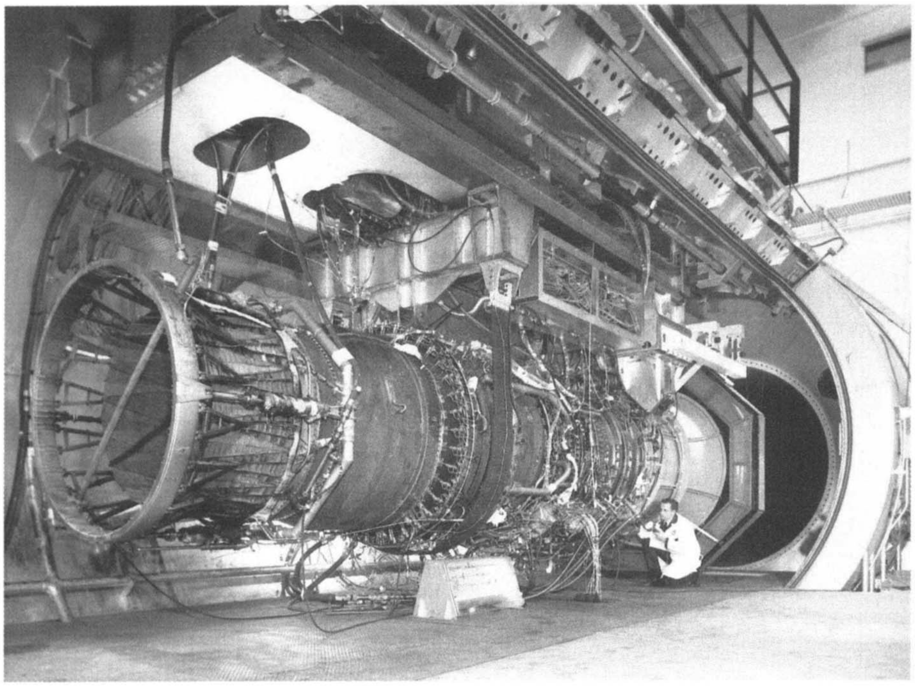
A handful of CJ-805-23C turbofans wee still flying in the new century. This aft-fan engine was created by adding a rear section with double-deck turbine/fan blades, downstream of a regular CJ-805 commercial turbojet (itself a J79). Note the linkage to the variable stators.



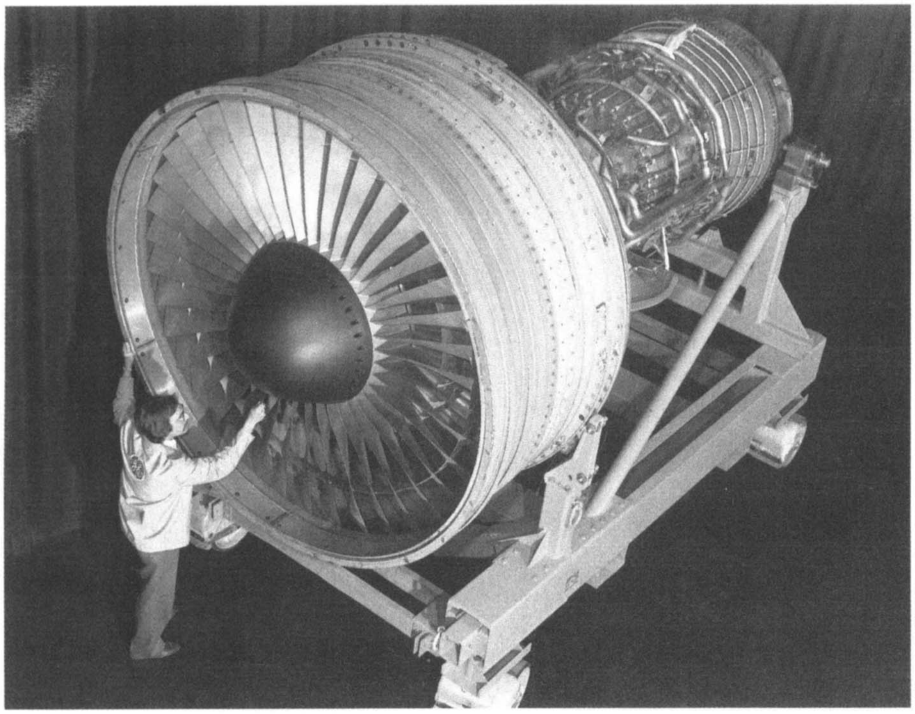
A J85-21 for the F-5F. Weighing 684 lb, this diminutive afterburning turbojet has an airflow of 53 lb/s and gives 5,000 lb thrust. Installed, it fits downstream of the auxiliary inlet doors seen open near the tail. Note GE overalls.



By 1950 the GE aero business was not $35 million but $350 million. Then came the Korean War, and output had to grow almost explosively, Studebaker and Packard being brought in to build an avalanche of J47s. To the original A-series engine of 4,850 lb thrust came the B of 5,000 lb, the C of 5,200 lb or 6,000 lb with water injection, the D with an improved 100 lb/s compressor and afterburner rated at 7,500 lb and the E in which several hundred mostly minor changes produced a reliable all-weather engine rated at up to 6,000 lb dry and 6,970 lb with water injection. At the latter ratings the Dash-25 engine powered the B-47E and, together with the F-86 and other types, demanded engines in such numbers that in 1953–4 output from GE, Studebaker and Packard was running at 975 per month. No other turbojet has been produced at such a rate, and the total at completion in 1956 reached 36,500. Late models were assembled vertically, then a novel idea, and the afterburning versions, which concluded with the 7,650-lb J47-33, were the first engines to have an electronic



The GE4/J5P, engine of the Boeing 2707-300 SST, was the most powerful aircraft turbojet ever built. Features included a nine-stage variable-stator compressor handling 633 lb/s, two-stage turbine for continuous operation at over 1,100°C and an afterburner and nozzle of awesome proportions. Weight was 11,300 lb; thrust hit 69,900, equivalent at Mach 2.7 to 333,000 hp.



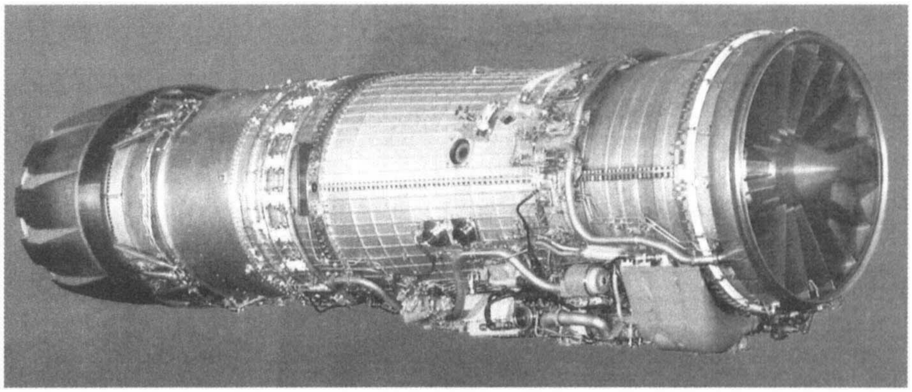
At one time a claimant to the title of 'most powerful engine', the first CF6-80C2 ran in May 1982 at 62,000 lb.

control system, which initially caused severe problems.

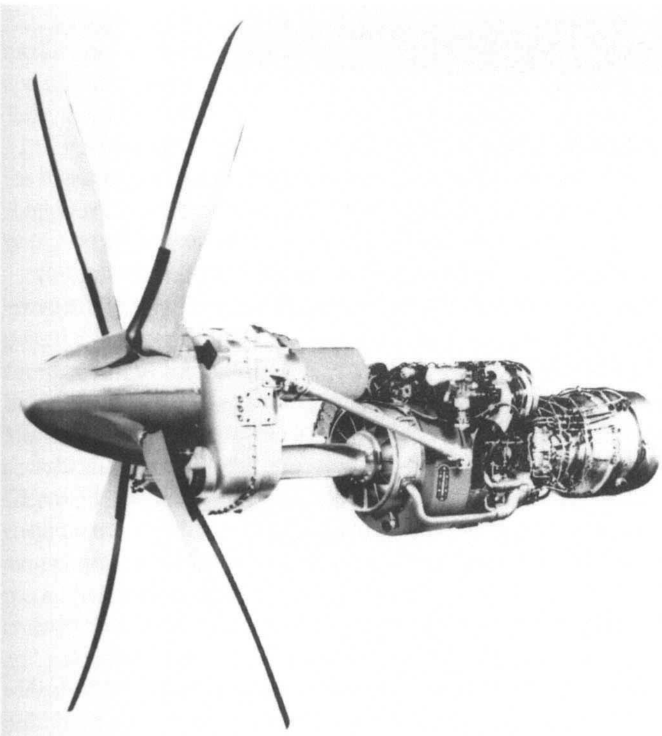
In 1947 the newly formed USAF asked GE to study a turbojet of unprecedented size and power. The result was the XJ53, which first ran in March 1951. The XJ53-1, for Mach 1.8 bombers, had a 13-stage compressor handling 264 lb/s at pr of 7.7; it passed a 50-h test in March 1953 at 17,950 lb with turbine entry at 871°C. The Dash-3 missile engine had the same 44-in diameter and 6,500 lb weight but passed 300.5 lb/s at 8.5 pr and ran a 50-h test in January 1954 at 21,000 lb. J53 applications faded, but scaled back to J47 frame size the J53 resulted in the J47-21 (later redesignated J73) of 1949 design under Neil Burgess. This went on test in mid-1950 and repeated the J53's variable inlet guide vanes, cannular combustion, two-stage turbine and titanium, and the 142 lb/s airflow resulted in a rating of 9,200 lb. Most applications failed to materialise, and only 870 J73s were produced, for the F-86H.

Probably GE's biggest single research programme began with the 1951 contract by the Atomic Energy Commission and

The sheer excellence of the F110 fighter engine has been rewarded by its selection not only for the F-14Ds but also future F-16s and some F-15Es. It is in the 28,000-lb thrust class.



GE's CT7 turboprop powers several new commuter liners, at ratings up to 1,940 shp. The power section is basically a helicopter T700.



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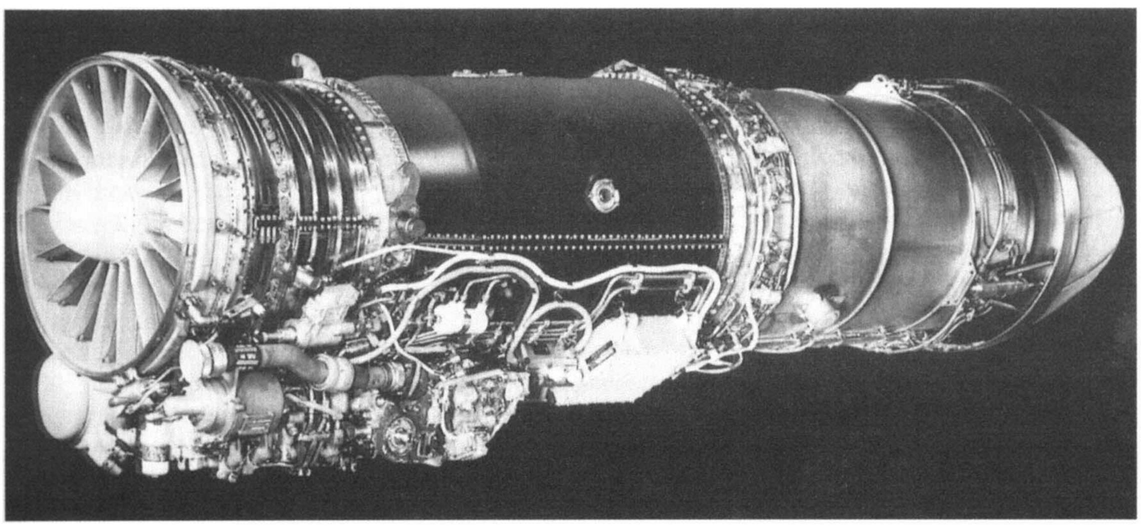
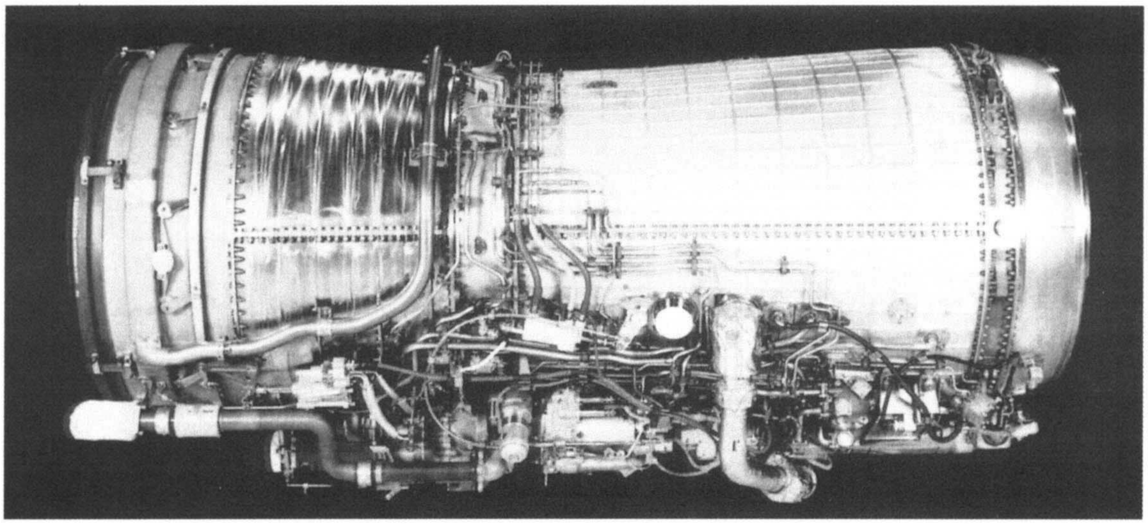
USAF for a five-year study on nuclear shielding requirements to help determine if a nuclear-powered aircraft was feasible. By 1954 the study hardened into a team effort with Convair, in competition with P&WA/Lockheed, for propulsion of the WS-125A NPB (nuclear-powered bomber). In June 1955 GE formed a task force to work on a direct-cycle engine in which the reactor replaced the normal combustion chamber, the engine airflow actually passing through it. The project was headed by Roy Shoults; the engine programme was managed by Bruno Bruckmann (see BMW) and another key figure was a fellow-countryman, Gerhard Neumann, destined to be GE's greatest aero-engine leader. Neumann ran a modified J47 on nuclear heat, but he eventually picked an unusual arrangement in the X-211 (J87) engine in which two colossal afterburning turbojets were linked on each side of one reactor, half the 330 lb/s airflow of each engine passing through the reactor and the rest bypassed via giant pipes. Several forms of reactor were tested, with cores at up to 1,100°C, and it was the thorny problem of how to service an intensely radioactive engine that led to the X-211 bypassing the problem by keeping the engine hardware outside the core. The X-211 compressor set new records with multiple variable stators and a pr exceeding 20, the overall engine being 41 ft long and having sea-level thrust



The F404-402 can be identified from earlier versions by its smooth black bypass casing.



The F118 has to meet unique requirements in the B-2 flying-wing 'stealth' bomber.

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for each half of up to 27,370 lb, achieved in January 1961. The NPB project was terminated on 31 March 1961.

Long before this time GE knew it had a new engine that was a world-beater. In 1952 the AGT Division was led by C.W. 'Jim' LaPierre, who urged continued technical leadership. What was wanted was a dramatic advance in the next major turbojet, with good fuel economy at Mach 0.9 but also the structural strength and high thrust for Mach 2, combined with reduced weight. The central route to all these objectives was increased pressure ratio, and in 1951 Neumann decided to go for the variable-stator compressor. The idea was that most of the stages of stator blades would be mounted in rotary bearings and, coupled by rings of linkages, be driven to the best angle for the engine operating condition by a fuel-powered hydraulic jack. His group built a VSXE (variable-stator experimental engine, inevitably known as the 'Very Sexy') and in March 1952 completed the layout drawing for the proposed X-24A engine. It looked impressive, but competing teams were set up; these quickly rejected bleed valves, but continued to study the dual-rotor (two-spool) arrangement. In October 1952 a management conference in Indiana under LaPierre took the fateful decision: go ahead with the variable-stator engine.

In November the X-24A was accepted by the USAF as the J79, the GE unclassified designation being MX-2118, and the rival Advanced J73 and J77 were dropped. To support the radical new engine the GOL-1590 demonstrator was designed to weigh only 2,935 lb and give afterburning thrust of 13,200 lb – figures beyond any previously attempted. The first test compressor was finished in August 1953 and gave results so high it was thought the instrumentation must be faulty (it was not). The GOL-1590 itself was started at 5.00 a.m. on 16 December 1953. Power was slowly brought up to the maximum; suddenly there was a deafening explosion and the front of the engine virtually disintegrated, the rest screeching to a stop. The cause: a faulty 'dog-bone' link holding the engine to the bed. The repaired GOL-1590 was back on test on 15 January; it ran as predicted. The J79 (MX-2118), whose original project head, Perry Egbert, had been replaced for health reasons by Neil Burgess, followed not far behind and the first went on test at Lockland on 8 June 1954. First flight was in a retractable pod under a B-45 at Schenectady on 20 May 1955. On 8 December 1955 GE chief test pilot Roy Pryor took off from Edwards in an XF4D powered by the new engine.

Since then 16,990 J79s have been built, 3,290 of them assembled by licensees, in a programme which has brought GE $4.5 billion and will require service support far into the twenty-first century. The engine set 46 world records, and so far has logged 35.9 million hours. Features include a 17-stage compressor with seven variable stators, handling a maximum airflow of 170 lb/s at pr 12.9 to 13.5, a combustor with 10 cans in an annular chamber, a three-stage turbine, and a long afterburner with profiled petals positioned by four rams driven by lube oil. Thrust rose from 14,350 lb in the first version to 17,820 lb in most current J79s. Later the LM-1500 version was developed for surface applications, while in 1956 GE launched both a simplified civil version, the CJ-805, and a novel aft-fan derivative. The CJ-805 eventually entered service in 1960 with the Convair 880, but it was a small programme. The aft fan, masterminded by Peter Kappus, had the advantage that it left the engine upstream unaffected by the large-diameter addition of a free-spinning ring of 'bluckets', so-called because each comprised a turbine blade (known as a 'bucket' in US parlance) carrying a superimposed fan blade handling fresh air in a short duct at the rear of the engine pod. The resulting CJ-805-23 raised thrust to 16,050 lb from the 11,200-lb turbojet, and dramatically improved sfc and noise; but again the marketing proved a disaster, to both GE and Convair, and only 37 fan-engined CV-990 Coronados were sold.

In 1953 GE's AGT division had diversified and reorganised, while the giant Ohio plant had been renamed Evendale, from a newly incorporated village in suburban Cincinnati. Meanwhile, at Lynn, studies of small engines led to a Navy contract for a helicopter turboshaft to weigh 400 lb and deliver 800 hp. GE like to beat the requirement, and in December 1955 the prototype T58 actually weighed 250 lb and delivered 1,050 hp. Subsequent versions reach 1,800 hp. Novel for a small engine in having a 10-stage axial compressor with four variable stators (handling 12.4 to 14 lb/s with pr of 8.4), it was ordered in large numbers, licensed to DH (now Rolls-Royce) as the Gnome and to Alfa Romeo and IHI. It also spawned the commercial CT58 and marine/industrial LM100.

In October 1953 the Small Aircraft Engine Department was formed by Jack Parker and Ed Woll. Its product was merely the T58, so in 1954 Woll started small-jet studies and proposed to the USAF engines of 10:1 thrust/weight ratio (2,500/250 were the figures) with pr of 5, 7 or 12. Back came a contract for the J85, with pr 7; it was wanted only for the GAM-72 Quail decoy missile, but under Fred MacFee the J85 soon gained manned applications, most notably in Northrop's T-38 and F-5 family. Today over 13,500 J85s have been delivered, as well as over 2,000 commercial CJ610s and over 1,100 derived CF700 aft-fan engines. The latest J85s are rated at 5,000 lb with afterburner, final models of CJ610 and CF700 respectively giving 3,100 and 4,500 lb.

In 1955 the USAF was funding two rival engines for the extremely fast F-108 interceptor and WS-110 CPB (chemically powered bomber). Neither engine was a GE product, yet by a combination of impressive technical design and willingness to fund demonstrator hardware, GE came from behind, and in May 1957 received contracts for its J93 engine to power both aircraft, the bomber having become the XB-70. The J93 was GE's biggest challenge to date. A high-pressure variable-stator engine, its first-stage turbine blades set a new high in temperature and introduced the STEM (electrolytic machining) method of drilling holes now used on almost all advanced engines. The J93-3 ran on special high-temperature JP-6 fuel and produced 27,200 lb of thrust in full afterburner for a weight of 4,770 lb. But the definitive J93-5 was designed to burn high-energy 'zip fuel' in its afterburner based on ethyl borane. Over $200 million was spent, mainly on USAF budgets, setting up a zip-fuel industry. The technical problems were desperate, and the hated boron-based fuels were abandoned in August 1959, followed by the F-108 a month later and the B-70 in December 1962.

Back in 1953 what became the T58 had been studied as the basis for turboshaft, turbofan, turboprop and turbojet engines for a wide range of contrasting aircraft. In 1961 Neumann asked MacFee to study the market for an engine between the J85 and J79. This led to an unprecedented application of the building-block concept, resting on a basic core engine, the GE1, developed under Jim Worsham. The GE1 itself, with a 14-stage variable-stator compressor, gave 5,000 lb thrust but was about half the length or frontal area of a J47; as the J97 it later flew in Compass Cope RPVs. Though little known, it was the starting point for almost all GE engines launched since that time. They include two seemingly totally different engines bigger by far than anything previously seen.

First came the GE4, for the American SST launched by President Kennedy in May 1963. It stemmed from the X279M of 1958, which was a variant of the J93. Under John Pirtle the GE4 quickly took shape as a scaled GE1 with J93 features, with hollow compressor blades, the biggest turbine (with air-cooled blades) and an afterburner tested by blasting two J79s into it. At 69,900 lb it was the most powerful turbojet known, but it died along with the SST on 29 March 1971.

More survivable was the TF39, the world's pioneer HBPR (high bypass ratio) turbofan. Under General Bernard Schriever the USAF had in Project Forecast in 1962 asked for masses of long-range industry data. GE provided truckloads, including input from its tip-drive lift-fan produced for the Ryan XV-5A VTOL. Sifted, the answer was that future transports needed HBPR engines – a fact clearly evident from Whittle's pre-war calculations. The USAF started its project for a gigantic airlift transport, the CXX, and GE's Don Berkey submitted a proposal for a remarkable engine of bypass ratio 8, with a '1½-stage' fan comprising a single stage of small fan blades to help supercharge the core, rotating inside a fixed ring, followed by a single-stage fan bigger than anything seen previously, with a diameter of 8 ft 4 in. The USAF liked this, but in March 1964 insisted that GE must demonstrate an engine.

The GE1/6 was built and demonstrated with sfc of 0.336 and the USAF accepted this, even though at 15,830 lb it was half the power of the required engine. To win the CXX competition GE had to produce 50 copies of a 90-volume proposal, and three days before the deadline the USAF asked for many extra volumes filled with specific information for evaluation teams. When oral presentations had to be made, in April 1965, GE sent the whole 'First Team' from Parker and Neumann down; it was worth it, and in October 1965 the AGT division won its biggest single contract, $459,055,000. The TF39 posed such challenges as a fan airflow of 1,549 lb/s, a 25-pr compressor and 1,371°C turbine, but today the total flight time on the C-5 aircraft is about 7 million engine hours and the TF39-1C engine is in service with the C-5B fleet. They are now being replaced by the CF6 (see below).

In 1954 the Small Aircraft Engine department began development of a larger turboshaft/turboprop with better sfc than the T58. The resulting T64 flew as a turboprop in 1960 in the Caribou and as a turboshaft in the CH-53 in October 1964. Another fixed-wing application is the G222, for which 188 T64s were licence-built by Fiat by late 1986.

In 1967 work started on projects that were to lead to five new families of engines, on which most current business is based. Biggest was the giant commercial turbofan. When Boeing/PanAm were seeking an engine for the 747, GE consciously 'walked away', aware of the fact that the CTF39 – derived from the existing TF39 – was not sufficiently powerful, and fearing the impact on the TF39 of the drain on resources needed to produce a bigger engine. Douglas and Lockheed were busy with twin-engine 'airbus' studies for which Rolls were offering the big RB.207, but the GE

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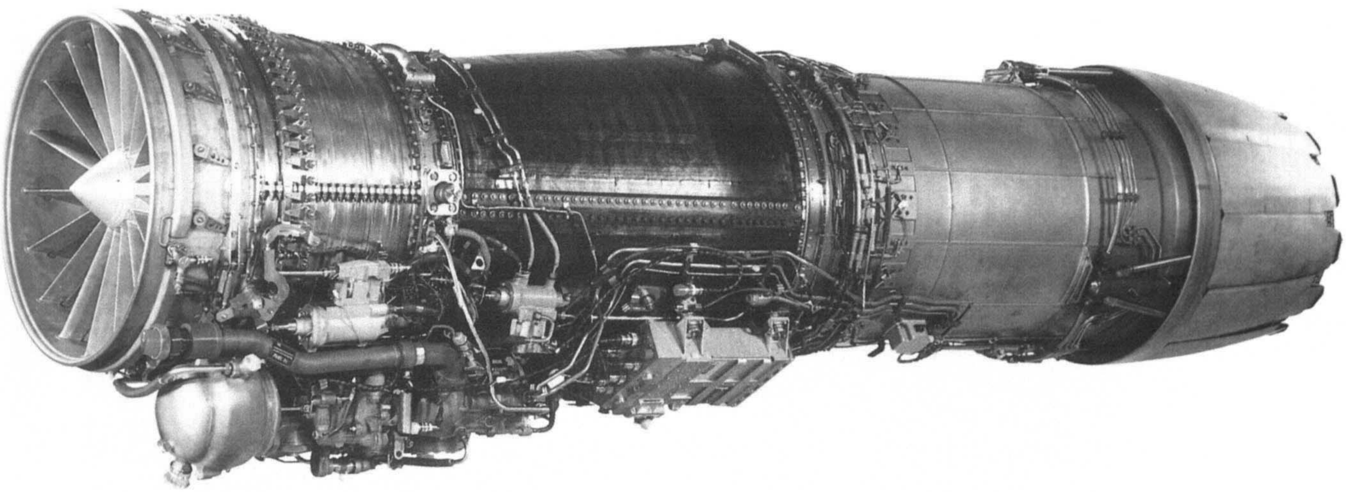


Derived from the F404, the F414 is considerably more powerful, with dry and augmented ratings of 12,500 and 22,000 lb.

Commercial Engine Projects team, formed under Ed Hood, succeeded in persuading the two US planemakers to consider trijet aircraft powered by the CF6 engine rated at 32,000 lb.

The engine went ahead on 11 September 1967 under Britisher Brian H. Rowe, but quickly had to grow, first to 40,000 lb as the CF6-6D for the DC-10-10 and in 1969 to 49,000 lb as the CF6-50 for the DC-10-30. The basic Dash-6 engine has a '1¼-stage' fan, 16-stage HP compressor, 30-nozzle annular combustor, two-stage 1,330°C HP turbine and five-stage 871°C LP turbine, weight being 7,896 lb. Several navies and some merchant ships use the derived LM2500. The Dash-50 has a fan rotating with three LP compressor stages with free-floating bypass doors, 14-stage HP compressor handling airflow increased from 194 to 276 lb/s and only four stages on the LP turbine. Original fan airflow was about 1,300 lb/s and overall pr 24.3, the latter rising in the Dash-50 series to between 28 and 30.

The first CF6 ran on 21 October 1968 and three of them quietly propelled the first DC-10 on its ceremonial rollout in July 1970. The CF6-50 first ran in September 1970. Right at the start, in March 1968, GE were shattered when the first three trijet customers to announce a choice of engine all picked the RB.211, but gradually GE's ability to offer an uprated engine made it No. 1, the choice of Airbus Industrie and even of 747 customers – which the company had not counted on. At the time of writing, total CF6 flight time exceeds 200 million hours. The advanced-technology CF6-80 family are in service in the A310 and 767, and the completely redesigned new-generation CF6-80C2 exceeded 62,000 lb thrust on its first run in May 1982, flew in an A300B4 on 19 August 1984 and was the subject of a technical collaboration agreement with Rolls-Royce.

Second of the 1967 launches was the TF34 turbofan for the US Navy S-3A anti-submarine aircraft, with a single-stage fan (338 lb/s), 14-stage compressor scaled up from the T64, and rated at 9,275 lb thrust for a weight of 1,478 lb and with sfc of 0.363 (better than most CF6s). Developed within a tight fixed budget, the TF34 later powered the A-10A, and has now been developed into a growing family of civil CF34 engines with ratings up to 18,820 lb.

The third 1967 project was the GE12, a 1,500-shp turboshaft demonstrator aimed at a major US Army helicopter competition. The compressor comprised five axial stages followed by a centrifugal, and a key factor in GE's win was not only the sustained good performance of the engine in extremely adverse test conditions but also advanced design features to reduce the number of parts – for example by making each axial stage from a single slab of steel, machined to form a 'blisk' (blades plus disk) – and minimise overall costs. The GE12 led to the T700 for the Sikorsky Black Hawk helicopter. From this has been developed the CT7 civil turboshaft and turboprop, with ratings from 1,622 to 2,325 shp. Over 12,000 T700/CT7 engines have logged 41 million hours in 24 types of aircraft.

Fourth of the 1967 projects was the GE15, a neat two-spool turbojet that GE thought might lead to its urgently sought 'next J79'. Derived from the GE1, the GE15 was a low-bypass afterburning engine to be rated at 14,330 lb and sized to replace a modified J97 as the engine of Northrop's P-530 Cobra. GE, recognising a massive gap between the J85 and P&W's F100, offered to develop the GE15 comprehensively for the Department of Defense at a cost of just $10 million. This led to the YJ101 which powered the YF-17 prototypes of 1974. For the second time (the first was in the F-14/F-15) GE lost to P&W in the lightweight fighter competition, but unexpectedly the Navy finally picked a more powerful derived engine, the F404, for its F/A-18 Hornet. The F404 has a bypass ratio increased to 0.34, an airflow of 142 lb/s and is rated in the F/A-18 at 16,000 lb for a weight of 2,180 lb. From the start it has proved an outstanding engine, and it has since gained other applications most notably including the Swedish JAS39 in which an uprated version is built by Volvo Flygmotor (*qv*). By 1998 1,260 F/A-18s were flying, later versions having the -402 engine with an afterburn rating of 17,700 lb. Including foreign applications 3,600 F404s are operating.

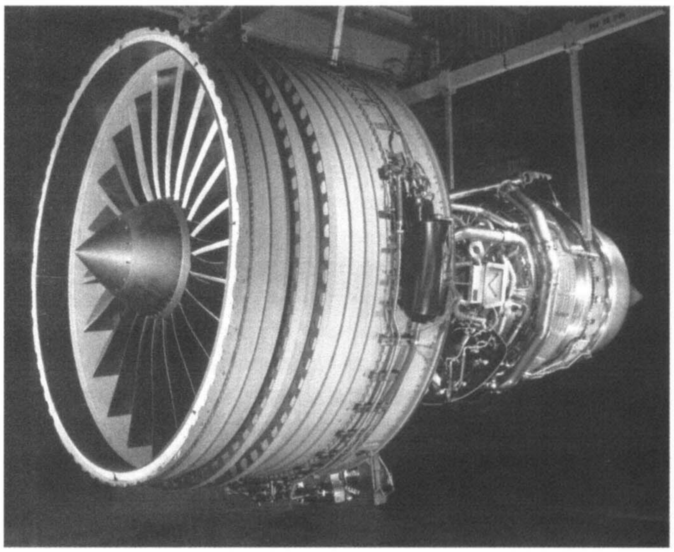
The fifth engine launched in 1967 was a derivative of the GE9, one of the GE1 offshoots. A large augmented turbofan, it drew heavily upon the X370 demonstrator created in 1960–1 by John Blanton's team to combine 10:1 thrust/weight ratio with the ability to fly at Mach 3.5, with turbine temperatures explored into the 2,200°C region. The work paid off and in June 1970 the USAF selected the GE engine which had become the F101, to power the AMSA, later the B-1. Under Worsham the F101 core ran in October 1971, and the complete unaugmented engine in January 1972. From it stemmed the F101-GE-102 which powers the B-1B, an engine in the 30,000-lb class with airflow of some 350 lb/s. Moreover, GE never gave up on big fighter engines, but built a series of F101 DFE (derivative fighter engine) demonstrators which were flown in the F-14 Super Tomcat, F-16/101 and F-16XL. This work also paid off; the 101DFE became the F110, a splendid engine in the 28,000 lb thrust class with airflow of some 260 lb/s. After prolonged competitive evaluation the F110 was ordered in 1984 to power future production F-14s and F-16s, and following testing in an F-15E the improved F110-129 (29,000 lb rating) is also available for that aircraft. Another engine derived from the F101 and F110 is the F118, with increased airflow and higher pressure ratio to give increased dry thrust (no afterburner is fitted); surprisingly, fuel economy is inferior to that of the fighter engine. The F118-100 of 19,000 lb thrust powers the B-2A Spirit 'stealth' bomber, while the F118-101 of 17,000 lb thrust has replaced the J75 in the stratospheric U-2S. Yet another offshoot from the F101 is the CFM56 shared with Snecma of France (see CFM).

Today GE Aircraft Engines has its headquarters at what is now called Neumann Way, Evendale. It has two main operating arms, one (previously Commercial & Military Transport Engines) in Ohio and the other (formerly Military & Small Commercial Engines) at Lynn, near Boston. Lynn announced in September 1976 the CT7, a civil family derived from the T700 and produced in both turboshaft and turboprop forms in the 1,700-hp class. Also at Lynn was a programme which consumed large resources and could have brought commensurate returns: the first propfan, for which GE registered the designation UDF (UnDucted Fan) as a trademark. It was basically an F404 providing gas to drive multistage contra-rotating turbines at the rear, with rings round each turbine on which were mounted variable-pitch blades resembling thin sweptback propeller blades. The goal was jet speed with propeller efficiency.

Early testing, on the ground and in 727 and MD-80 aircraft, involved basic GE36 engines with the F404 core and various fan systems. This work, in 1983–7, broadly proved the concept and suggested that engine performance, vibration, cabin noise and community noise would be as predicted or better. This encouraged Boeing to launch a gigantic programme for a 150-seat 7J7 powered by GE36-B22A engines of 24,000 lb thrust, and McDonnell Douglas to propose the MD-91X powered by GE36-B14 engines of about 15,000 lb thrust. A joint German/Chinese 75-seater, the MPC-75, with two GE38-B5 engines of 9,450 lb thrust was also suggested. Snecma of France discussed taking a 35 per cent share in the whole UDF programme, and Alfa Romeo also expected to share in the proposed GE37 and GE38 versions. However, nobody wanted to commit billions in the absence of a market. The growing success of the conventionally powered A320 resulted in Boeing shelving the 7J7 and instead developing improved 737s wth ordinary CFM56 engines. The apparent abandonment of the propfan (except in former Soviet countries) is difficult to explain. One indication is that GE recently produced a large book describing their history in great detail, and it does not mention the UDF programme.

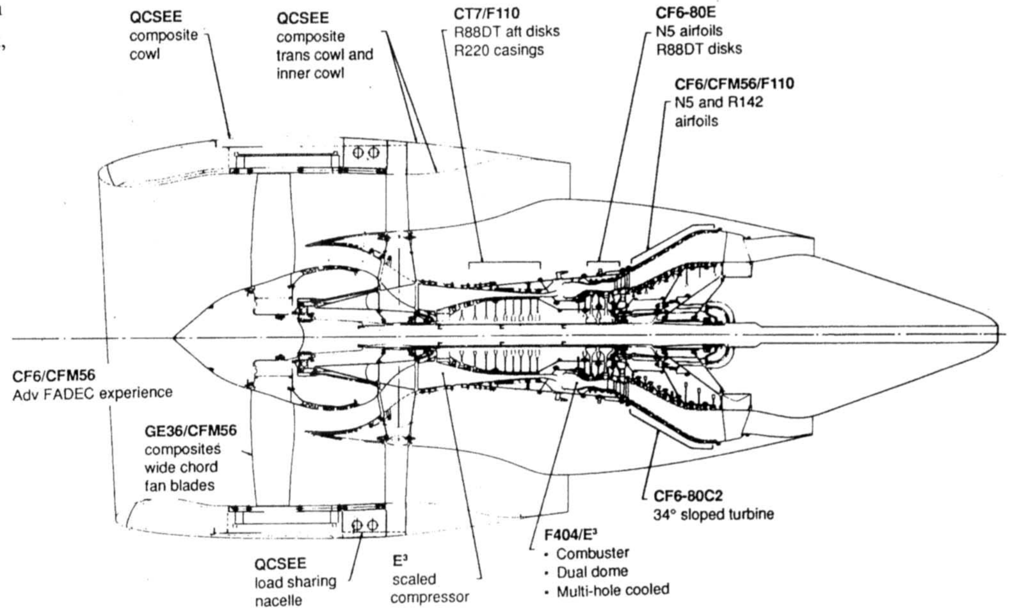
In the military field, GE continues to make life tough for Pratt & Whitney. The F404 goes from strength to strength, having (unlike the rival Turbo-Union RB.199) found ten applications. From it has been developed the F414, for the F/A-18E/F Super Hornet. With dry and afterburning ratings of 12,500 and 22,000 lb, the F414 has fan airflow increased to 169 lb/s and other advanced features. Like later versions of F404 the bypass duct is fabricated in black PMR-15 composite material.

Via the YF120, losing engine in the Advanced Tactical Fighter competition, GE developed the outstanding F136 in partnership with Rolls-Royce. The intention was that this, the

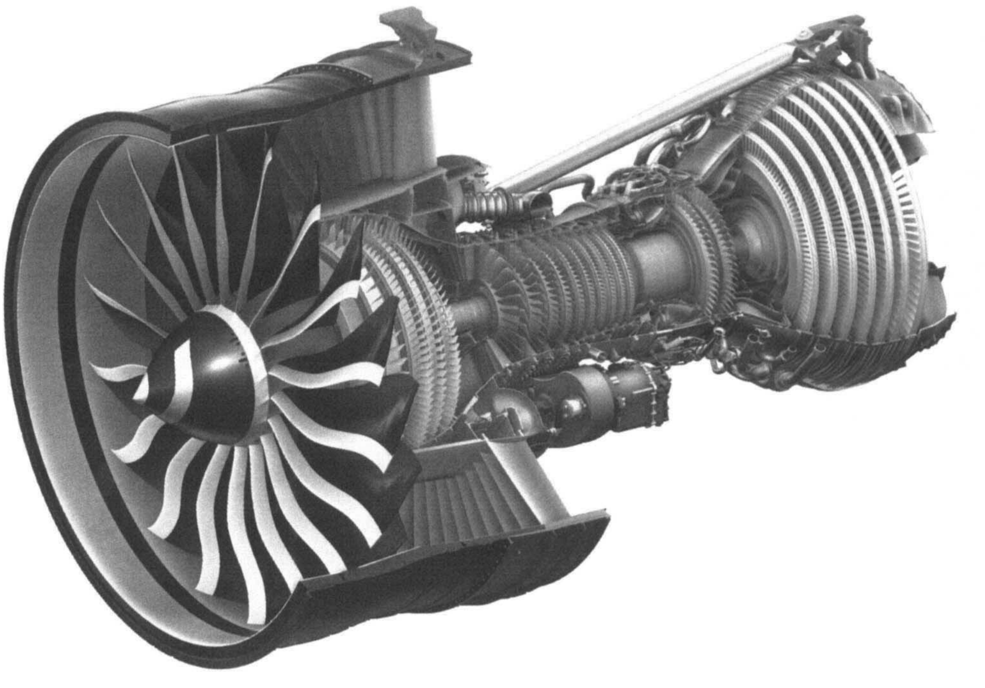


Originally the largest and heaviest aircraft engine in the world, the GE90 is seen here in GE90-85B form, rated at 84,700 lb. The Dash-115B version is even larger.

The GE90 is the biggest aero engine in the world. Despite its bulk and weight, and many development problems, GE beat its rivals on the Boeing 777 by getting an exclusive deal on the bigger GE90-115B..



The GEnx is one of two engines selected by Boeing to power the 787, and is the exclusive engine of the 747-8. ***(GE)***



most powerful fighter engine in history, would be an option available on the F-35 Joint Strike Fighter, but it was cancelled by President Bush in January 2006. Since then it has battled for funding.

In January 1990 GE announced that it was designing the GE90, the world's biggest, heaviest and most powerful aero engine, to power the Boeing 777. Its investment was reduced to 59 per cent by risk-sharing partners Snecma, Avio and IHI. It has a fan of 123 in diameter with 22 giant graphite-epoxy blades driven by a six-stage turbine; another feature is a double annular combustor intended to minimise emissions. First run in April 1993, the GE90 had a troubled start, with several serious problems, but by 1996 was establishing a good record in service on the Boeing 777 at thrusts from 84,700 to 92,000 lb. The basic engine weighs 17,250 lb. From this monster has been derived the even bigger GE90-115B, with a fan diameter of over 128 in and weight of 19,315 lb. Rated at 115,000 lb thrust, it is the exclusive engine of the heavyweight 777-200LR, -300ER and 777 freighters. GE and Boeing have not disclosed the terms of the exclusivity deal. In contrast, to power the all-new 787 Boeing called for proposals. Though the thrust requirements, in the bracket 53,000–72,000 lb, could have been met by the GP7200, GE and Pratt & Whitney decided to bid completely new designs. Boeing picked the General Electric GEnx and Rolls-Royce Trent 1000. The GEnx was later also selected for the A350 XWB, and (exclusively) for the Boeing 747-8.

GE Honda (INTERNATIONAL) In 1988 Japan's Honda car company began developing a small turbofan. In 1995 the resulting HFX-01 was in flight test, followed by the HFX-20 in 2000. This underpinned the HF118-2 of 1,700 lb thrust, which General Electric is helping to market. Single-stage turbines drive the fan and centrifugal compressor.

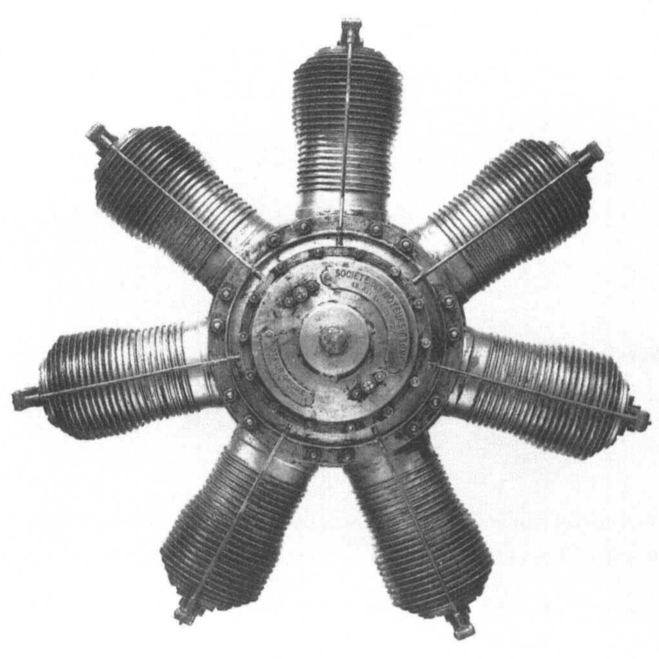
Glushenkov *See* OMKB.

Gnome (FRANCE) The Gnome took the Paris-centred aviation world by storm when it was marketed in spring 1909. Designers Louis and Laurent Seguin had built conventional Gnome petrol engines from 1892, but studied the profusion of rotary engines in which the cylinders revolve round a stationary crankshaft. Aviation examples included Hargrave (1888, compressed air), Burlat (1905) and Adams-Farwell (picked by Berliner for his 1907 helicopter, though really a car engine). They may have designed their Gnome rotary aero engine as early as 1907, but it was revealed in about November 1908. The first version had five cylinders of 100 mm bore and stroke, 3.4 litres, weighed 60 kg and is said to have developed 34 hp at 1,300 rpm. According to some accounts it was fitted to Roger Ravaud's hydroplane at Monaco in January 1909 (other reports say the seven-cylinder was used), which, curiously, had contra-rotating propellers; not surprisingly, it failed to fly. The first Gnome to fly thus appears to have been the seven-cylinder of 101 mm bore and 120 mm stroke, 7.98 litres, rated at nominal 50 hp at 1,200 rpm, bought by L. Paulhan and flown in his Voisin on 16 June 1909. In the close-knit Paris *aviateur* fraternity the Gnome spread like wildfire and several more were quickly sold. Henry Farman removed his Vivinus during the Reims meeting and with the Gnome won the Grand Prix de Distance on 27 August and the Prix des Passagers on the 28th.

Not only was the Gnome novel in being a radial rotary but in these early pusher applications it was actually mounted behind the propeller. The weight, thrust and vibratory loads were all taken by the tubular crankshaft, bolted to the airframe. Through it mixture from the carburettor passed to the crankcase, from where it reached the cylinders through valves in the heads of the pistons. These valves were forced shut by the combustion pressure; on the return stroke they were opened by a pair of pivoted counterweights inside the piston. Exhaust gas was expelled straight to the atmosphere through a valve in the centre of each head, driven by a cam ring and pushrod. Construction was almost entirely machined from solid forged nickel-steel, to a high standard. The master rod had a big end in the form of two large discs, each running on the crankpin with its own ball bearing and carrying holes for the wrist-pins of the secondary or link rods.

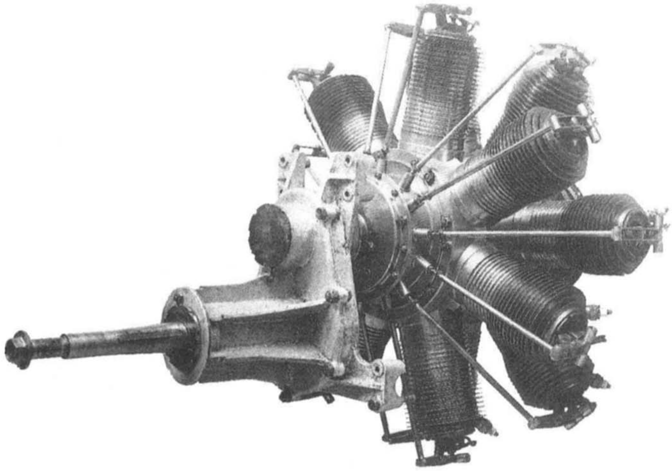
The whole engine had to be stressed to withstand up to over 100g because of the rotation, cooling of the cylinders was uneven, and no normal lubrication system would have worked. Cylinder distortion was partly overcome by adding a very flexible obturator ring, made of thin bronze, above the normal piston rings. For lubrication, oil was added – to the fuel mixture in quantities of 25 to 35 per cent. The result was that the head of each cylinder spewed fire and unburned oil, so a cowling was essential in tractor installations. As the oil had to be immiscible with petrol a vegetable-based type (usually castor) was used, the aroma being as inseparable from rotaries as kerosene was from early turbojets. Advantages were light weight, typically 75 kg for the 50-hp (which usually gave about 40 hp), automatic damping of propeller vibration without the need for a flywheel, and adequate air cooling even on the ground. Well-maintained, reliability was fair, but the valves in the pistons caused dangerous backfires through the carburettor, and often complete failure.

By 1910 the basic seven-cylinder had been enlarged to about 70 hp, while the original size had been doubled up to provide a 14-cylinder two-row unit of 100 nominal hp. The Seguin brothers also studied ways of eliminating the troublesome piston valves, and in 1912 came out with the Gnome Monosoupape (i.e., single-valve). Holes were simply cut in the cylinder walls uncovered by the piston near the



This Gnome Omega was No. 966, which was still on British charge after the formation of the RAF in 1918. The plugs are invisible behind the 22-fin cylinders.

G



An unusual Gnome BB 18-cylinder engine with a geared drive. Rated at 240/250 hp, this was the most powerful of the 'Mono' family.

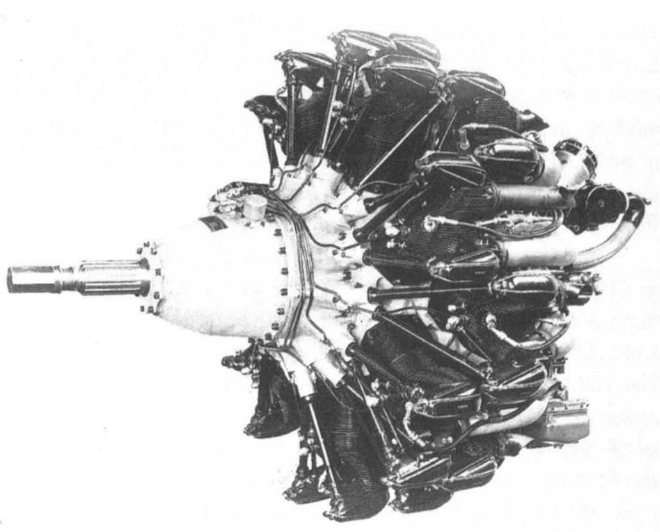
bottom of its stroke, through which very rich mixture could be admitted. The operating cycle was as follows: ignition 20° before top dead centre (TDC), useful power from TDC to 90°, exhaust (head valve) open from 90° right round to TDC (total 270°), induction of pure air (through exhaust valve, still open) from TDC to 135°, the continued downstroke then producing a partial vacuum into which rich mixture was admitted from 20° before BDC (bottom dead centre) to 20° after, followed by compression of the diluted mixture to the ignition point. Most Gnomes, prior to the Mono, had a throttle lever as well as a fine-tuning mixture control, but no control over ignition timing. The Mono, however, had no throttle, and the so-called fine-adjustment lever gave extremely coarse control; accordingly a blip switch on the control column enabled the pilot to cut ignition in or out (often on any selected number of cylinders) at all times on the ground and during the approach.

Thus by 1914 Gnome, and their agents in all major countries, had a large range of rotary engines. The original pattern, often assigned Greek letters by the company such as Lambda (and, for the corresponding two-row engine, Lambda-Lambda), was marketed chiefly as the 80-hp (actually about 62) with cylinders 124 × 140 mm and priced in Britain at £430, and in small numbers as the 100-hp 10-cylinder and the 160-hp 14-cylinder. During the war the Mono engines were more numerous, the chief models being the 80-hp, the 100-hp with nine 110 × 150 mm cylinders, 12.83 litres (actually giving about 103 hp at 1,200 rpm), the rarer 150-hp with nine 115 × 170 mm cylinders, 15.89 litres, actually giving about 157 hp at 1,250 rpm, and important 18-cylinder engines of 205–40 hp.

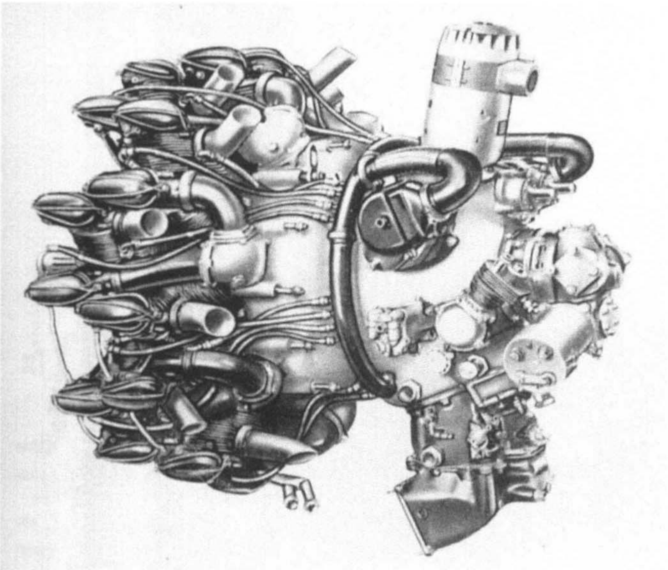
The Japanese Shimadzu was a direct copy of the original Gnome series, while the German Oberursel began as such but later copied Le Rhône. Other rotaries, such as the Clerget, Le Rhône and Bentley, are discussed separately.

Gnome-Rhône (FRANCE) In 1914 the Gnome company bought out its rival to form the Société des Moteurs Gnome et Rhône, though during the war the Le Rhône design team were allowed to get on with their own engines. There appear to have been no Gnome designers other than the Seguins, and in 1921 they were anxiously wondering how to keep producing saleable engines. In October of that year they wisely took a licence for the new Bristol Jupiter. With it came two Bristol resident staff: Norman Rowbotham was appointed chief engineer and general manager and Roger Ninnes became chief designer. They were joined by another Englishman already at the Boulevard Kellermann factory testing the company's motorcycles: Ken Bartlett. All three headed the GR aero team through the 1920s, and all later became directors at Bristol, Bartlett on the aircraft side.

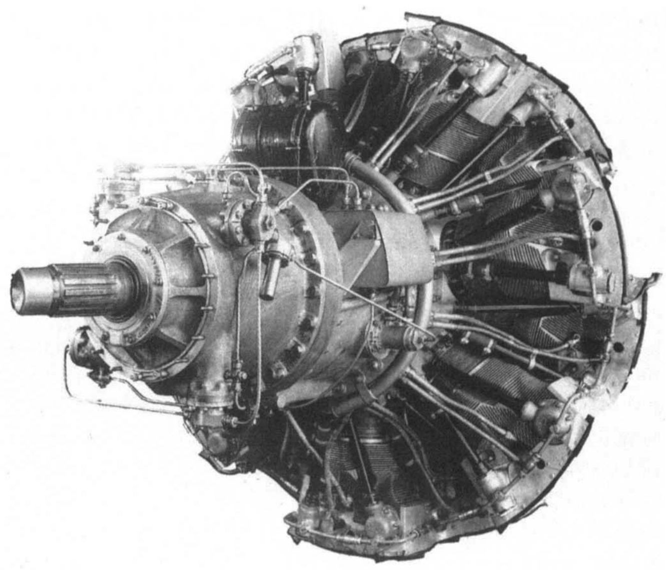
In 1925 GR introduced the Farman reduction gear, and by this time was looking for ways to evade the terms of its licence. In 1927 the company began not only building the Bristol Titan, without paying a royalty, but it began developing it into GR engines, first into the seven-cylinder Titan 7Ksd (almost a copy of the parent firm's Neptune), then in October 1927 into the nine-cylinder Mistral, and finally, in December 1928, into the first Bristol-derived two-row engine, the 14-cylinder Mistral Major, still with the 146 × 165 mm cylinder but with capacity of 38.7 litres (the same as Bristol's later Hercules). In order to achieve reasonable valve gear the Major had only two valves per cylinder, all valves being operated by sloping enclosed pushrods from inlet and exhaust cam rings at the front of the crankcase. GR were ahead of Bristol in enclosing the valve gear (on a separate forged head on an open liner) and at least equal in providing greater area of cooling fins per cylinder. The Mistral Major, known as the 14K with suffix letters for sub-variants, began life at a weight of some 660 kg and power



The Gnome-Rhône 14K Mistral Major was one of the most important engines of the 1930s, and one of the pioneer high-power two-row radials. This is a 1933 model, with long reduction gear.



The Germans picked the Gnome-Rhône 14M of 700 hp to power the Henschel Hs 129B anti-tank aircraft. This illustration comes from a Luftwaffe training slide.



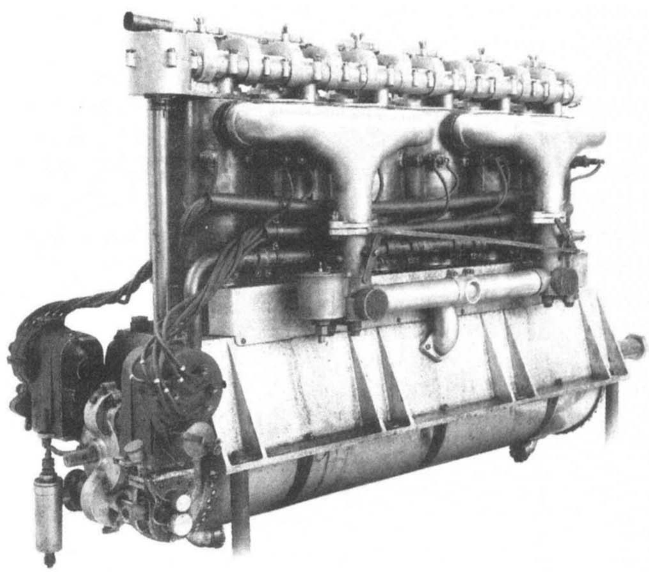
Last of the Gnome-Rhône radials, the GR 14U of 1949 was a 44-litre engine rated at 2,200 hp and weighing 1,250 kg. The long gearbox/torquemeter package was configured for a low-drag cowl.

750 hp, and by 1932 was in major production at powers between 800 and 900 hp, which was higher than any other production radial of its era.

Thus, GR managed to sell a lot of engines and even licences, to Italy, Japan and the Soviet Union, among others, and by the 1930s their own engineering staff was large and capable. The 14K was progressively developed until 1953, via the extremely important 14N family of 900–1,100 hp of 1935–50, the 1,500–1,600-hp 14R of 1939–50 and the post-war 14U of 2,200 hp. In 1945 the company vanished into the nationalised group SNECMA, and the final member of the family was the 1,600-hp SNECMA R.210. Small numbers were made of the L-series, with stroke increased to 185 mm, the 14L being a 1,400-hp unit and the 18L a giant 56-litre engine of 1,900 hp, both dropped in 1939. Far more important was the attractive 14M Mars series, with smaller cylinders 122 × 116 mm, capacity 18.98 litres. The Mars was only 0.95 m in diameter at first, later versions being about 1 m, and this helped it gain many applications in 1936–43 at ratings from 600 to 710 hp at 3,100 rpm. SNECMA later developed these engines into the 14X with output up to 820 hp at 3,400 rpm, an exceptionally high speed for a large radial.

Granit (RUSSIA) Founded in 1945 jointly by Mikulin and Klimov as OKB-45, this Moscow bureau played a central role in getting the Nene into production, and developing it into the VK-1. It later produced the Lyul'ka AL-7 and AL-21 fighter engines, and Soyuz R-15B for the MiG-25. Later work has included developing three small engines, the MD-120 turbojet of 265 lb thrust, TVD-150 turboprop of 150 shp and TVD-400 turboshaft of 400 shp.

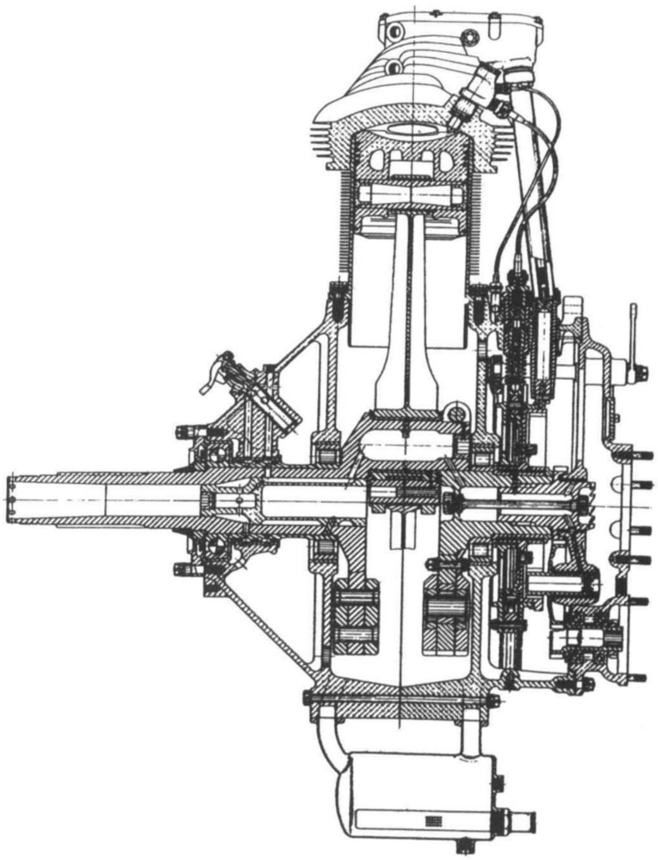
Green (UNITED KINGDOM) Gustavus Green, who died in 1964 at 99, was unrelated to Major F.M. Green of the Royal Aircraft Factory. He built his first lightweight four-in-line water-cooled engine in 1905. His patents were administered by an office in Berners Street, London, and manufacture was handled by the Aster Engineering Company. All his engines were seemingly massive water-cooled in-lines with shining copper



Probably made in 1914, this six-cylinder Green was rated at up to 82 hp. However, not many of these all-British engines were used in aircraft.

water jackets, held on the steel cylinders by rubber seals which part-vulcanised with the heat. Two valves per cylinder were worked by an overhead camshaft and rockers, the gear being enclosed from 1910 on. Other features included force-feed lubrication, HT magneto ignition, flywheel and four large bolts to hold down each cylinder and, in most cases, also secure the phosphor-bronze/white metal bearings of the crankshaft. Green won both the British government prizes for an aero engine, £1,000 in 1909 and £5,000 in 1914, with his two main production engines. These were the 30-35, rated at 30 hp at 1,100 rpm and 40 hp at 1,220 rpm, with cylinders 105 × 120 mm and weighing 150 lb, and the 50-60, rated at 50 hp at 1,050 rpm and 70 hp at 1,200 rpm, with cylinders 140 × 146 mm and weighing 259 lb. Green made a 100-hp V-8 and in December 1911 impressed everyone with his six-in-line, with two Zenith carburettors each feeding three 140 × 146 mm cylinders and rated at 82 hp. Like all Greens it was beautifully made and reliable, but at 450 lb the weight was a problem and wartime production went into fast boats. The 275-hp V-12 of 1915 remained a prototype.

GTRE (INDIA) The Gas Turbine Research Establishment is located at Bangalore, which is also the home of the main centre of India's aircraft industry, HAL. By far its biggest task is developing an afterburning turbofan, called the Kaveri, to power the LCA (Light Combat Aircraft). Over many years it has passed through different forms, but now has a three-stage LP compressor and six-stage HP, and a maximum thrust of 18,210 lb. The complete engine first ran in September 1995, but 11 years later the Indian Air Force is still having to buy General Electric F404 engines to power the production LCA, named *Tejas*.



Section through the Guiberson A-1020 diesel. The injector squirts into the tiny space above the piston. The inlet valve is on the far side (exhaust valve not shown).

Guiberson (USA) Guiberson Corporation of Dallas made oil-industry equipment, and from 1928 researched diesel aero and automotive engines. In 1932 Guiberson Diesel Engine Company was registered, and Austrian F.A. Thaheld had by that time not only designed the A-980 nine-cylinder diesel radial but had begun flight testing in a Waco. Rated at 185 hp at 1,925 rpm, the A-980 took the Waco 960 miles to Detroit on 96 gallons of furnace oil at 7c a gallon. An Approved Type Certificate was awarded in November 1931. Next came the A-918, under chief engineer C.C. Spangenberger, rated at 253 hp and sold to the Navy in 1934. Last was the A-1020, for which an ATC was awarded in February 1940 and which flew over 1,000 h in a Reliant. This had nine 5.125 × 5.5 in cylinders, 1,021 cu in, and for a weight of 653 lb gave 310 hp at 2,150 rpm, with sfc of 0.382. The 1020 started easily with a Coffman cartridge starter and was flown to 18,500 ft in the Reliant (well above normal ceiling) while still climbing strongly. Buda Corporation planned to make it, but during the Second World War Guiberson had to make tank engines and subsequently was never able to get enough orders for the otherwise excellent 1020.

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H

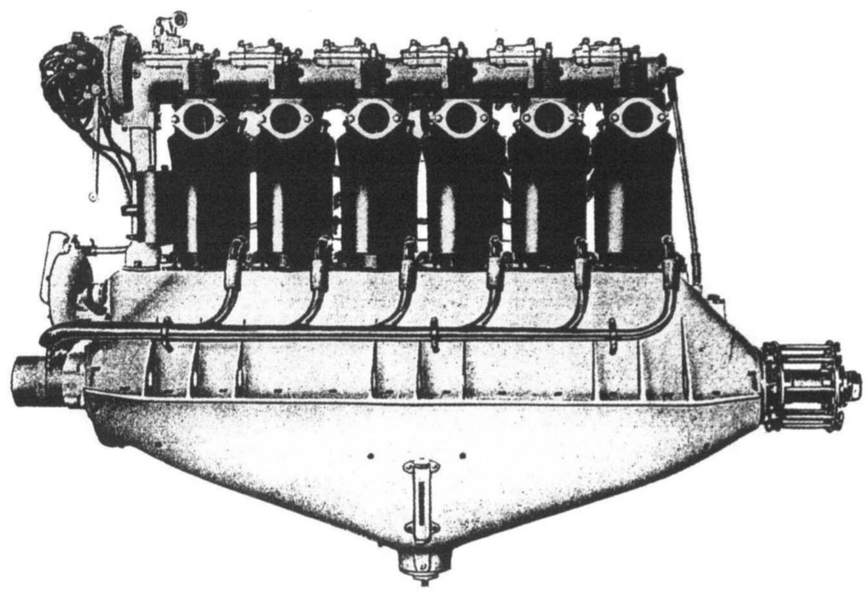
Halford (UNITED KINGDOM) Major Frank Bernard Halford graduated from Nottingham, became a flying instructor at Brooklands, was appointed an engine examiner at the newly created AID (Aeronautical Inspection Directorate), was posted to France in the RFC and in early 1916 was recalled to produce what became the BHP. After the war he did important work with Harry Ricardo in Britain and the USA and then headed the engine section of Airdisco where he redesigned the Puma into the Nimbus, with capacity of 20.7 litres and rpm increased to 1,600, using the stronger crankshaft of the Galloway Atlantic; it was rated at 335 hp. He also redesigned the big Fiat A 12. He designed all the Cirrus engines, followed by all the Gipsy engines. In 1928 he agreed to design also for Napier, producing the Rapier, Dagger and Sabre, finishing with the de Havilland gas turbines.

Hall-Scott (USA) With Curtiss, this San Francisco company was the US leader in water-cooled engines prior to the First World War. The first (pre-1908) engine was a four-in-line supposed to give 30 hp, with cylinders 4 in square. Subsequent engines were mainly six-in-lines or V-8s, one of the latter (designated an A-2) rated at 60 hp at 1,100 rpm flying at the 1910 Belmont Park meet. The A-3 had stroke increased to 5 in, giving 80 hp, while the A-4 was the corresponding six-in-line. The A-5 of 1912 was a V-8 built in quite large numbers, the camshaft being moved from the top of the crankcase to a position above each cylinder block; rating of this enlarged (5 × 7 in cylinders, 1,100 cu in) engine was 125 hp at 1,250 rpm. Smaller numbers were made of the four-in-line 100-hp A-7 and the corresponding 200-hp V-8. The big 5 × 7 in cylinder was the starting point of the Liberty.

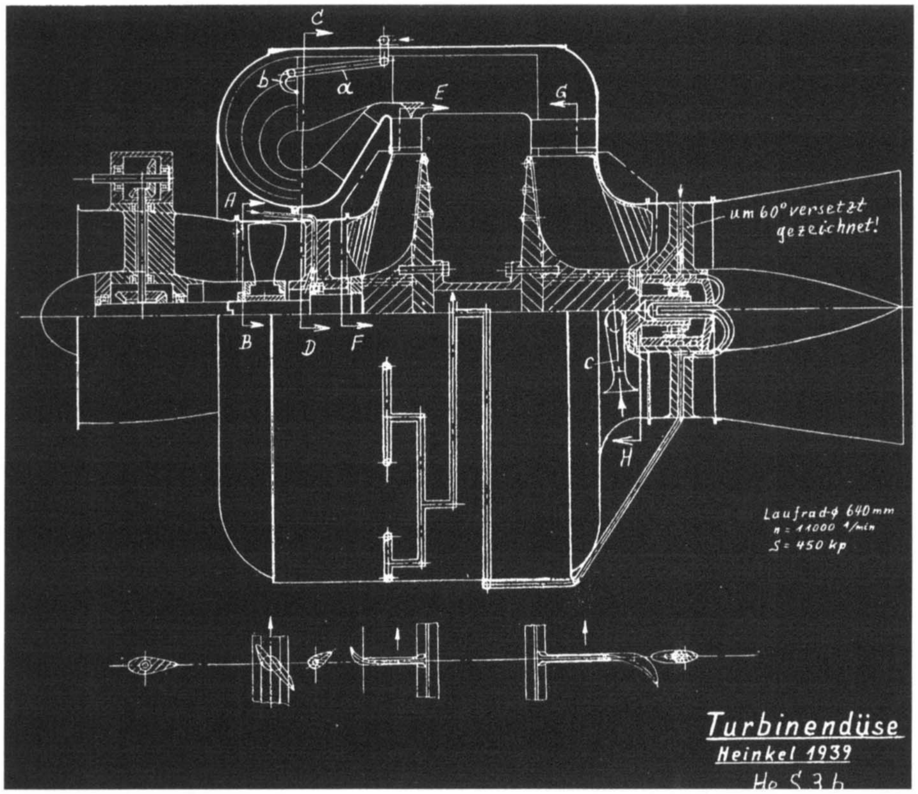
Heinkel (GERMANY) In February 1936 Professor R.W. Pohl of Göttingen persuaded Ernst Heinkel to hire one of his post-graduate students, Hans-Joachim Pabst von Ohain. A few months earlier von Ohain had obtained a patent for his turbojet, with an axial-plus centrifugal compressor, annular combustor (patented by fellow-student Max Hahn) and inward radial turbine. In later years von Ohain, who stayed in the USA after being sent there in Operation Paperclip in 1945, denied that he knew anything of Whittle's work, though his colleague Dipl-Ing Wilhelm Gundermann (who worked with him at Heinkel from the start in April 1936) has recorded, 'We kept fully up to date with such patents as Whittle's and Milo AB in Sweden.'

Heinkel had no engine facilities or staff, but let his new protégé construct a simple rig to prove whether the idea worked. It was in no sense a turbojet but a demo rig burning hydrogen gas to avoid the problems of liquid fuel atomisation. Called the HeS (S for strahl = jet) 1, it was ready in March 1937 and eventually gave about 136 kg thrust. No company wanted to assist with burning liquid fuel at such intensity, and Heinkel was forced to gather a small research staff at Rostock-Marienehe to help design the HeS 2, the first flight engine.

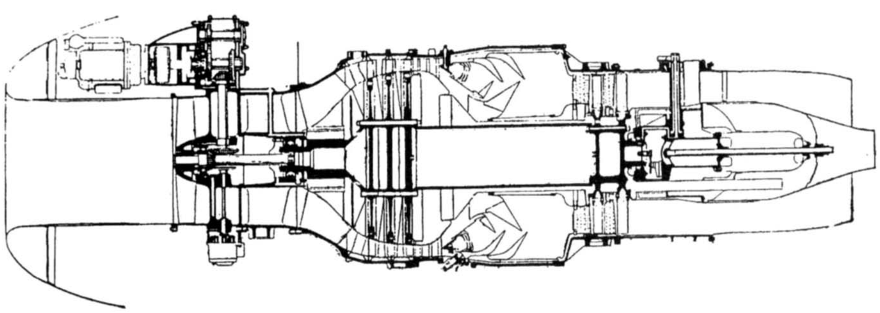
As built in August 1938 this comprised an enlarged axial/centrifugal compressor, now with a ball bearing between the stages, delivering to a flow divider, one flow diluting the flame and the other passing through 16 so-called partial chambers separated by radial walls. Each of these contained a vaporiser tube heated by an externally supplied hydrogen flame; once the 16 vaporisers were glowing the liquid fuel was turned on and the gas disconnected. The burning length had



A typical Hall-Scott six-in-line, derived from the Liberty cylinder, the L-6 had a capacity of 825.67 cu in, dry weight of 546 lb and was rated at 200 hp at 1,675 rpm, but at 1,830 rpm could give 244 hp.



Dipl-Ing Wilhelm Gundermann's original rough drawing of the Heinkel (or Heinkel-Hirth) HeS 3B, the first turbojet to propel an aircraft in August 1939. The only feature seldom seen today is the inward-radial turbine.



The Heinkel-Hirth HeS 109-011 turbojet had an axial 'inducer' stage at the inlet followed by a diagonal axial/centrifugal stage and then three axial stages.

to be many times greater than in the original rig and a large folded combustor was used, the inward-radial turbine having to be moved downstream from the compressor. As originally built it gave less than 20 per cent of the design thrust of 500 kg, and several rebuilds were needed to provide more room for a larger compressor and much larger combustion system, all of which considerably increased the engine's diameter. The result was the HeS 3, the first example of which, designated HeS 3A, was air-tested slung beneath He 118 V2 (D-OVIE) in about May 1939. The engine had a diameter of 1.2 m and weighed 360 kg. As first run at the start of 1939 the 3A gave 400 kg thrust, but this increased by various improvements to 450 kg at the time of first flight, this figure falling to 370 kg at 200 km/h and 345 kg at 400 km/h, in all cases at 11,000 rpm.

Meanwhile, the He 178 aircraft had been designed around the engine, which for this application was designated HeS 3B, with a long inlet duct and rear jetpipe. These additions reduced thrust to a best figure of 380 kg (838 lb). Erich Warsitz began He 178 taxi trials (with a brief hop) on 24 August 1939, followed by a full flight on 27 August. This was the world's first jet flight, though the 178 flew seldom thereafter. It was a very defective aircraft and was limited to 300 km/h even with the later S6 of 450 kg thrust.

In early 1939 Heinkel's Robert Lüsser had gathered a team to design the He 280 twin-jet fighter, to be powered by two HeS 8A engines. Heinkel had not informed the RLM (German Air Ministry) of his jet work until late 1938. He received no support until late 1939; even then he was discouraged, as an aircraft manufacturer with no engine facilities. However, believing he was well ahead with something very important, Heinkel was determined to press ahead, even with his own money and in a climate where good engineers were almost unavailable. To avoid the losses caused by long ducts the He 280 had underwing engines, and in turn this forced the HeS 8A to be of small diameter. Redesignated 109-001, it matured at only 775 mm diameter and a weight of 380 kg, but was nowhere near the hoped-for thrust of about 480 kg when the He 280 was flown on 2 April 1941.

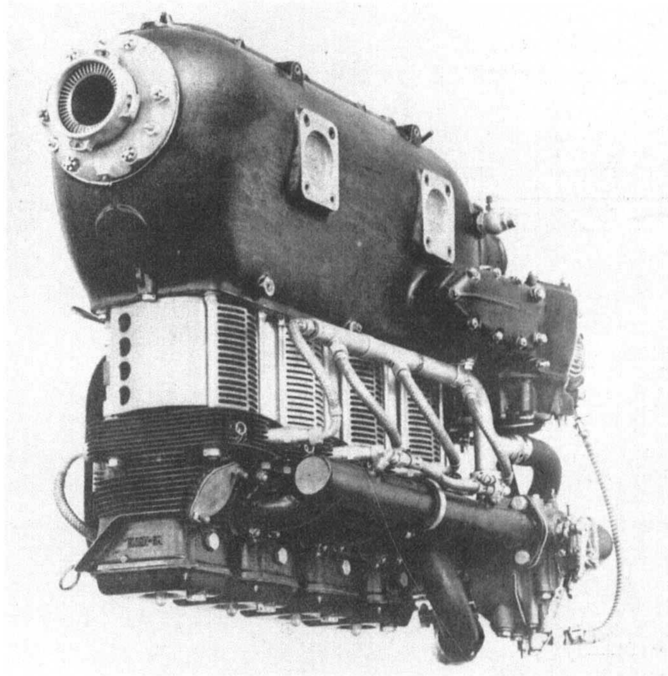
By this time Heinkel had hired Max Adolf Müller from Junkers to develop the 109-006 axial turbojet, was trying to build various ducted-fan engines, and was fast falling behind Junkers and even BMW in timing. He had, however, become chief shareholder of Hirth, and took over part of that company's plant in late 1941 to expand his engine operations. This enabled him to scrap earlier projects and with RLM backing undertake a completely new and important turbojet, the Heinkel-Hirth 109-011. Von Ohain was in charge, and development got under way in September 1942; the 001 was dropped, having reached about 590 kg thrust. The 011 had a diagonal compressor followed by three axial stages, a 16-burner annular combustor with turbulence 'fingers', two-stage turbine with hollow blades, and a nozzle with a sliding bullet which was retracted only for idling. Diameter was 875 mm, weight 950 kg, and design thrust 1,300 kg at 10,000 rpm. Ten 011s ran, the first in September 1943, and one flew slung under a Ju 88. The corresponding 109-021 turboprop was never completed. As for the 006 turbojet, this made amazing progress but was dropped in early 1943 because of the (probably mistaken) RLM belief that an engine of 617 mm diameter could not be sufficiently powerful for combat aircraft.

Hiero *See* Avia.

Hiro (JAPAN) The chief engine made by this aircraft firm was the Type 91, a water-cooled W-12 derived from the Napier Lion, rated at 620–750 hp. It was in production in the first half of the 1930s.

Hirth (GERMANY) Hellmuth Hirth was a famous pre-1914 aviator and no mean engineer. During the First World War he planned an improved form of engine with roller bearings throughout, including big and little ends of the conrods. In turn this meant a multi-section crankshaft, and brother Dr Albert Hirth patented the Hirth coupling now used on many gas turbines to ensure automatically perfect assembly of adjacent sections. Other features included cast-iron cylinders with light-alloy heads, pushrods with ball-ended tappets driving the overhead valves via needle-roller rockers, very small metered oil flow to the thrust bearing and cylinders (with oil splash to other bearings), carburettor air taken warm from the crankcase (cast in Elektron magnesium alloy) and an overall exceptional standard of finish.

The first engine to be marketed, the HM 60 inverted four-in-line of 65 hp, ran in June 1923 and was initially sold in 1924 by the Versuchsbau Hellmuth Hirth at Stuttgart-Zuffenhausen. Despite its almost mistakenly high quality it did so well, in particular winning the Rundflug and eight other major sporting events from 1927 onwards, that the factory expanded and a new company, Hirth-Motoren GmbH, was founded in 1931. The HM 504, 506 and 508 quickly appeared, with inverted 4, 6 and V-8 layout, with cylinders



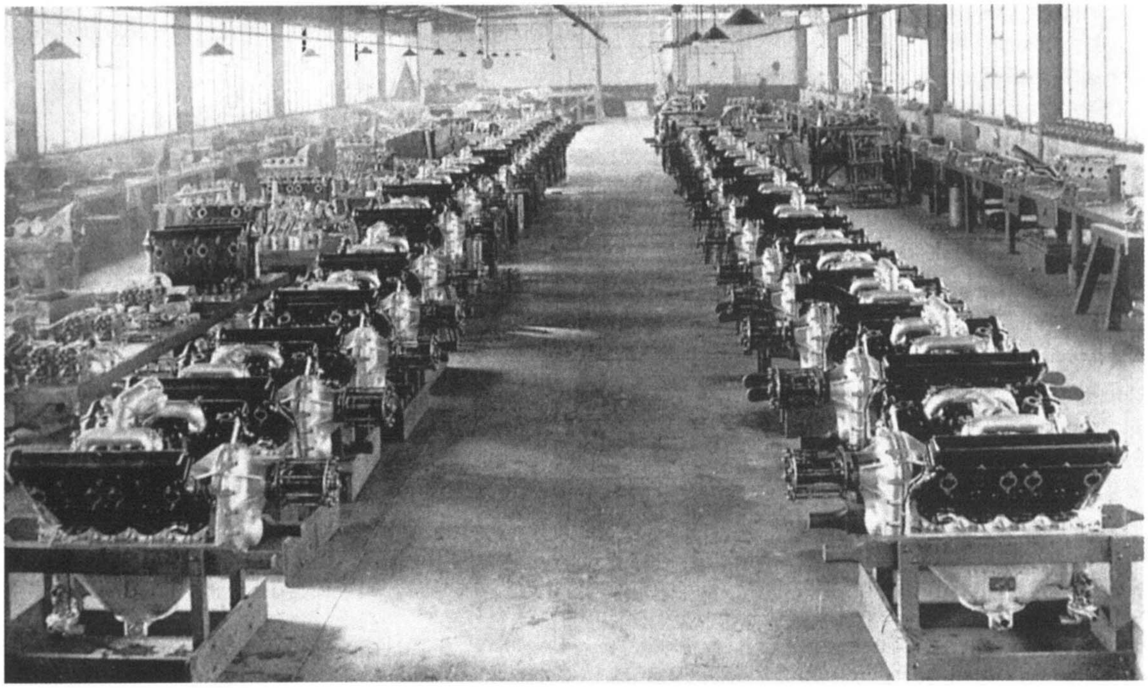
The HM 504 was the basic inverted four-in-line of Hirth's family of beautifully made air-cooled engines which culminated in the HM 512A inverted V-12 of 400 hp.

105 × 115 mm. The 504 was mass-produced at 105 hp at 2,530 rpm, the 506 was rated at 160 hp and the 508 at 280 hp at 3,000 rpm. A few HM 512 inverted V-12s rated at 400 hp were sold after 1938. Hellmuth died in June 1938, and to give Heinkel an engine team and floorspace the RLM tried to arrange for a takeover by the aircraft firm in May 1941. This was blocked by Messerschmitt but eventually was forced through by the end of the year, subsequently Heinkel jet engines being known as Heinkel-Hirth.

After the Second World War Hirth resumed operations, and today GoblerHirthmotoren produce a range of small piston engines, mainly two-strokes, with output from 3.5 to 110 hp.

Hispano-Suiza Assigning a nationality to this company is difficult. The name means Spanish-Swiss, because Marc Birkigt (1878–1953) was Swiss but in 1904 set up his great factory at Barcelona, chiefly to make cars of the highest quality. In April 1911 he formed the Soc. Hispano-Suiza at Levallois-Perret, Paris, soon moving a few kilometres to Bois-Colombes where the French factory soon far outgrew its Spanish original. In 1915 he began production of his first aero engine, and from this stemmed engines which by 1918 had been licensed to Aries, Ballot, Brasier, Chenard & Walcker, Delaunay-Belleville, De Dion Bouton, Doriot-Flandrin-Parant, Fives Lille, Leflavie et Cie, Mayen, Peugeot, SCAP and Voisin in France; Wolseley Motors in Britain; Itala, Nagliata and SCAT in Italy; Wright-Martin in the USA; H-S itself in Spain; the National Arsenal in Czarist Russia; and Mitsubishi in Japan.

H



Geared Hispano-Suiza V-8s in production in England in 1917. Such engines gave serious trouble in the SE.5a programme, but the basic design was superb.

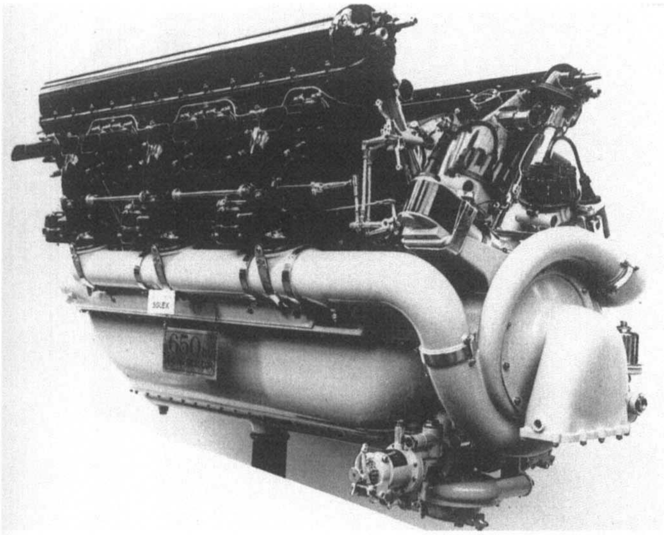
H

Clearly Birkigt's engine was important, and yet, while it was ahead of all others in some respects, it made demands on builders which many licensees could not meet, and this caused prolonged difficulty. The original November 1914 engine, the Type A, was a water-cooled V-8 with cylinders 120 × 130 mm, capacity 11.76 litres. It weighed 202 kg and was rated at 140 hp at 1,400 rpm. Its most striking feature was that the two cylinder blocks, set at 90°, were monobloc aluminium castings. These gave adequate strength to the thin but deep crankcase which contained all oil not going round the unprecedented force-feed system to all parts of the engine.

Each cylinder block was stove-enamelled to combat porosity, and into each were screwed machined steel cylinder liners threaded over their entire length, with closed tops into which the valves seated. Radial shafts at the rear drove the overhead camshafts, the valve gear being totally enclosed. A vertical shaft at the rear drove the oil and water pumps, and a cross-shaft the two magnetos. The Zenith or Claudel carburettor sat between the blocks feeding via bifurcated pipes and then through passages cast in the blocks. Similar passages carried out the exhaust on the outer sides, and it was to be a trademark of Hispano engines that the intermediate cylinders in each block were to have exhausts grouped into pairs, so that a six-cylinder block resembled letter 'P' in Morse. Fork-and-blade conrods were used, running in plain bearings on a short crankshaft without balance weights, the latter running in four plain bearings and a rear ball bearing.

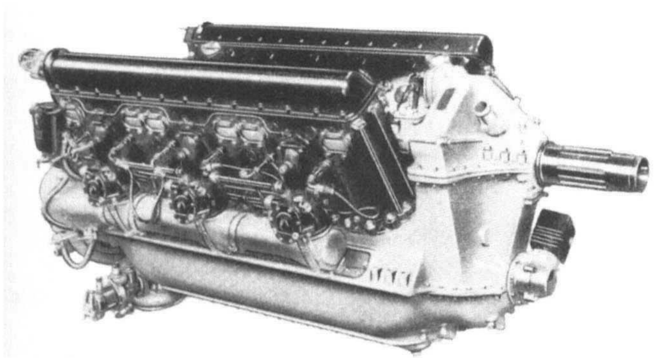
Overall, the Hispano A was the most promising engine in production in 1915. It was short and compact compared with the big six-in-lines, had lower frontal area than a rotary and set an excellent figure for specific weight. The production A gave 150 hp at 1,400 rpm, and a few Type B 4-cylinder in-lines were made weighing 143 kg and giving 75 hp. By December 1915 the developed 8Aa was in production, rated at 175 hp at 1,700 rpm, soon followed by the 200–5 hp 8Ab cleared to 2,000 rpm and 8Be rated at 215 hp at 2,150 rpm. The 8Ba of 1916 introduced the geared drive, rated at 220 hp at 2,150 rpm. The Wolseley W.4A Python was a copy of the Type A, but heavier at 445 lb. The W.4A Viper had higher compression (5.3 instead of 4.8) and gave 200–210 hp, while the W.4B Adder had a balanced crankshaft and reduction gear. Wright-Martin's Simplex Model E was very like an 8Aa, rated at 180 hp at 1,750 rpm. In general a Hispano-built engine was a high-quality product which, if maintained with great care, would give high and reliable performance for about 20 h between overhauls. Less successful attributes were the poor cylinder cooling, distortion of the thin exhaust valves, and a series of major problems with geared engines including uneven heat-treatment of the helical pinions and fatigue failures of the crankshaft. From summer 1917 there was a crisis in SE.5a deliveries because Wolseley crankshafts seldom lasted more than 4 h. As a stop-gap the firm was told to switch to the direct-drive engine; instead of rushing through the 1,100 engines, Wolseley went back to the drawing board to get the same 200-plus horsepower from the high-compression Viper. Eventually good geared engines were produced, and some were fitted with Hispano's patented *moteur canon* in which a gun (up to the massive 37 mm Puteaux) was mounted between the cylinder blocks to fire through the hub of the propeller. Guynemer's SPAD XII, in which he gained four victories with the 37 mm gun, first flew on 5 July 1917.

In December 1916 the Model H introduced cylinders 140 × 150 mm, capacity 18.47 litres, rated at 308 hp at 1,850 rpm for a weight of 270 kg. By this time the original geared



The Hispano-Suiza 12Xcrs was an important member of a V-12 family which lasted from 1918 until after the Second World War. Rated at 690 hp, this supercharged engine powered the Dewoitine D.501 fighter, among other aircraft.

Dating from 1935, the Hispano-Suiza 12Y-31 continued the arrangement of having a supercharger delivery manifold along each side, feeding three Solex carburettors each serving just two cylinders. Rated at 860 hp, it powered the MS.406 fighter (which in consequence was outfought by the more powerful Bf 109E). Klimov's VK-103 and 105 were Soviet copies.



engines were giving up to 240 hp, and the bigger model was developed to 340 hp. This was later built as the Wright-Hispano. Total output of all models in 1915–18 is believed to have been 49,893, comprising 12,593 of 150–80 hp, 28,977 of 200–20 hp and 8,323 of 300 hp.

After the war the main aero-engine factory continued to be Bois-Colombes, in a road renamed for Captain Guynemer. Here Hispano-Suiza gradually improved their range so that they required less constant attention and became among the most reliable of all engines, setting numerous speed and distance records. By 1925 the most important products were 60° V-12s, but there were six-in-lines, W-12s and even W-18s, the commonest cylinder size being 150 × 170 mm, giving capacity of 36.05 litres for a 12-cylinder engine. By far the most important family was the 12Y of 1933, some 18,000 of which were made at ratings from 800 to over 900 hp, the commonest fighter engine being the 860-hp 12Y-31. Compared with the Merlin of the same period the 12Y engines were of larger capacity (similar to the Griffon), lighter and of lower power, largely because they were limited to 2,400 instead of 3,000 rpm. In 1934 the HS 12Y was licensed to the Soviet Union, and as the M-100, became the baseline engine for the VK series developed by V. Ya. Klimov (*qv*).

The most powerful mass-produced engine was the 12Y-45 with Szydlowski (Turbomeca) supercharger, rated at 910 hp. The 1,100-hp 12Y-51 was entering production at the time of the capitulation, and the 1,280-hp 89ter powered the Arsenal VG39 fighter of February 1940. The 12Z with direct fuel injection ran at 1,800 hp at 2,800 rpm before the capitulation, and powered the D.520Z in February 1943.

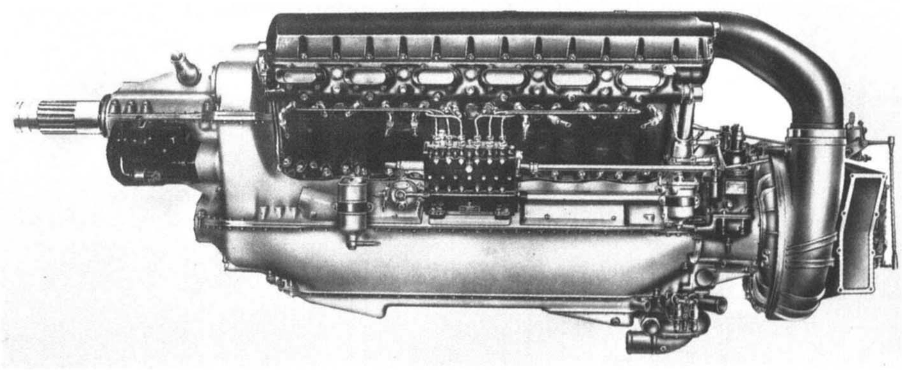
During the war the design of an H-24 engine with four 12Z cylinder blocks was slowly completed, and this big engine was tested in 1949–52. It had four Lavalette injection pumps, dual two-speed superchargers on a transverse shaft, and each half engine drove half the contra-rotating propeller. The 24Z gave almost 4,000 hp.

The war interrupted design of the 12B, but this ran in 1945 and emerged in several forms in 1947 with ratings up to 2,200 hp. Still using the 150 × 170 mm cylinders, the 12B was mechanically a completely different and much stronger engine, but it was too late. In 1938 a French equivalent of the German HZ-anlage had been the use of a fuselage-mounted HS 12Xirs of 690 hp driving a three-stage compressor to supercharge the two HS 12Y-32/33 wing engines of the NC 150 (flown for the first time on 11 May 1939) which were rated at 955 hp at 9 km (29,530 ft).

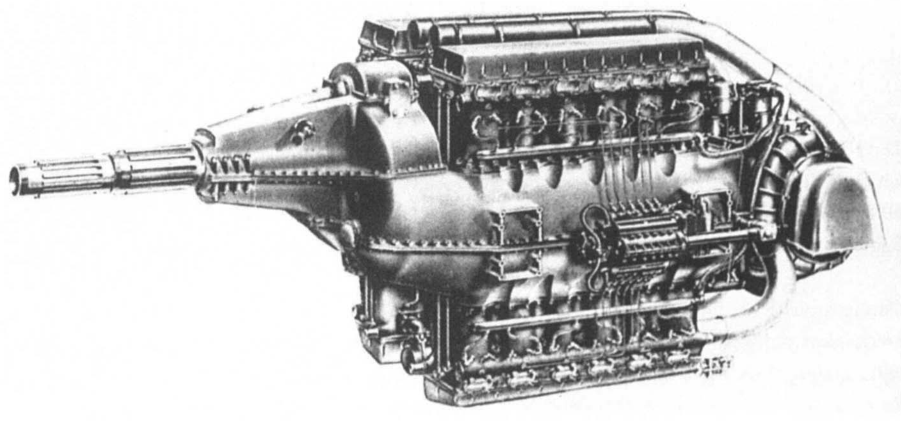
In 1929 the company bought a licence for the Wright Whirlwind, and subsequently produced about 2,500 radials with various numbers of cylinders, the most important being the 14AB, an extremely compact 14-cylinder unit rated at 650 hp in 1934 and up to 800 hp in the 14AB-12/13 of late 1939. This family are often confused with the bigger 14AA of 1,100–1,350 hp. Hispano also built small numbers of HS 9V and related nine-cylinder engines of greater diameter than the 14s, rated around 600 hp, but none of the company's radials (all using Wright features) made much impression on the GR-dominated market.

In 1946 Hispano-Suiza obtained a licence for the Rolls-Royce Nene turbojet, and large numbers were made of Mks 101, 102, 104 and 105, as well as prototypes of the afterburning Mk 102B. Hispano itself developed the R.300 with increased airflow and hollow air-cooled turbine stators, rated at 2,700 kg. This was dropped in 1951 in favour of a licence for the Tay 250 of 2,850 kg thrust; the afterburning 250R of 3,850 kg thrust remained a prototype. The final derived engine was the Verdon 350, first flown in a Mystère in August 1953, in which further increases in mass flow, rpm and temperature increased thrust to 3,500 kg at 11,100 rpm, weight being 935 kg. The company participated in the

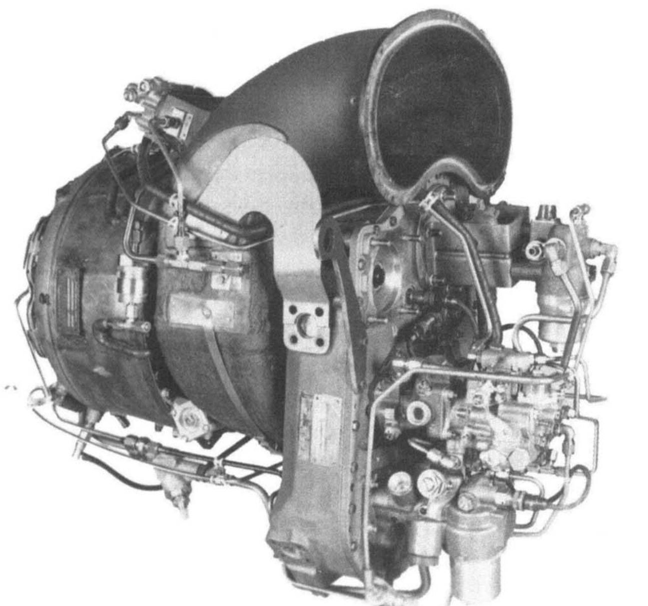
One of the last of the pre-war Hispano-Suiza V-12s, the Hs 12Z was giving 1,800 hp in early 1940, with Turbomeca supercharger and direct injection.



Spurred by the threat of Arsenal with its monsters derived from the Jumo 213, Hispano-Suiza went mad as well and produced the 24Z, with four six-cylinder blocks of 12Z type.



Textron Lycoming Williamsport's LT101 range of turbines in the 600-hp class show how today the engine is dwarfed by the inlet, gearcase and accessories. This is a digitally controlled LTS101-750A-3, which today is a product of Honeywell.



Avon installations in the Caravelle airliner and Dassault fighters, and in 1954 designed a small axial turbojet, the R.800, for light fighters. Rated at 1,800 kg at 12,200 rpm, this had a seven-stage compressor, diameter of 692 mm and weight of 303 kg. It was dropped in early 1956. Hispano-Suiza then diversified, later engine work including production, for SEP of the SEPR 844 rocket for the Mirage III, and licence-assembly and participation in manufacture of the RR Tyne. In December 1968 the company was acquired by Snecma.

Hitachi (JAPAN) This large conglomerate made aero engines from about 1929, and concentrated on low-powered engines up to the collapse in 1945: the GK2 Amakaze nine-cylinder radial of 340–610 hp, the Ha-12 and Kamikaze seven-cylinder radials of 150–160 hp, the Ha-13, Ha-42 and Tempu nine-cylinder radials of 310–510 hp, and the GK4 and Ha-47 inverted four-in-lines of 100–110 hp.

Honeywell (USA) In June 1999 this multifaceted giant decided to enter the aero-engine business. It initially merged with AlliedSignal, which five years earlier had purchased Garrett and the turbine-engine business of Textron Lycoming. At the merger AlliedSignal was the larger partner, yet that is the name that was dropped, leaving Honeywell as a company employing almost 130,000, with revenues of over $25 billion. Major engine programmes are the all-new 6,500-lb-thrust HTF7000 civil turbofan (replacing the LF502 and 507), the best-selling TFE731 turbofan and TPE331 turboprop, and the T53 and T55 helicopter engines, still being made after almost 50 years. The small LTS101 turboshaft and LTP101 turboprop were in 2006 on the point of being replaced by the all-new HTS900.

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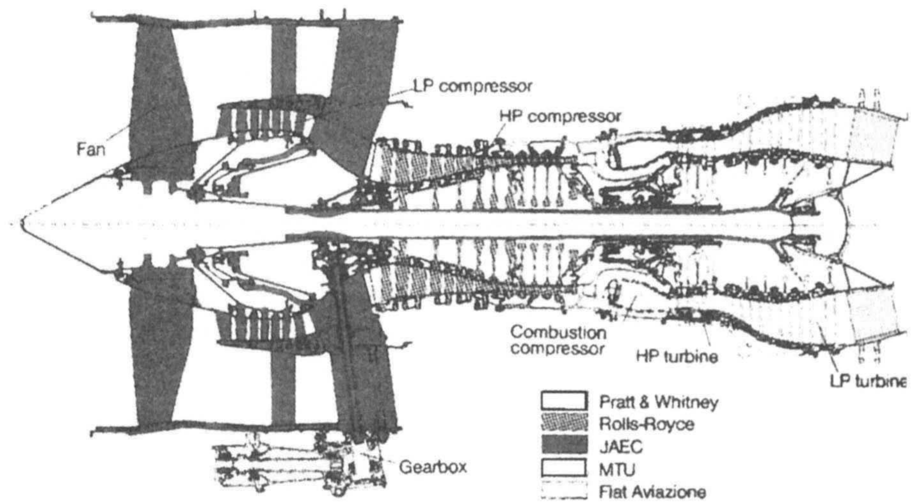
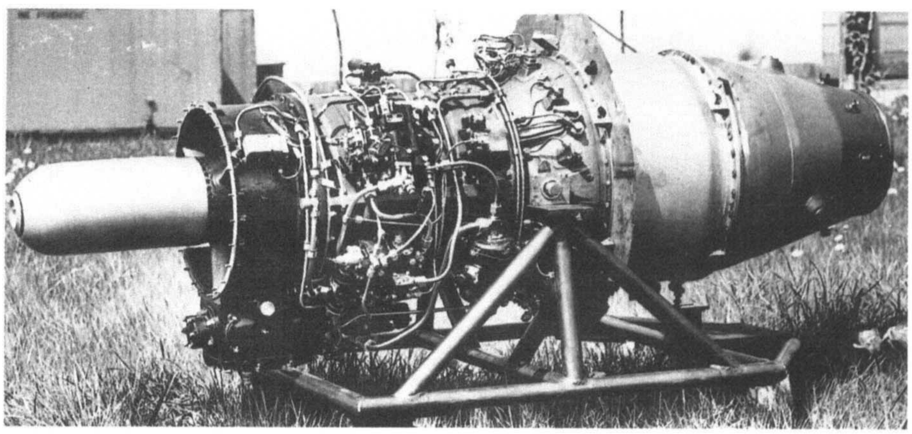
IAE (INTERNATIONAL) International Aero Engines AG is a company incorporated in Switzerland with operating HQ at a new site at Glastonbury, Connecticut, USA, near Pratt & Whitney. Its members are that company and Rolls-Royce (each 30%), JAEC (23%), MTU (11%) and Avio (previously Fiat) (6%). JAEC, Japan Aero Engine Corporation, is formed by IHI, Kawasaki and Mitsubishi. Seldom have such multinational resources been applied to a single product, this being the V2500 commercial turbofan in the 25,000-lb class, for certification in April 1988. RR had previously collaborated on an engine known as the RJ.500 and this is one of several engines which contributed to the V2500. This is claimed to beat the CFM56-5 in head-on competition. Basic responsibilities are: Japan, fan and LP spool; UK, HP spool; USA, combustor and HP turbine; West Germany, LP turbine; and Italy, accessory gearbox.

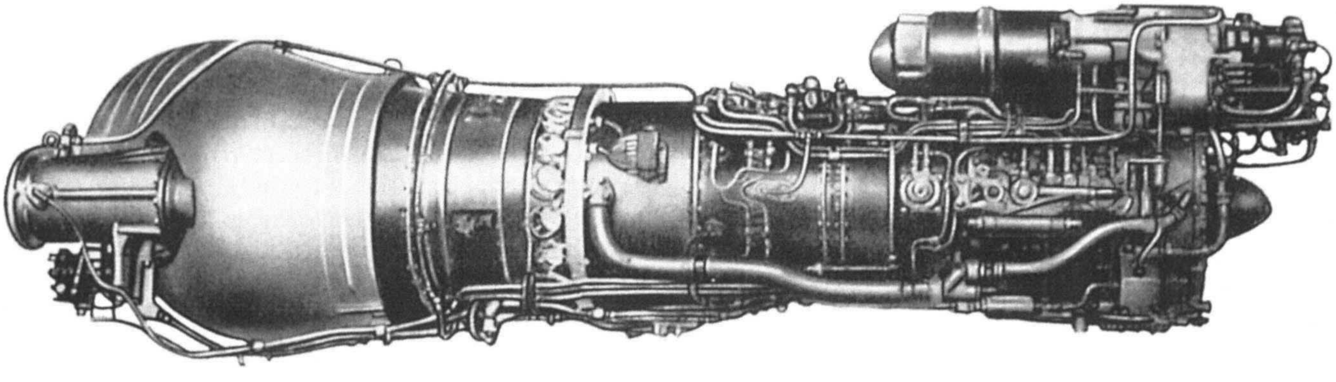
In 1986–7 quite serious trouble was being experienced with the HP compressor. One of the more important modifications was to redesign the LP compressor, rotating with the fan, to have three stages instead of one. This enabled stage loading of the 10-stage HP spool to be eased, while holding pr at 36. By the end of 1987 IAE could claim the V2500 to be on course for certification in June 1988. The first engines for the A320 were despatched (one from Connecticut and the other from Derby) on 24 February 1988. At Toulouse they were fitted into pods made at Rohr Industries and delivered at the end of March to the A320 production line complete with reversers and all other equipment. Production engines are assembled at the rate of 100 per year by Rolls-Royce and Pratt & Whitney. Today IAE produces a range of A5 engines for the A319/320/321 and D5 engines for the MD-90, with ratings from 22,000 lb to 33,000 lb, and with a growth version planned to start at 35,000 lb. IAE claim superiority in reliability, fuel economy (by a clear margin), noise and emissions over its rival. On the Airbuses it has been winning up to 70 per cent of the orders, but it has never dislodged CFM from its position as sole *motoriste* of the 737.

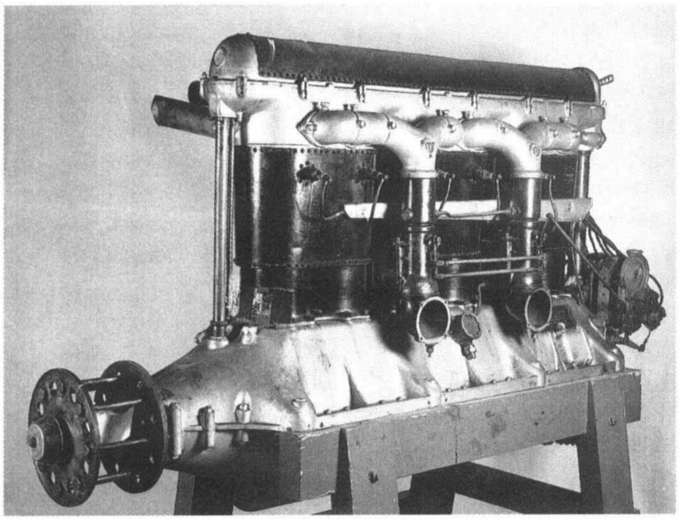


The production IAE V2500 has a three-stage LP compressor and new HP spool. It flew in a Boeing 720 testbed in May 1988 and in the A320 in July that year.



Poland's IL (Instytut Lotnictwa) has designed a series of basically simple military single-shaft turbojets. This example, an SO-1 rated at 2,205 lb thrust, is of a design made in large numbers to power the TS-11 Iskra trainer.





Isotov's TV2-117 helicopter engine is typically conservative, with a pr of only 6.6 despite having 10 stages with four variable stators. The drive shaft can be seen emerging from the handed jetpipe.

The Isotta-Fraschini V.6 of 1917 was one of the first engines to have totally enclosed valve gear. It was made in large numbers, and also licensed to Bianchi, San Giorgio and Romeo.

IHI (JAPAN) The enormous conglomerate Ishikawajima-Harima Heavy Industries built up a large gas-turbine business, mainly on licensed American fighter and helicopter engines. Today it shares in the General Electric CF34, GE90, GEnx and F110, the Rolls-Royce Trent and RB211, and the IAE V2500. In 1959 it began designing the small J3 turbojet, followed by the F3 turbofan to power the T-4 trainer.

Innodyn (USA) Innodyn Turbine Engines is marketing a range of extremely simple turboprops with a single main rotating part, a disc with the compressor on one side and the turbine on the other. Ratings vary from 165 to 255 shp.

Isotov (SOVIET UNION) General Constructor Sergei Pietrovich Isotov (1918–83) was responsible for two important helicopter turboshaft engines. For the Mi-8 his bureau developed the TV2-117A, and the associated VR-8A gearbox which combines the drive from left and right engines. Very conservative by Western standards, the TV2 has a 10-stage compressor (pressure ratio 6.6 at 21,200 rpm), annular combustor with eight burners, and two-stage gas generator and power turbines. A large jetpipe turns the gas through 60° to a side exit upstream of the rear output shaft. The engine is 2,835 mm long, weighs 330 kg without the generator or other accessories, and has a maximum rating of 1,700 shp, with sfc of 0.606 lb/h/shp. This engine was in production at 1,400 shp in 1962 and fully rated by 1964. From it stemmed the uprated TV3 series used in Kamov helicopters and later Mil machines. Fitted with a pneumatic starter, the TV3-117MT is rated at 1,900 shp (two-minute contingency 2,200) while the electrically started civil TV3-117V is rated at 2,225 shp.

For the small Mi-2 Isotov developed the GTD-350 which exactly followed the Allison 250 in layout with seven axial and one centrifugal compressor stage (pr 6.05 and airflow 2.19 kg/s at 45,000 rpm), twin lateral pipes leading to the single reverse-flow combustor, single-stage gas-generator turbine and two-stage power turbine, the latter running at a constant 24,000 rpm. Weighing 135 kg, the GTD-350 has a take-off rating of 400 shp with sfc of 0.805 lb/h/shp. Like the helicopter, this engine was passed to Poland for production. Isotov died in 1983, and today the bureau is the Klimov Corporation (*qv*).

Isotta-Fraschini (ITALY) Like many famous European aero-engine firms, this company began as a builder of high-quality cars, Fabbrica Automobili Isotta-Fraschini being established in 1898. Early aero engines, the first in July 1910, were massive water-cooled four-in-lines, about 50 of which powered Italian airships, land aeroplanes and seaplanes before August 1914. During the war the company claimed to have delivered 'nearly 5,000 engines' and 'nearly all the aero engines produced in Italy were made under Isotta-Fraschini licence' – a claim which appears to overlook Fiat's total of just over 15,000.

Early engines were prefixed V (volo = flight), most being six-in-lines with cylinders of cast-iron made in pairs with common heads; bore and stroke varied tremendously, but most models had take-off rpm of 1,800, giving powers from 120 to 280 hp. The V.5 of 1915 was a long straight-8 of 19 litres rated at 200 hp but weighing a massive 351 kg. Easily the most important of all the company's engines was the V.6 of 1917 with six cylinders, 140 × 180 mm, and giving 250 hp at 1,650 rpm. Many derived engines followed, most having a monobloc cast aluminium head for each bank of cylinders, while retaining separate iron cylinders, usually with sheet water jackets added. In 1920 the company collected various improved features and used them in the first Asso (ace), a name used for engines of every conceivable configuration and power including (for example) the Asso 80 (80 hp) four-in-line and Asso 1,000 (1,000 hp), both of 1928, the latter having 57.26 litres in three banks of six cylinders: three push-pull pairs of these monster engines powered the vast Ca 90.

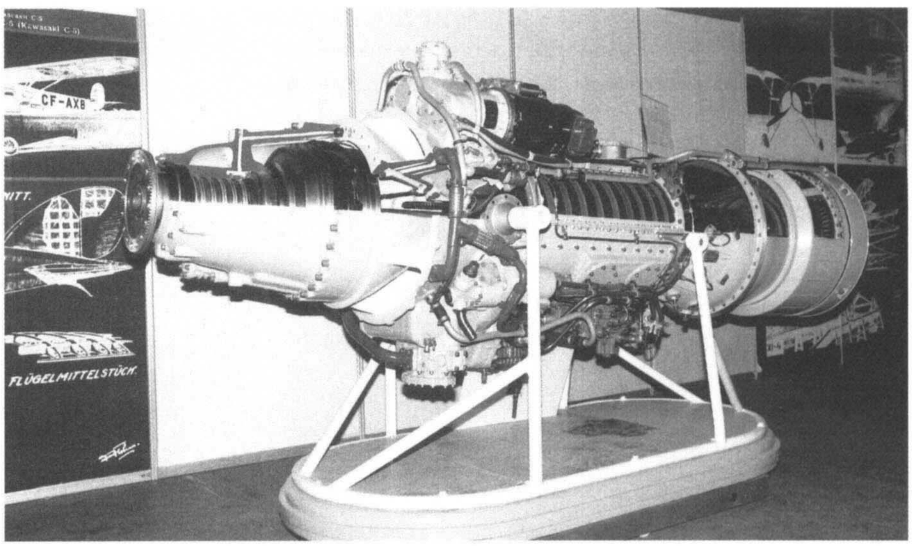
By the time of the Second World War Isotta-Fraschini was firmly in the trap of having a profusion of contrasting engines all made in very small numbers. The only real production was of the Delta RC 35, an inverted V-12 (with air-cooled cylinders introduced in 1927 with the 480hp Asso Caccia upright V-12 for fighters) of which over 3,300 were made at powers around 750 hp. Other Second World War engines included the 500-hp Gamma RC 15 inverted V-12, 900-hp Asso L 121RC40 liquid-cooled V-12, 450-hp Astro 7C40 and 890-hp Astro 14C40 7 and 14-cylinder radials, the 1,500-hp Asso L 180RC145 liquid-cooled inverted W-18, and the 1,200 hp Zeta RC 25/60 air-cooled X-24 (almost two Deltas) which ran in December 1941 and powered the Caproni-Vizzola F.6Z fighter.

Ivchyenko (SOVIET UNION) General Constructor Aleksandr G. Ivchyenko began his career with small piston engines, being permitted to use his own AI designations from 1944. Fair numbers were made of the AI-4 air-cooled four-stroke flat-four qualified in 1946 at 52 hp and produced mainly for helicopters at 55 hp. Small numbers were produced of the AI-10 five-cylinder radial, qualified at 80 hp in 1946. A year later the first production version of the AI-14 was qualified at 240 hp. This radial has nine cylinders 105 × 130 mm, capacity 10.16 litres, and many thousands have been produced at 260 hp, 285 hp (the 14VF for helicopters) and 300 hp (the 14RF).

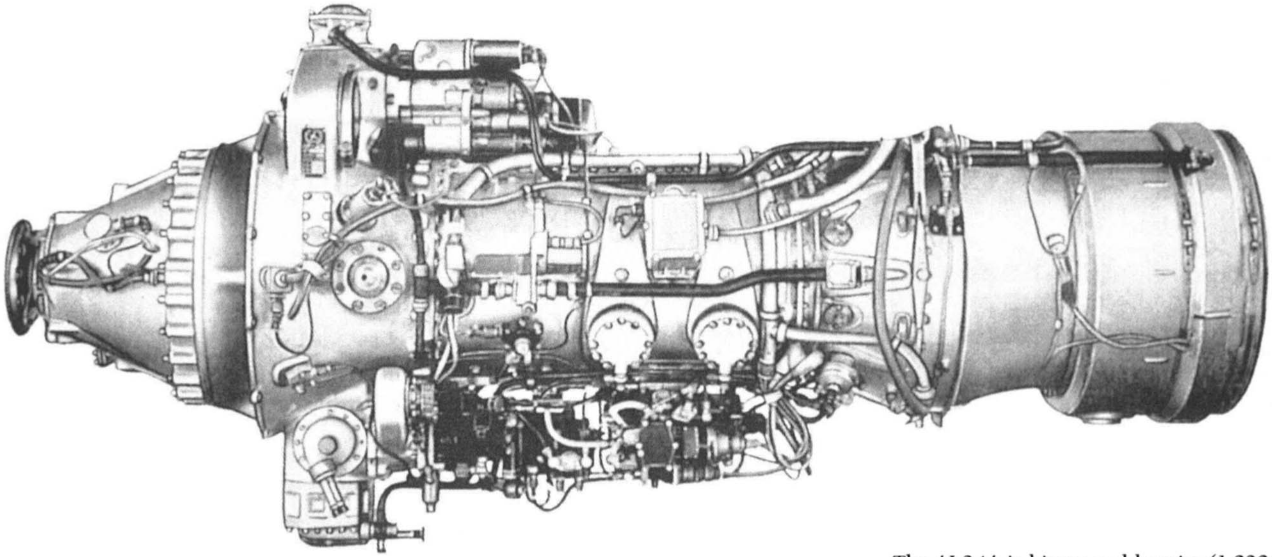
Since 1952 these have been licensed to Poland, where the chief model built at PZL-Kalisz is the 260-hp AI-14RA, and also developed by Vedeneyev. The more powerful AI-26 has seven cylinders 155.5 × 155 mm, 20.6 litres, and was qualified in 1946 at 500 hp, subsequently being mass-produced in fixed-wing and vertical installations at up to 575 hp. Licensed to Poland, it has been developed into the PZL-3 (*qv*).

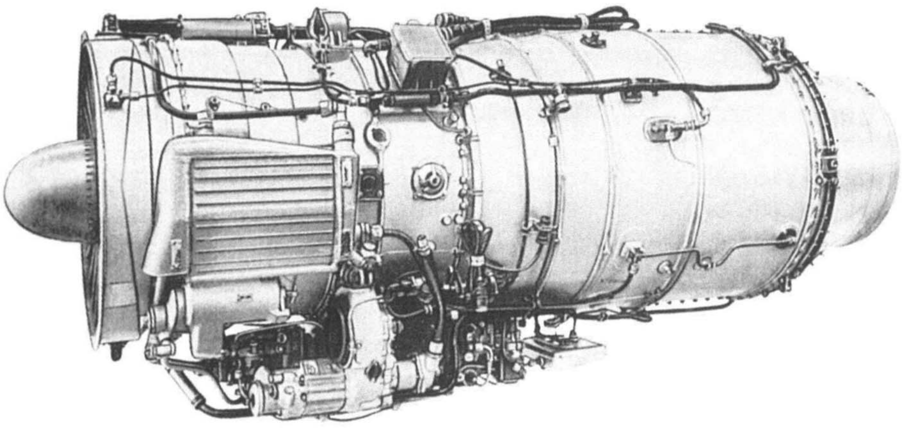
Clearly Ivchyenko had to learn about gas turbines, and he built up a strong design collective at Zaporozhye in Ukraine. His first major task was the AI-20 turboprop. This was not significantly better than the rival Kuznetsov NK-4, but when both designers were called to the Kremlin, Kuznetsov irritated the Soviet leaders by lecturing them, while Ivchyenko merely said, 'We have the engine and it works.' A constant-speed engine (12,300 rpm), it has a 10-stage compressor handling 20.7 kg (45.6 lb)/s and with pressure ratio at altitude cruise conditions of 9.2; the annular combustor has 10 typically Russian conical burner mixers, and the turbine has three stages and is overhung. Qualified in 1955 at 3,750 ehp, it was produced as the AI-20K at 3,945 ehp (also made at Shanghai as the Wo-Jiang 6), the 20M at 4,190 ehp, the marinised 20D at 4,190 ehp and the 20DM at 5,180 ehp.

The AI-24 is almost an AI-20 scaled down to an airflow of 14.4 kg (31.7 lb)/s at constant 15,100 rpm, pressure ratio at max-cruise altitude being 7.85; the combustor has eight burners of Simplex type, but otherwise the layout is similar to the bigger engine. One of the material differences is that the compressor casing is steel and made in left/right halves instead of magnesium in upper/lower halves. The AI-24 was qualified at 2,515 ehp in 1960, and was followed by the 24A rated at the same power maintained to hot/high conditions by water injection; this is made at Shanghai as the WJ-5A. The 24T is



This Ivchyenko AI-20M has been cut away for display purposes.





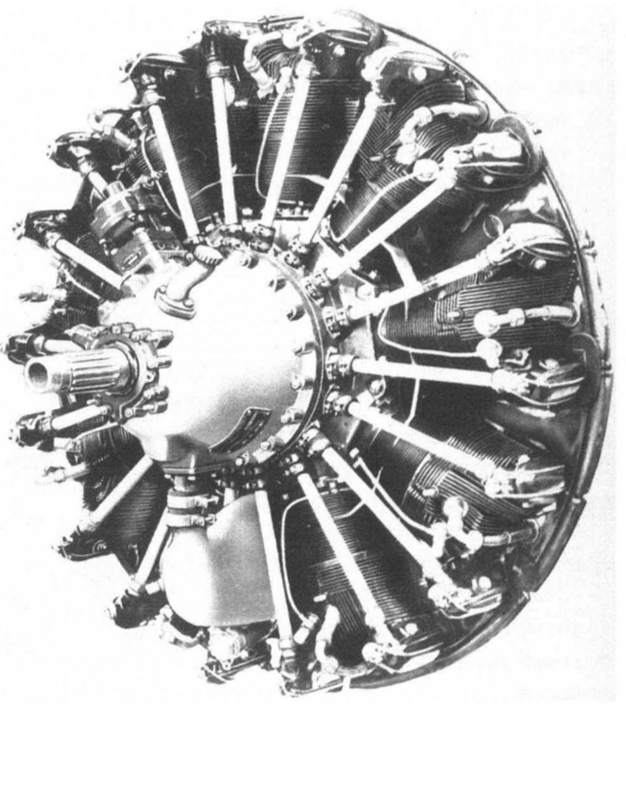
The AI-24A is bigger and heavier (1,323 lb) than equivalent Western engines, but has been made in the Soviet Union and China in large numbers.

Ivchyenko again went for robust simplicity rather than performance in the A1-25 turbofan, though he tried to reduce weight by using aluminium, magnesium and titanium alloys where possible. This version weighs 639 lb without accessories.

Made in Poland since 1952, Ivchyenko's AI-14RA is started by compressed air piped to the cylinder heads.

uprated to 2,820 ehp, but was replaced in production in 1980 by the slightly improved 24VT. These engines have been used in widespread propfan testing since the 1970s.

For the Yak-40 Ivchyenko produced the AI-25 turbofan, a robust and conservative engine which achieves a mere 8:1 pressure ratio from a three-stage fan (1.695) and eight-stage compressor (4.68); there are 12 burners in the annular chamber, a single HP and two-stage LP turbine, and pneumatic starter. Bypass ratio is 2. The AI-25 powered the Yak-40 on its first flight in 1966 but was not qualified until later, take-off rating at 16,640 rpm being 1,500 kg (3,307 lb) with sfc 0.56. The long-jetpipe AI-25TL powers the L 39 trainer, while a variant with air-cooled turbine is rated at 3,850 lb. On Ivchyenko's death in June 1968 the bureau became led by Lotarev (*qv*).



J

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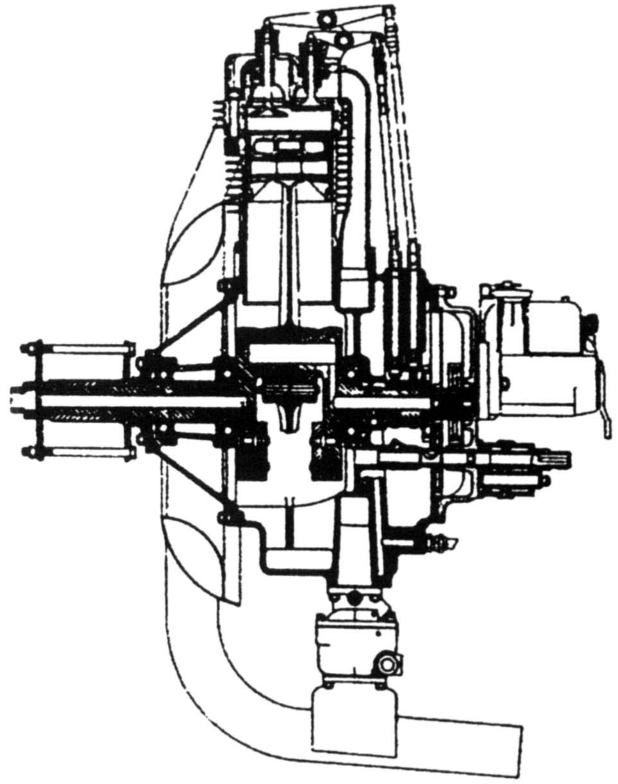
Jacobs (USA) The Jacobs Aircraft Engine Company was formed in 1930 in Camden, New Jersey, later moving to Pottstown, Pennsylvania. Starting with small 55-hp three-cylinder engines, it quickly progressed to a seven-cylinder of 150 hp and then in 1933 enlarged this from 589 to 757 cu in to create the L-4, which had an active life of 50 years. Better known today by its wartime designation of R-755, it has steel cylinders 5.25 × 5 in with aluminium-alloy heads incorporating aluminium-bronze valve seats. The earliest L-4 versions were rated at 200 hp at 2,000 rpm, but postwar geared models developed up to 350 hp at 2,500 rpm. One of these R-755E variants was for helicopters. Much smaller numbers were made of the larger seven-cylinder L-5 of 285 hp of 1935 and the L-6 (R-915) of 5.5 in bore and stroke used at 330 hp in various wartime aeroplanes and autogyros. In the 1970s Page Industries of Oklahoma bought all rights and for a few years manufactured small numbers of R-755s and spares, including the turbocharged R755S.

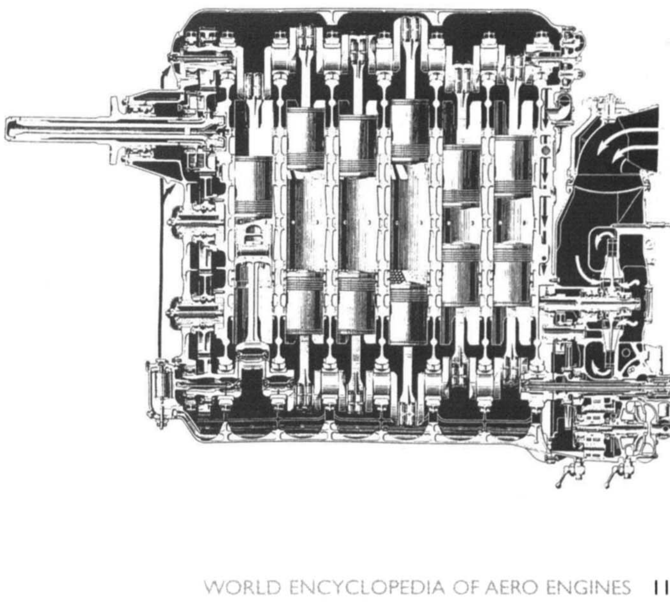


Introduced in 1931, at the height of the Depression, the Jacobs L-3 was a three-cylinder engine with a displacement of 190.8 cu in and power of 55 hp. This drawing would be little changed for the seven-cylinder engines.

Jalbert (FRANCE) Sponsored by the French Air Ministry, Ateliers et Chantiers de la Loire built prototypes of three types of diesel to Jalbert designs. First to run, in 1928, was a four-cylinder water-cooled in-line, of 160 hp, followed by a 235 hp inverted six-in-line and a challenging water-cooled H-16 intended to give 600 hp at 2,400 rpm.

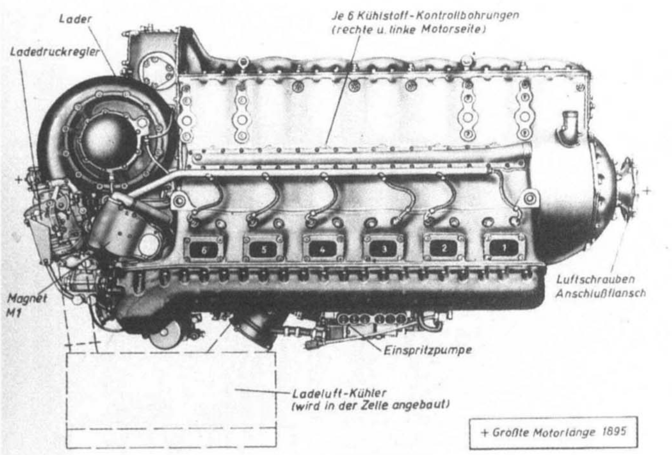
Jendrassik (HUNGARY) Another of the forgotten pioneers, György Jendrassik built the world's first turboprop, and it was in most respects a sound engine of commendably modern design. A senior engineer at Ganz wagon works, Budapest, he began design of a 100-hp unit in 1932 and ran it in 1937. By this time he had completed design of the Cs-1 turboprop, to be rated at 1,000 hp at 13,500 rpm. Features included a cast inlet housing the 0.119 reduction gear, a 15-stage compressor and 11-stage turbine hung between two bearings and joined by a large-diameter tubular shaft, a folded reverse-flow annular combustor, air-cooled turbine discs and extended-root blades. The Cs-1 ran in August 1940 and was so promising that design of the X/H (also called RMI 1) twin-turboprop fighter/bomber went ahead (under Varga at the RMI). The whole project was killed by the war situation in 1941, and supply of DB 605 engines of higher power.

A Junkers drawing showing the arrangement of the opposed pistons and crankshafts in the Jumo 205 two-stroke diesel. White arrows show airflow into the blower used for scavenging.

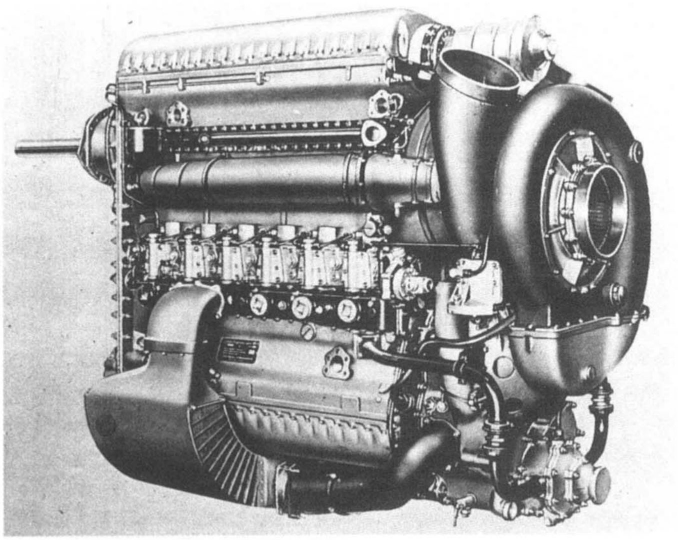


JPX (FRANCE) Located at Vibraye, near Le Mans, this firm is famed for its engines for light aircraft, ranging through two- and four-strokes (derived from VW engines) to baby turbojets. Among the more important are the 4T/60 of 65 hp and the 4TX 75 to be rated at 75 hp.

Junkers (GERMANY) Professor Hugo Junkers set up a factory making small marine diesels in 1913 (two years before he



The Jumo 211J was produced in large numbers for the Ju 88. The supercharger was on the right, unlike the DB engines. Photo from Luftwaffe handbook.

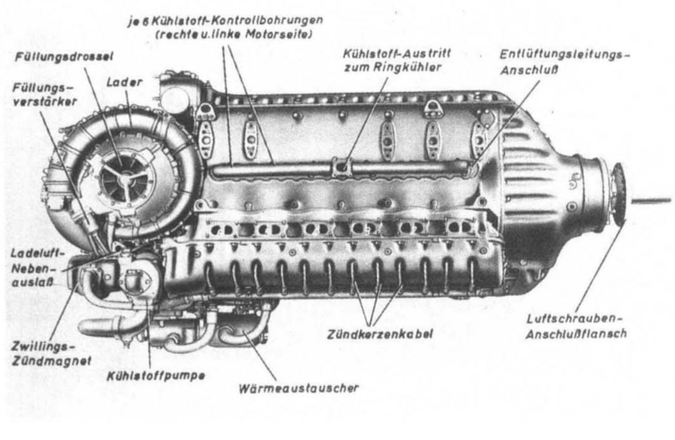


The Jumo 207B-3 was the ultimate production model of two-stroke diesel. Its climbing power of 750 hp was maintained from sea level to almost 40,000 ft.

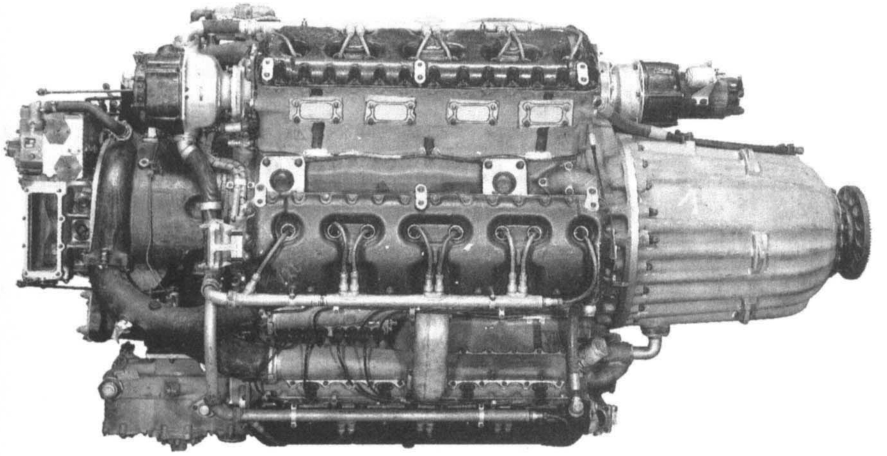
made aircraft), and in the same year built a rather primitive aero oil engine (using spark ignition), the MO-3 four-in-line, followed by the MO-8 six-in-line of 1914. In 1916 he ran the giant FO-2 rated at 500 hp at the high speed of 2,400 rpm, and even designed the corresponding V-12 to be rated at 1,000 hp, though this was not built.

After the First World War Junkers decided to develop ordinary petrol engines for his own aircraft, and for possible sale to others, and quickly produced a series of conservatively rated water-cooled in-line engines, notable chiefly for having ball-type main bearings and two exceptionally large valves per cylinder. The Ll of 1921 was a six-in-line rated at 80 hp, and the bigger six-cylinder L2 began life at 195 hp and grew to 220 hp, or in the L2a to 230. The most important of the early engines was the big L5 of 1922, with cylinders 160 × 190 mm, giving capacity of 22.92 litres. Weighing about 325 kg, these massive engines began at only 280 hp at 1,450 rpm, but most production L5s were rated at 310 hp and the L5g at 340. Using the same size of cylinder, Junkers then redesigned the L5 to run at 2,000 rpm and give 400 hp, the result being the L8 of 1923, in which year a separate engine company, Junkers Motorenbau (Jumo) was formed. A very few L55s were built, these being V-12s based on the L5 rated at 600 hp. More important was the L88 of 1925, the V-12 derived from the L8. The production L88 was normally rated at 800 hp, and the high-altitude L88a (flown in the Ju 49 to over 12.5 km) had advanced superchargers maintaining power to 700 hp at 5.8 km (over 19,000 ft).

By 1924 the oil-engine team had switched to full compression-ignition diesels, using a totally different configuration in which two opposed pistons work in each very long cylinder, crankshafts above and below the engine driving the propeller via trains of gears up the front of the engine. Junkers adopted the two-stroke cycle, one piston uncovering the exhaust ports round the cylinder and the other piston the inlet ports, these being shaped to swirl the air to help expel the exhaust and assist mixing the oil spray injected into the extremely hot compressed air near top dead centre. Such engines tend to be tall and thin, and structural considerations demand massive construction. The first of this important series was the FO3 of late 1925, which had five (in effect 10) giant cylinders and was rated at 830 hp at 1,200 rpm. By 1927 the FO4 had run, using six (12) smaller cylinders and rated at 720 hp at 1,700 rpm. By early 1929 this was mature enough to be flown in the aircraft company's F 24 testbed. This massive engine was put into production as the Jumo 4, later renumbered 204, rated 770 hp at 1,800 rpm and used by Lufthansa in the Ju 52 and re-engined G 38.

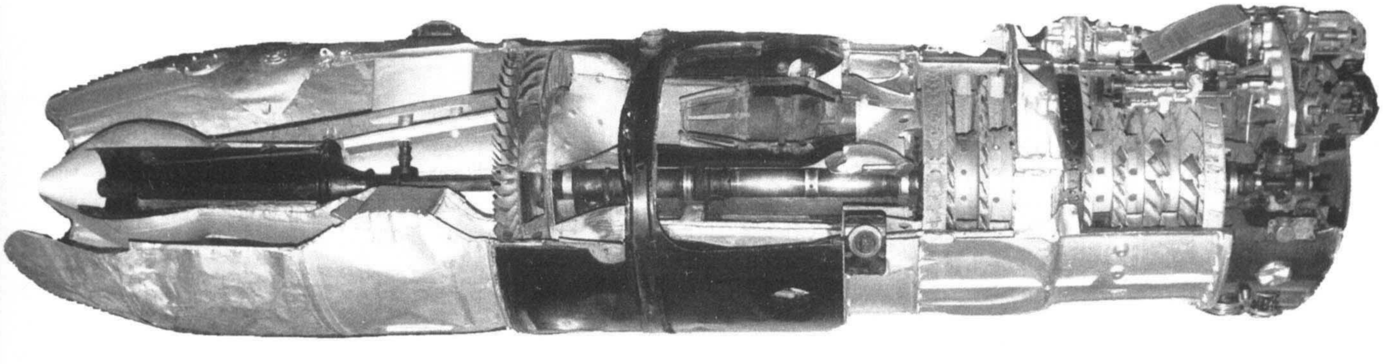


In many respects an outstanding engine, the Jumo 213A-1 powered the Fw 190D-9 at a rating of 2,240 hp with MW50 injection. Similar engines were produced in France by Arsenal after the war.



This MoD(PE) photo shows a Jumo 222A tested at Farnborough in April 1945. At far left is one of the rectangular air inlets, ahead of which is one of three supercharger delivery pipes, which branches to feed Nos 6 and 1 blocks. Above the supercharger is one of the two 24-cylinder magnetos, driven off No. 2 block camshaft. Weight was 2,394 lb.

This Jumo 004B turbojet is one of a large number made after the war in the Soviet Union as the RD-10, shown cut open for display.



In 1932 the cylinder size was reduced yet again, to 105 × 160 mm (160 being the stroke of each piston), giving capa-city of 16.62 litres. The resulting Jumo 205 was cleared to run at 2,200 rpm, giving 600 hp, and the wartime 205D with pressure-glycol cooling was rated at 700 hp at 2,600 rpm. The exhaust at barely 500°C made it easy to install a turbocharger, and the wartime Jumo 207 added both a turbo and a gear-driven supercharger, giving 1,000 hp at 3,000 rpm for take-off and 750 hp at 2,800 rpm at up to 12.5 km. The final wartime engines were staggering in concept, the Jumo 223 being a family of related 'box' engines comprising four opposed-piston diesels in one unit with a crankshaft at each corner; weighing 2,370 kg, it gave 2,500 hp at up to 6,000 m. In 1942 it was dropped in favour of the Jumo 224, which was even bigger and designed for 4,500 hp.

In 1933 the Jumo firm wisely embarked on completely new high-power petrol engines, starting with the Jumo 210 and 211, both of which ran in 1936. These were inverted V-12s cooled by Glysantin (glycol), but with different sizes of cylinder, the 210 being 124 × 136 mm (19.7 litres) and the 211 cylinder being 150 × 165 mm, giving 35 litres. Both were fitted with carburettors, and had similar construction with the entire crankcase and cylinder blocks being a single high-quality light-alloy casting. The steel cylinder liners were tightened into the one-piece head by four wet bolts, 14 studs then being used to tighten each six-cylinder assembly on the main block. The 210 began at 600 hp and reached 730 hp at 2,600 rpm in the 210Ga fitted to the Bf 109C. The bigger 211 was first tested in a Ju 87A, and 68,000 were built in the Second World War at ratings from 1,000 to 1,530 hp (one giving 1,380 hp at 10 km), almost all production versions having direct fuel injection. The 211 had one exhaust and two inlet valves per cylinder, and the supercharger was on the right side at the rear. A typical weight (211A) was 640 kg.

At the start of the Second World War Junkers was engaged in refining the 211 into the 213, a particularly advanced engine with all mechanical features redesigned for continuous running at 3,000 rpm and take-off at 3,250. Typical of the refinements was the addition of a steel flywheel at each end of the underhead camshafts. The basic 213A was rated at 1,776 hp, for a weight of 920 kg, while the 213J, with four valves per cylinder, was rated at 2,600 hp at 3,700 rpm, a remarkable speed for so big an engine. Deliveries of 213s reached 9,000. In 1939 work was also well advanced on the totally new Jumo 222, planned for large-scale production but destined to fly in prototypes only. It was a liquid-cooled radial, with six banks each of four 135 × 135 mm cylinders (46.5 litres). It had many unusual features, and the 222A series weighed about 1,080 kg and gave 2,500 hp at 3,200 rpm. The A and B Srs 2 had bore increased to 140 mm, and the C and D had cylinders 145 × 140 mm and gave 3,000 hp at 3,200 rpm.

Gas turbines

Back in July 1936 the engine and aircraft companies had been amalgamated, though the two divisions carried on as before. The main board under Koppenberg supported the brilliant and highly political head of airframes, Herbert Wagner, who thought the engine team under Otto Mader too conservative and slow. Before the amalgamation, in April 1936, Wagner started a secret cell at Magdeburg developing a gas turbine, and by 1938 this effort (unknown to Mader) included a profusion of turbojets, turboprops and even stationary plant. The team leader, Max Adolf Müller, managed to get the Jumo 109-006 axial turbojet on test by autumn 1938. This slim (617 mm) axial engine, with pressure ratio 2.9 from five stages, had much potential though it was only just able to run under its own power (the Magdeburg group began to switch their effort to diesel-driven ducted fans). Meanwhile, the engine division at Dessau under Mader continued studies, started as early as 1933, of turboprops and free-piston gas turbines, and in August 1938 put Anselm Franz in charge of a survey of all gas turbine prospects, accepting an RLM (Air Ministry) study contract a month later. After detailed weight estimates of a free-piston jet engine Franz accepted that only a simple turbojet would be sufficiently light. In April 1939, after acrimonious scenes, the RLM welcomed the engine division's takeover of the Magdeburg work. Wagner had already arranged another job, and Müller and half his staff went to Heinkel. By the summer Junkers had an RLM contract for a bigger and conservatively rated turbojet, the 109-004 (the 006 went to Heinkel). Mader insisted on the main effort staying on piston engines, but by 1942 Franz had managed to gather a staff of some 500.

The 004 was designed for a thrust of 600 kg at 900 km/h, and despite much greater familiarity with centrifugal compressors Franz chose an eight-stage axial of 3.1 pr, six combustors, single-stage turbine, and jetpipe arranged for afterburning and with a nozzle bullet to maintain constant gas temperature. Encke designed the compressor blading (as he did for the BMW 003) and the AEG company assisted with the turbine, which at first had solid blades. The 004A ran in November 1940, but many snags took until early 1942 to overcome. No. 5 engine reached 1,000 kg thrust, its weight being 848 kg; on 15 March 1942 another 004A flew slung under a Bf 110, and on 18 July 1942 two A-0 engines powered the Me 262 V3 on an extremely successful flight. About 30 A-series engines were built, followed in 1942–3 by a few B-series in which strategic materials were cut by half, partly by using sheet instead of castings, reducing weight to 748 kg and greatly reducing man-hours and price. The B-1 introduced a compressor with improved blades in the first two stages, raising thrust to 900 kg. This ran in May 1943 and powered the Me 262 V6 in early November. Production on a massive scale was then arranged, the first B-1s becoming available in March 1944. It had a light-alloy compressor of spigoted disc construction with wrapped-sheet stators, aluminised mild-steel combustors burning diesel oil, 61 solid Ni-Cr steel turbine blades soldered and pegged into the martensitic steel disc, a jetpipe bullet positioned by a servo-motor and rack/pinion, and a 10-hp Riedel two-cylinder two-stroke starter in the nose bullet (which after the war was popular for go-karts). After much research hollow turbine blades were perfected, and these entered production in December 1944 in the B-4. The engine was still conservatively rated, and in early 1945 production was about to switch to the D-4 rated at 1,050 kg. Roughly 5,000 Jumo 004B engines were built (today's MBB claims over 6,000), TBO being 30 h.

Junkers had a contract for a bigger and more advanced turbojet, the 109-012, and the corresponding 022 turboprop. Planned for the Ju 287, the 012 had an 11-stage compressor and two-stage turbine, was to weigh 2,000 kg and give 2,900 kg thrust. The first 012 was never completed.

K

K

Kawasaki (JAPAN) This famous company was the fourth largest in Japan in terms of engine production in the Second World War. From 1931 it made over 2,000 Ha-9 water-cooled V-12s rated at 710 to 950 hp. Its effort was concentrated on liquid-cooled engines, Kawasaki having produced many thousands of water-cooled BMW VI and derived engines in 1927–40. In 1939 a licence was obtained for the DB 601, and this was redesigned at the Akashi plant to meet local requirements, going into production as the Ha-40 in November 1941.

By 1942 work was well ahead with the 1,500-hp Ha-140, but this was persistently down on power and unreliable. The Ha-201 was an installation of two Ha-40s in the Ki-64 fighter, one ahead of the cockpit driving the rear (fixed-pitch) unit of a contraprop and the other behind the cockpit with a long shaft to the constant-speed front propeller. This extraordinary machine flew in December 1943.

Since 1953 Kawasaki has overhauled and licence-built many gas turbines, and in 1981 the company ran the first KJ12 small turbojet, rated at 150 kg thrust for a weight of 40 kg and intended for RPVs and small sporting aircraft. Today KHI (Kawasaki Heavy Industries) produces the Honeywell (Lycoming) T53 and T55 and Pratt & Whitney F100 under licence. It is also a partner on the V2500, RB.211, Trent and PW4000.

Many hundreds of wartime Kinners are still being lovingly maintained; this is a 160-hp R-55.

Kinner (USA) Kinner Airplane & Motor Corporation was established in Glendale (Los Angeles) in 1919, and began producing a five-cylinder radial. From 1931 it also made light aircraft, but it went bankrupt in 1937. In its place came Kinner Motors of 1939, and this enjoyed major wartime production, its engines clattering roughly but reliably in thousands of trainers. The K-5 series had cylinders 4.25 × 5.25 in, 372 cu in, and at 100 hp were a close equivalent to Shvetsov's M-11. The B-5s had bore 4.625, 441 cu in and 125 hp, and the R-5 and derivatives (such as the R-55) went to 5 in, 540 cu in, and 160–75 hp. All looked spiky because the cylinders (with widely splayed valve gear driven by five camshafts) were bolted to raised platforms on a tiny crankcase drum. In 1944 Kinner launched a very modern flat-six of 225 hp (geared, 250 hp) which in contrast ran like a sewing machine, but the firm went swiftly downhill from 1945.

Klimov (SOVIET UNION) Vladimir Yakovlyevich Klimov was one of the first specialists on water-cooled aero engines in the Soviet Union, and played a major role in developing the M-17 from the BMW VI, working with Mikulin. In late 1933 the GUAP (aero industry directorate) picked the Hispano-Suiza 12Y as a major engine for fighters, and Klimov was instructed to open a KB (construction bureau) to develop it beyond the original licensed engine. The latter was designated M-100, but in December 1940 under the revised designation system for all aviation items Klimov was permitted to use his own initials, which are used here exclusively.

The baseline engine had 2 mm shorter stroke than the French engine, giving capacity of 35.09 litres, and despite many confusing reports to the contrary this never altered in subsequent engines. Production engines of 1935 had single-speed superchargers and a rating of 750 hp, the 100A of 1936 reaching 860 hp at 2,400 rpm. The VK-103 with two-speed supercharger was qualified in January 1937 at 860 hp, the 103A reaching 960 hp in 1939 and later 1,100 hp on 100-PN fuel. The most numerous model was the VK-105 cleared to 2,700 rpm, made in vast numbers with *moteur canon* and various refinements, the 105 being rated at 1,050 hp and sub-types being the 105P of 1,100 hp (sometimes with TK turbo-supercharger maintaining power to 4 km), the PF of 1,260 hp, PF-2 of 1,280 hp and RA of 1,100 hp. VK-105s accounted for 101,000 of the total of over 129,000 of all these V-12 engines in 1935–47. The 1,200–1,350 hp VK-106 remained troublesome prototypes. The VK-107 introduced an air scavenge valve to supplement the previous one exhaust and two inlet valves per cylinder, and being restressed to 2,800 rpm was rated at 1,400 hp on 94/95 fuel in 1942, and 1,650 hp on 100-grade fuel in 1943. Unlike earlier Hispano-derived engines the exhaust outlets were evenly spaced. No production was

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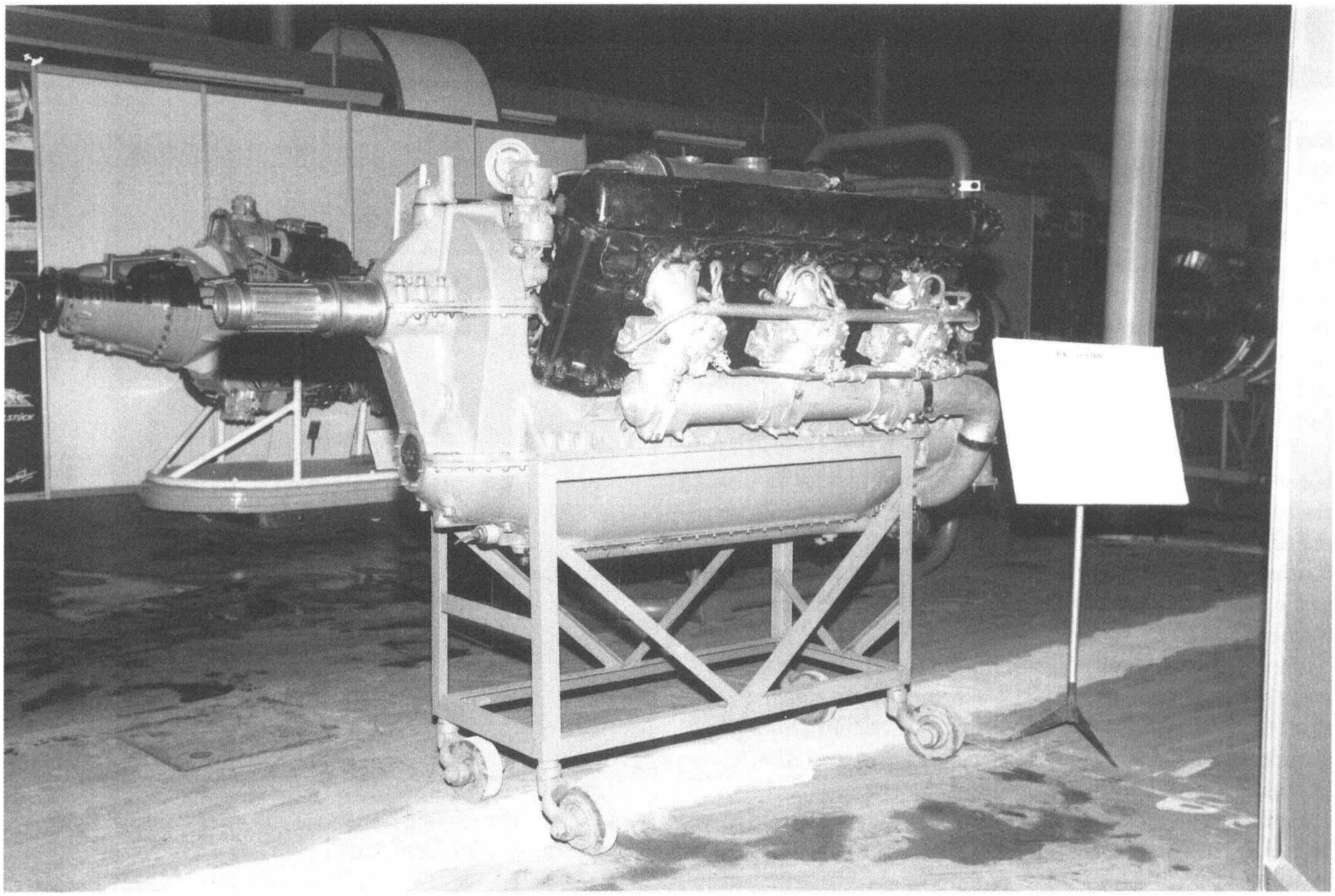
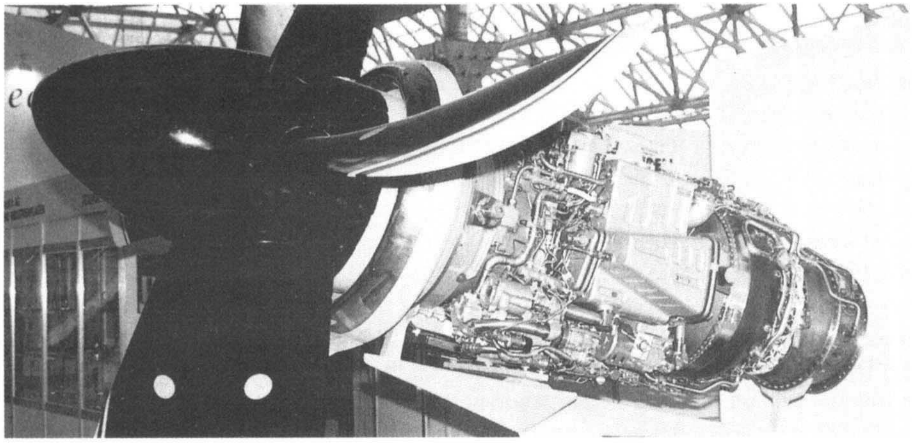




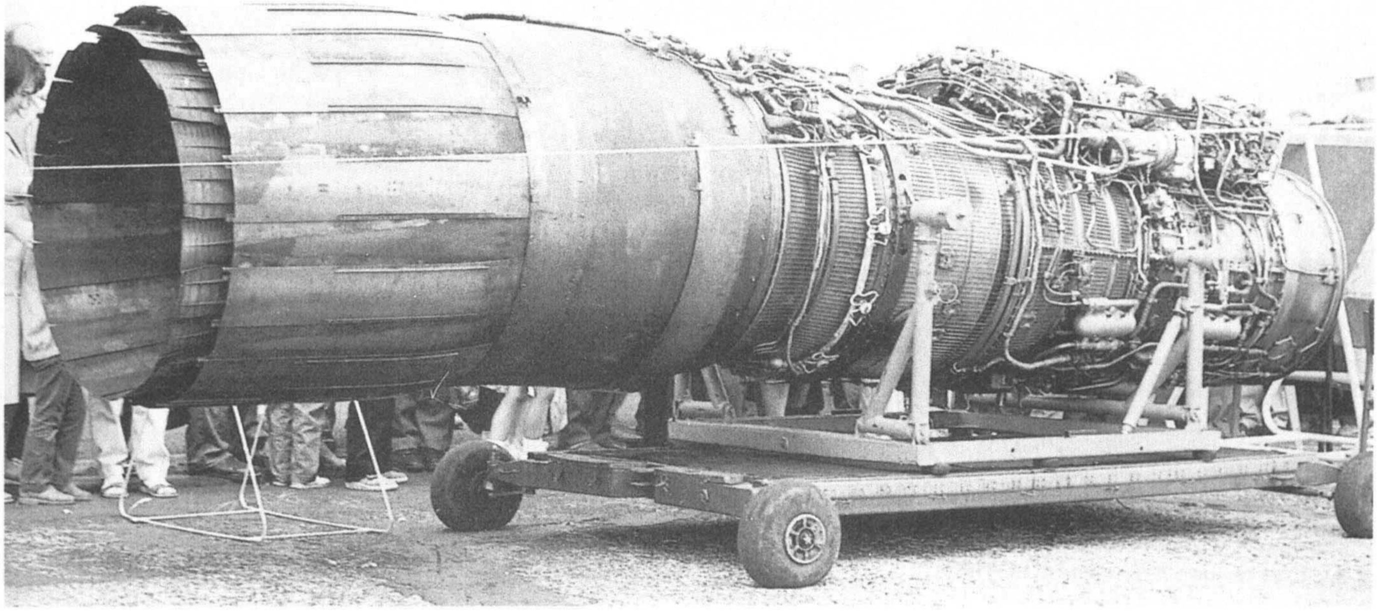
In 1935-46 over 129,000 of Klimov's Hispano-derived engines were produced for Soviet combat aircraft. Most numerous of all was the 1,260 hp VK-105PF. Note the three carburettors on each side.

In the Ilyushin Il-14 the TV7-117S drives a six-blade SV-34 carbon-fibre propeller.

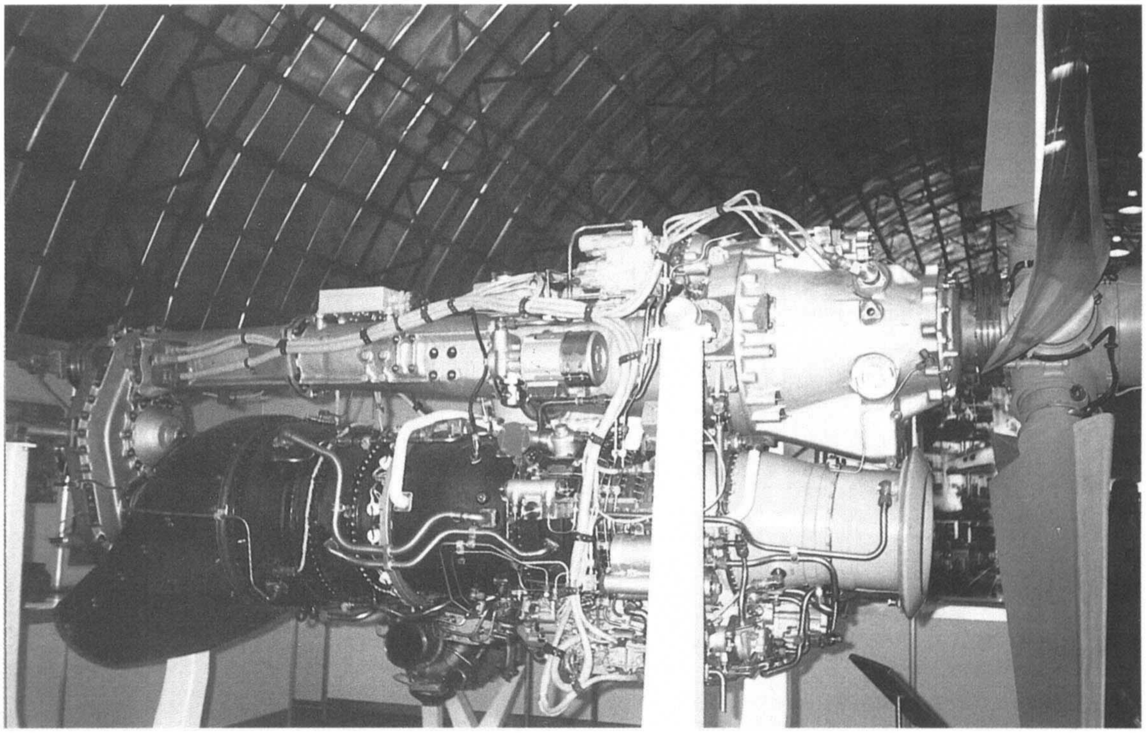
undertaken of the 1,800-hp VK-108 or 2,073-hp VK-109 of 1945.

By 1945 Klimov was a Major-General Constructor, and member of the Academy of Sciences, heading KBs at GAZ (factory) No. 45 in Moscow and GAZ-117 in Leningrad, where S.P. Isotov was his deputy. In early 1946 his GAZ-117 team began trying to copy the RR Nene, but in September 1946 arrival of the actual engine in Moscow resulted in instant scrapping of this primitive effort. Klimov went straight to GAZ-45, with a top team of GAZ-117 engineers, copied the British engine in every detail and, designating it RD-45 after the factory, put it into mass production. Klimov directed round-the-clock work on improving the RD-45 and in December 1948 the VK-1 was cleared for production, albeit with a TBO of only 25 h. Airflow was increased from 41 to 45 kg/s, ratings being 2,700 kg, the same as for the VK-1A with different accessory gearbox and longer life, and 3,380 kg for the VK-1F with afterburner.

In late 1949 production began at GAZ-45 and at GAZ-16 at Ufa and GAZ-19 in Kuibyshev, over 39,000 being produced.



All RD-33 engines at present in service have an advanced 24-flap afterburner nozzle. Later derivatives have vectored nozzles.



Klimov's TV3-117VMA-SB2 drives the six-blade Stupino propeller via an external shaft along the top of the engine. Thus, the reduction gearbox is above the intake

Klimov's first gas turbine, the VK-2 single-shaft turboprop, was developed at GAZ-117 from 1947, with eight-stage axial compressor, seven can-type combustors, two-stage turbine and planetary reduction gear. In 1950 the VK-2 achieved its design sfc of 270 g/hp/h; this was lower than Kuznetsov's rival NK-4, and Klimov ordered all effort to be switched to reliability. This proved a mistake, and in 1952 official tests showed the NK-4 to have a lower sfc and it was picked over the VK-2. The VK-3 was again a totally new design, a single-shaft bypass turbojet directed by S.V. Lyunevich at GAZ-117 in 1952. New features included a supersonic first stage to the axial compressor and an annular combustion chamber. It led to the VK-7. The VK-5, begun at GAZ-117 in 1949 under A.S. Mevius, was the ultimate turbojet derived from the Nene; 10 prototypes were bench and flight tested, with pressure ratio 5.05 and dry thrust of 3,100 kg, but it could not compete with new axial engines.

Klimov was succeeded by his deputy, Isotov (*qv*), who in 1983 was followed by Vladimir Stepanov and now Aleksandr A. Sarkisov. Today the bureau has been renamed for its founder, and Factory 117's number is perpetuated in the designation of many Klimov engines. The TV2-117 and TV3-117 have been made in vast numbers, and are now joined by the TV7-117. The TV7 began as a turboprop in the 2,500-hp class for the Il-114, but it is now developing in various forms up to 3,500 hp for aeroplanes and helicopters, with a turbofan version planned. The other big programme is Sarkisov's RD-33, designed from 1968 to power the MiG-29. This augmented turbofan has four LP and nine HP stages, and has a maximum rating of 18,300 lb, uprated in the RD-33K to 19,335 lb. This very successful engine has led to many derived versions, including the RD-33N (Russian designation for the Aerosud SMR-95) and the RD-93 which is in major production (and is expected to be made in China) to power the Sino-Pakistani JF-17 Thunder. In 1993 Klimov signed a collaborative agreement with Pratt & Whitney Canada.

Kolesov (SOVIET UNION) Piotr A. Kolesov took over the design bureau of V.A. Dobrynin, and produced most of the vertically mounted lift jets for Soviet V/STOLs. Today the bureau is Rybinsk (*qv*).

K

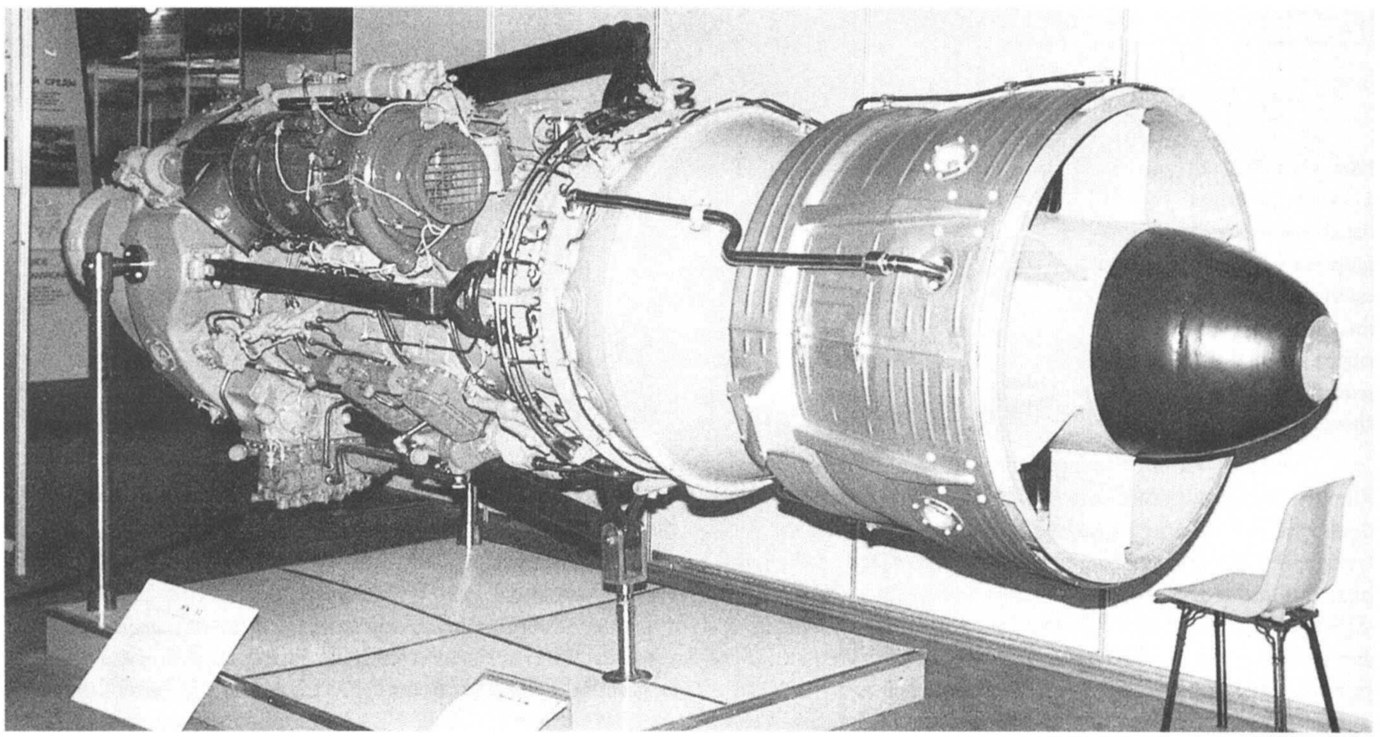
Kossov (SOVIET UNION) M.A. Kossov was an assistant to Shvetsov in the early 1930s, and in about 1935 was permitted to carry out his own developments of the M-11. Known products include the MG-11 of 1937 rated at 165 hp, the MG-11F with ratings up to 180 hp, the seven-cylinder MG-21 of 1938 rated at 200 hp, the nine-cylinder MG-31 of 1938 rated at 300 hp, and the MG-31F of 330 hp. Designation MG-40 was apparently a refined M-11 of 1934, rated at 140 hp.

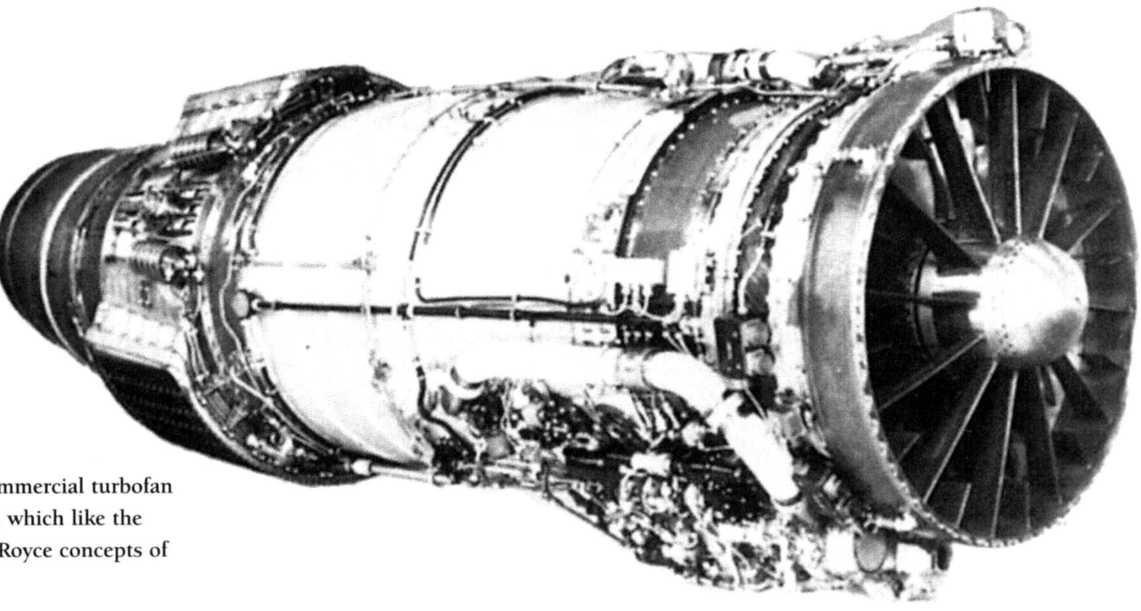
Kuznetsov (SOVIET UNION) Nikolai Dmitriyevich Kuznetsov was Klimov's deputy throughout the Second World War, and managed GAZ-16 at Ufa. In 1948 he was promoted to General Constructor, setting up his KB at GAZ-19, Kuibyshev. He clearly had a large engineering team because work began almost simultaneously on four extremely challenging turboprop projects, the NK-2, -4, -6 and -12; the staff included over 240 German prisoners taken from wartime gas-turbine development teams.

None of the early projects went into production, though 200 examples were built of the NK-4 turboprop before it was beaten by Ivchyenko's AI-20. The NK-2, derived from the Junkers 109-022, led to various TV-2 versions, notably the 7,650 shp TV-2M for the Tu-91 and the amazing 2TV-2F twinned version of 12,000 shp which powered the 95/I, the first 'Bear' prototype. This was fortunately replaced by the hastily developed NK-12.

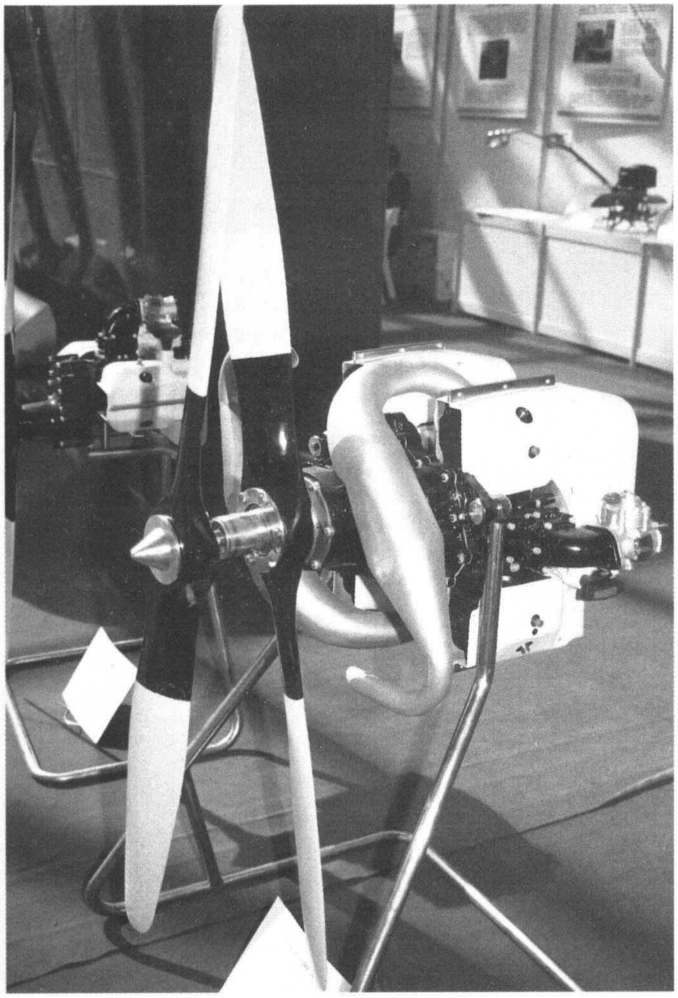
The giant NK-12 was an incredible technical achievement which could have been a disaster but was in production until 1985. Created by a mainly German team, led by Dipl-Ing

A specially prepared NK-12 for display with the propeller drive at the far end. For nearly 50 years this has been the world's most powerful turboprop. Today the Kuznetsov bureau is called NK.





The Kuznetsov NK-8-2 commercial turbofan is seen here with reverser, which like the engine, is based on Rolls-Royce concepts of the 1950s.

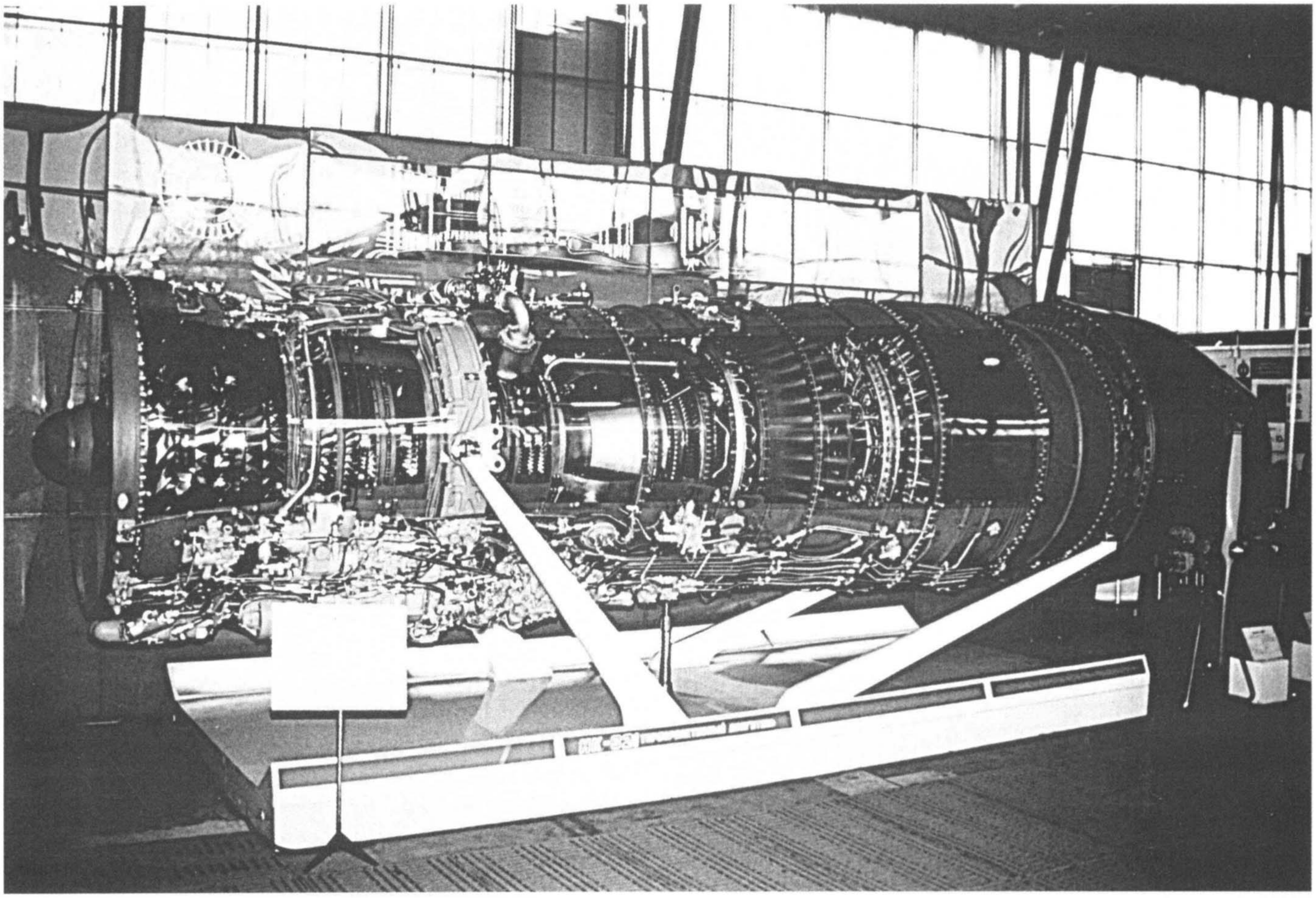


The latest version of the P-065 light-plane engine on display in 1994.

Ferdinand Brandner (an Austrian), it was a single-shaft turboprop which is still more powerful than any successor. The 14-stage axial compressor was designed to handle 62 (later 65) kg/s at a constant speed of 8,250 (later 8,300) rpm, the pressure ratio being varied by several blow-off valves between nine and 13. The cannular combustor contains 12 conical flame tubes, delivering into a five-stage turbine. The gearbox provides two co-axial shafts for the AV-60N contraprop with eight solid blades of 5.6 m diameter, each half-propeller being able to be pushed round on the ground without moving the other. Cruising propeller rpm is 750, in extremely coarse pitch, with electric (today electronic) control of fuel flow to maintain sea-level power to 8 km and 66 per cent power to 11 km. The NK-12 was qualified in late 1955 at 11,995 shp, but within two years the 12M family had been developed to 14,995 shp, and there are several other versions. A typical NK-12M weighs 5,180 lb. The even more powerful NK-16 and NK-20 remained prototypes.

In 1959 the awesome NK-6 duct-burning turbofan for supersonic bombers was tested at a thrust of 44,092 lb. This did not go into production, and the much smaller NK-8 transport turbofan was not ready for the prototype Il-62, but was finally qualified (behind schedule) in 1966 complete with reverser. Features include an inlet with 15 fixed stators (30 ahead of the fan bypass flow), a two-stage fan with swept anti-flutter blades (pr 2.15 at 5,350 rpm) rotating with two IP compressor stages, a six-stage HP spool largely of titanium with overall pr 10.8 at HP rpm of 6,950, annular combustor with 139 burners, single-stage HP and two-stage LP turbines all with shrouded blades, and in some applications a Rolls-type reverser. Take-off ratings are from 20,945 lb to 23,150 lb, and a great deal of testing, including flying in a Tu-155 (modified Tu-154), has been done with engines fuelled by liquefied natural

K



The NK-321, seen here as a cutaway exhibit, powers the most powerful military aircraft in history, the Tu-160 supersonic bomber.

gas and even, in the NK-88, with liquid hydrogen. The NK-8 was the basis for a family of NK-144 engines for the Tu-144 supersonic transport, with ratings (with afterburning) from 38,580 lb to 48,500 lb. This in turn led to the engines of the Tu-22M bomber, the NK-22 rated at 48,500 lb and the NK-25 of 55,115 lb. The NK-32 high-pressure core was then used for the three-shaft NK-321. This impressive three-shaft turbofan, with an airflow of 805 lb/sec and take-off rating of 55,077 lb, powers the Tu-160 strategic weapon-carrier. This aircraft has capabilities no Western aircraft can even approach, but today's cash-strapped Russia is finding it difficult to assemble one Tu-160 a year from existing parts. Among many other NK engines were the NK-56 turbofan intended for the Il-96-300, the NK-62 turboprop of over 19,000 shp, the NK-93 contra-rotating propfan, and the 40,000-lb-thrust NK-118 pusher propfan.

In a totally different field, KKBM is also producing tiny two-stroke piston engines. The P-020 flat twin is rated at 20 hp, and the four-cylinder P-065 has concentric drive shafts to contra-rotating propellers, even though the total output is 65 hp.

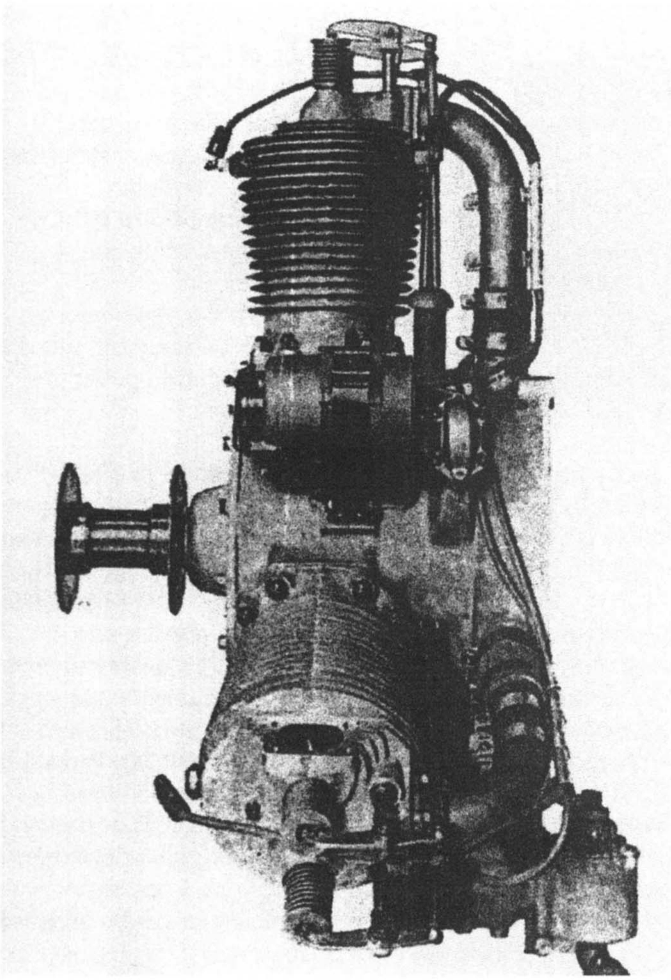
L

L

Lawrance (USA) Charles R. Lawrance designed racing-car engines from 1910, but in 1917 founded the Lawrance Aero-Engine Corporation to create a flat-twin air-cooled engine for the Shinnecock light plane. The firm had one room on New York's Broadway, buying parts from outside. An amazing feature of the 28-hp Model A was that both pistons worked on the same crank. Despite the resulting vibration, and a weight near 200 lb, 450 were built under licence by Excelsior for 'Penguins' (Army non-flying trainers). The Navy became interested and got Lawrance to develop the Model N, giving 40 hp for a weight of 80 lb, and by 1918 this became the three-cylinder Model L, of 65 hp and weighing 147 lb, sold in useful numbers (20 to 30) to the Army also. Lawrance was thus able to move into a small loft building and do his own experimental work, and in 1919 began developing two nine-cylinder radials, the J for the Navy and R for the Army.

The R was almost three Model Ls, with the same 4.25 × 5.25 in cylinders and with a carburettor for each group of three, capacity being 670 cu in. A 50-h test was passed in 1921 at 147 hp at 1,600 rpm, weight being 410 lb. The Model J had cylinders 4.5 × 5.5 in, 787 cu in, and the J-1 gave 200 hp at 1,800 rpm, for a weight of 476 lb. These were the first air-cooled radials in production in the USA, and it was a major act of faith by the Navy in an untried engine.

After thinking it could put its tiny competitor out of business, mighty Wright, in the person of F.B. Rentschler, bought up Lawrance, but retained him as vice-president along with several engineers. The result was the famed Whirlwind (*see* Wright). After Rentschler resigned to form Pratt & Whitney Aircraft, Lawrance became president of Wright.

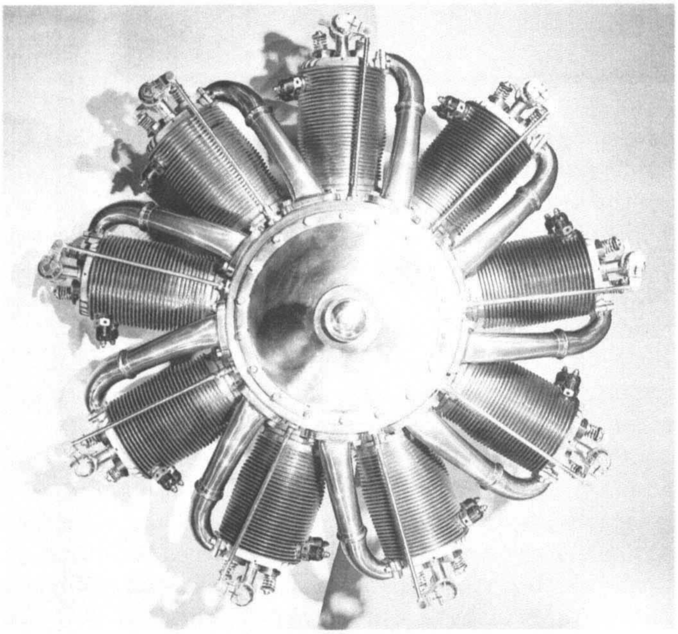


One of the profusion of Lawrence engines, the L-5 was the first of the 65-hp three-cylinder L family to have magnetos, instead of battery ignition.

Leduc (FRANCE) René Leduc was the greatest pioneer of the ramjet aeroplane. In 1935 years of research led to a small unit which developed 4 kg thrust at 300 m/s (671 mph). He immediately began design of a remarkable piloted aircraft, the O.10, with an integral ramjet fuselage internally divided into concentric zones, each with a ring of burners, the maximum thrust at 900 km/h at sea level being 2,250 kg. Construction began in 1938 and was finished in 1946. Gliding flights from a Languedoc were followed on 21 April 1949 by the first flight of a true ramjet aircraft, over 800 km/h being attained in a climb at high altitude with only half the burners working. Two more aircraft followed, and the fourth was the enlarged and much more advanced O.21, with a design thrust at 1,000 km/h of 6,500 kg. First flight was on 16 May 1953. Last came two impressive O.22s, with an integral Atar turbojet for take-off and planned to reach Mach 2, thrust at sea level then being 60 tonnes. The first flew on the Atar alone in December 1956, but government support tapered off and so did Leduc's dreams.

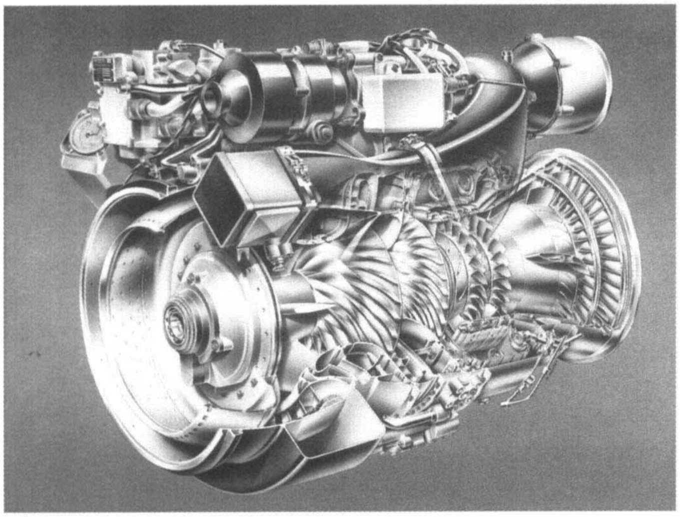
Le Rhône (FRANCE) The Société des Moteurs Le Rhône produced its first rotary in 1910, and between then and the takeover by Gnome in 1914 established its products as being in many ways superior to the Gnome. Its two design engineers were wisely permitted to continue development during the war, and production of nine-cylinder Le Rhônes was on a large scale, with different cylinder sizes giving 80, 110 or 130 or (not built in numbers) 180 hp.

Thulin built them in Sweden, Union Switch & Signal in the USA, the German Oberursel designs were often more Le Rhône than Gnome, and in the Soviet Union it was the M-2. All Le Rhônes had a cylinder with a cast-iron liner fed with mixture via prominent copper pipes. These had a telescopic section to accommodate changes in cylinder length,



Rear view of a Le Rhône 9C, showing the extensible induction pipes, twin cylinder-head valves worked by a single rod and dual plugs. Unlike many rotaries the Le Rhône could idle smoothly at 600 rpm.

This cutaway of the LHTEC T800 shows the robust and compact design with tandem centrifugal compressors. This engine is lighter and more powerful than the very similar European MTR390.

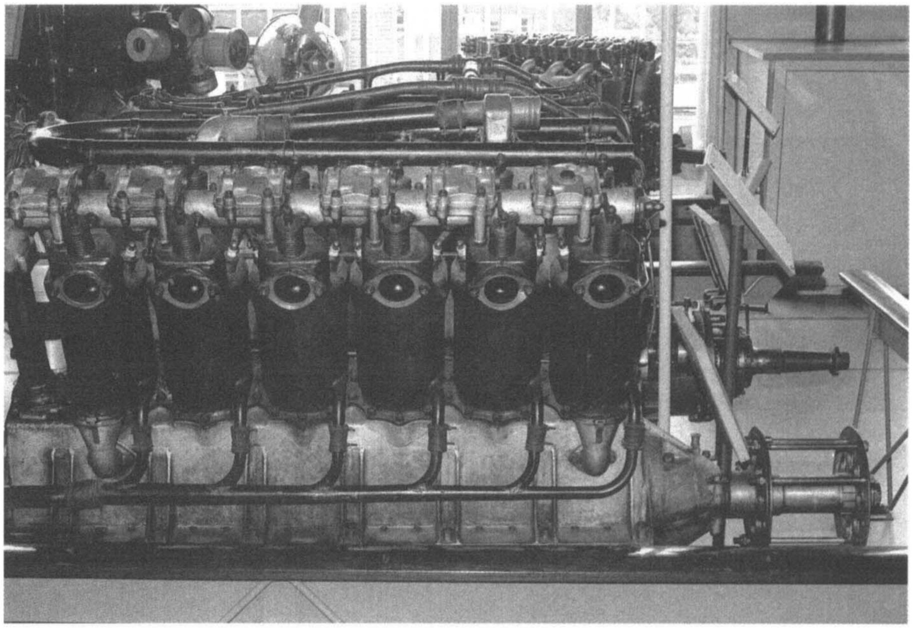


it being possible to adjust compression by varying the number of turns the cylinder was screwed into the crankcase. At the head were inlet and exhaust valves both operated by a single push-pull rod; thus, the timing diagram was quite unlike that of a Gnome.

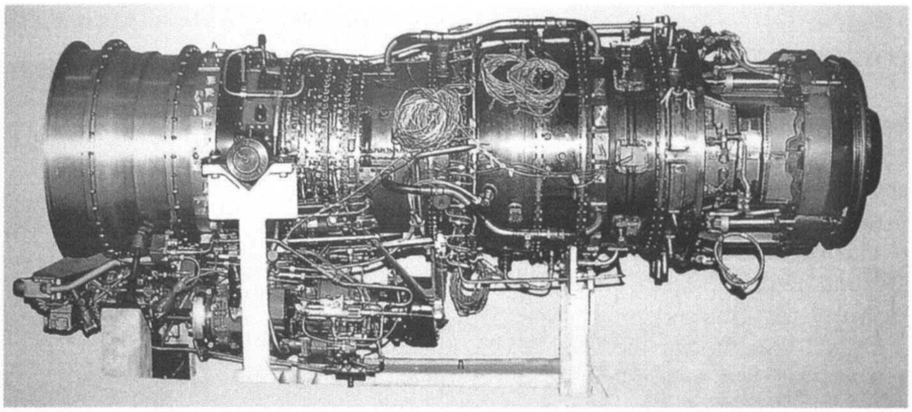
Oddest of all, the conrod big ends were in the form of curved shoes, three short rods, three slightly longer and three longer still. They drove on three concentric bronze-lined circular grooves on the inner faces of two steel discs linked together facing each other. Each rod occupied almost 120° of its own particular groove. On the outer face of the two discs was a flange locating a ball race running on the stationary crankpin. Le Rhône were justified in claiming lower fuel and oil consumption than, say, a Gnome Mono. The '80-hp' Le Rhône with cylinders 105 × 140 mm, actually delivered 93 hp at 1,200 rpm for consumption of 6–7 gal/h, compared with 10 for the 100-hp Mono; its oil consumption was half, at 1 gal/h. It was also cheaper, and weighed 240 lb (UK production) compared with 300 lb for the Gnome.

LHTEC (USA) When, in October 1988, Allison and Garrett won the contract to provide engines to power the multi-service RAH-66 Comanche armed helicopter, they formed the Light Helicopter Turbine Engine Co. to manage the programme. The engine is the T800, with tandem centrifugal compressors fed by an inlet with a particle separator which extracts over 97 per cent of all solid matter entering the inlet. This outstandingly robust and efficient engine has swiftly become a best-seller. The initial production version, the T800-800 for the Comanche, weighs 310 lb and has a contingency rating of 1,600 shp, though the Comanche was cancelled in February 2004. The civil-certificated CTS800-0A has flown in the Agusta 129, Lynx, HH-65, Panther and Indian ALH. The CTS800-4N is a civil engine with integral gearbox for all these helicopters plus various Bells. More unexpected is the swift development of the CTP800 turboprop. The initial 1,350-shp version has transformed the performance of the US Army RC-7B (DHC-7) reconnaissance aircraft, and LHTEC is now coming into production with other variants, notably including the CTP800-4T twinned model. Launched by a massive order by Federal Express for the Ayres Loadmaster cargo aircraft, this is a 2,700-shp package developed by Soloy, with twin power sections driving a common propeller gearbox.

Liberty (USA) This famous engine was designed by Jesse Vincent of Packard and E.J. Hall of Hall-Scott, in a Washington hotel suite between 30 May and 4 June 1917. The first engine, a V-8, was on test by 3 July. Altitude testing was done on 14,109 ft Pike's Peak, Colorado. The Liberty was a massive US War Department project to provide vast numbers of aero engines quickly. It was inevitable that the configuration chosen should have been a separate-cylinder water-cooled V, and the cylinder was virtually the same as the 5 × 7 in Hall-Scott; other features were incorporated from a new V-12 by Packard. The angle between the cylinder banks was only 45° to reduce width, and another unusual feature was the coil ignition. The overhead valve gear was exposed, and along each side of the crankcase was a heavily braced mounting platform. The intention was to produce Liberties in four-, six-, eight- and 12-cylinder versions, the first engine being a Liberty 8, rated at 250 hp. Only very few Liberties were made except for the 12, and this quickly went into mass production at established auto factories, 20,478 being delivered, almost all of them prior to November 1918. Most were rated at 400 to 500 hp.



No engine in aviation history can quite equal the Liberty 12's record of quick design, quick qualification and quick mass production. Remarkably, it also had a very long active life. This particular engine is in the Science Museum, London.



The only known picture of the Chinese WS10 turbofan engine, derived from the CFM56.

Typically weighing 790 lb, this V12, 1,649-cu in (same as the Merlin) engine was a sound and generally reliable powerplant, though quality apparently varied depending on the builder. Many thousands continued in military and civil use until 1933 (RAF) and 1934 (US Army), experimental versions having geared drive, two-speed geared drive, mechanically driven supercharger, turbosupercharger, cast blocks (eliminating the persistent cracking of the welded water jackets caused mainly by detonation on poor fuel) and, by Allison, a complete inversion of the engine with air-cooled cylinders.

Limbach (GERMANY) This company is famed for its four-stroke and two-stroke piston engines for light aeroplanes and powered gliders. All are 'flat' (opposed) air-cooled types, most being the closely related four-cylinder SL 1700 (1,680 cc, 68 hp), L 1800 (1,756 cc, 66 hp), L 2000 (1,994 cc, 80 hp) and L 2400 (2,424 cc, 87 to 130 hp).

LM (CHINA) With a name meaning Daybreak, Liming Engine Manufacturing Corporation is one of the largest in China. Set up in 1954, it began by making the WP6 (Chinese designation for the Tumanskii RD-9B), followed by the WP7 (Tumanskii R-11F-300). From 1964 the new design team tried to create the WS9, an afterburning fighter engine in the 27,500-lb class. This was eventually abandoned and replaced by the much better WS10. This was cunningly based on the CFM56, which had just come into Chinese service in 737s and A320s. By replacing the big fan by extra compressor stages, and adding an afterburner, the result is an excellent supersonic turbofan in the 30,000-lb class. It was designed by the 606 and 624 Institutes, who incorporated features of the Russian AL-31F, which the WS10 is hoped to replace in Chinese Su-27 fighters.

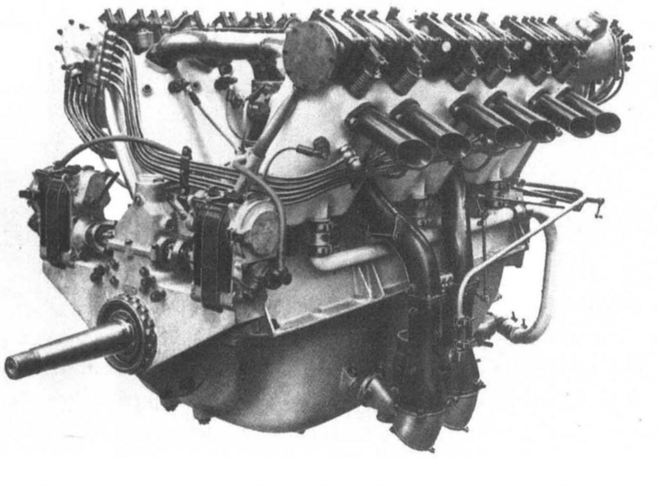
LMC (CHINA) Also known as the Guizhou factory, Liming Machinery Corporation has produced large numbers of different versions of WP7 (not identical to those made by LM) followed by the WP13, derived from Gavrilov's R-13.

Lockheed (USA) It is not widely known that this company was a pioneer of the turbojet. Nathan C. Price, a steam-turbine engineer, flew a Travel Air biplane on a steam turbine on 12 April 1933. It was intended only as a publicity stunt to draw attention to the turbine, but was amazingly quiet, smooth and successful (the Boeing School took up the idea). By 1940 Price was with Lockheed, and by this time was firmly set on jet propulsion, using a steam turbine. In 1940 he switched to the L-1000, an incredible engine for which the L-133 canard jet fighter was designed, with integrated propulsion and boundary-layer control, and with reaction-jet controls.

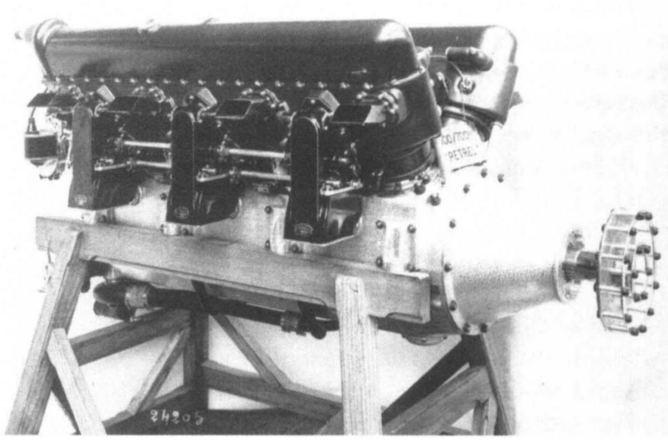
The L-1000 was planned to be more efficient than piston engines, with axial and reciprocating (later axial plus axial) compressors in series, an annular combustor and two intercoolers downstream of the compressors. Sea level thrust was to be 5,500 lb. Hall L. Hibbard rightly thought that no engine firm would want to be involved, but it should have been obvious that the L-1000 was a giant task. In 1943 long-term support was obtained, with designation XJ37, but in October 1945 Lockheed wisely gave the project to Menasco to carry on, under licence. Prototype XJ37s were run, but Menasco in turn handed the project to Wright, which terminated this remarkable programme in 1952.

LOM (CZECH REPUBLIC) *See* Avia.

Lorraine (FRANCE) The Société Nationale de Construction de Moteurs (Lorraine-Dietrich) began designing water-cooled aero engines in 1915. At least two in-line prototypes were tested to perfect the Mercedes-style separate-cylinder design before production of the V-8 type began in August 1917, mainly in the form of the 275-hp 8B and 8Bd. There followed a succession of V-12s and 'broad arrow' W-12s, the latter configuration producing the 12Ed of 1922 with cylinders 120 × 180 mm (24.4 litres), rated at 450 hp and used for several famous long-distance flights. This and related engines had cylinders in pairs sharing a common welded water jacket,

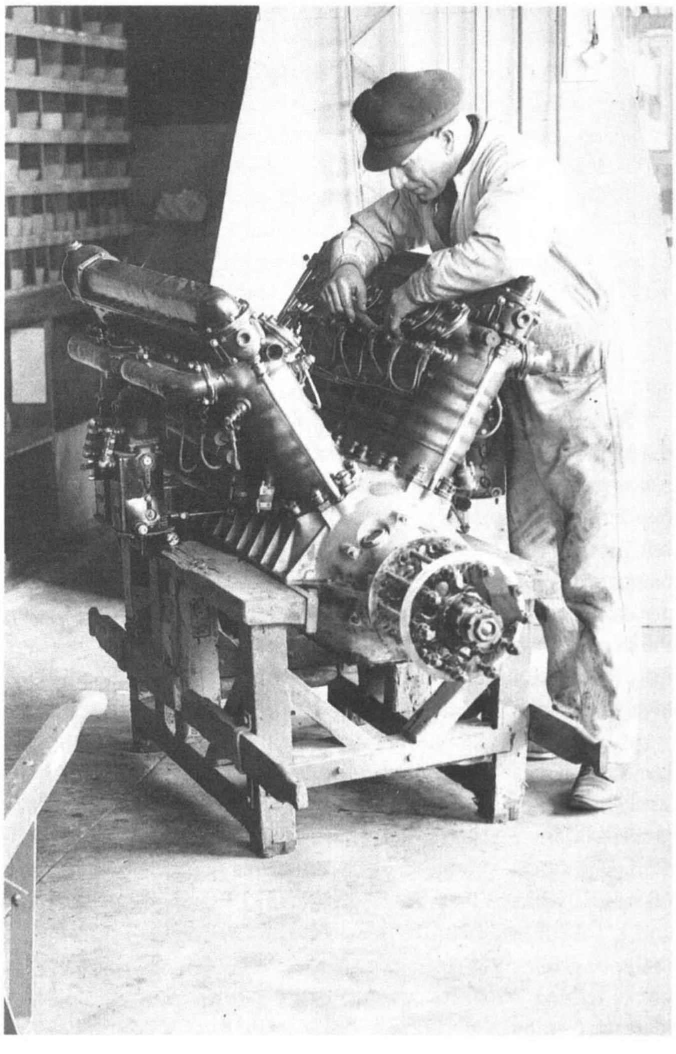


The Lorraine 12D was a typical V-12, with magnetos at the front, carburettors low on each side and water pump at the rear. Rated at 400/425 hp it powered the LeO 12 night bomber.



In 1932 Lorraine saw that the future lay with monobloc cast banks of cylinders, and produced the Petrel V-12. It had many odd features, but still grew from 500 to 860 hp; this 1934 specimen is of 650 hp.

A *mécanicien*, possibly of Air Union, photographed at Croydon in about 1923 with a Lorraine-Dietrich V-12 of 400 hp.



with overhead camshafts and exposed valve gear. By this time Lorraine had overcome the problem of persistent crankshaft breakage, thought to have been caused by poor mixture distribution.

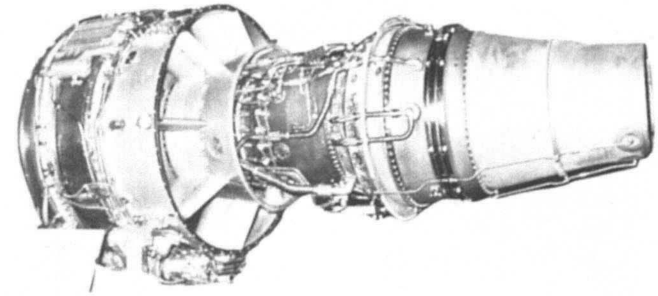
By 1926 the company had switched to cast-block engines, with steel sleeves screwed into the light-alloy block and in most cases with a mix of plain and roller main bearings, four valves per cylinder driven by twin overhead camshafts and, from 1928, a supercharger and geared drive. This family was named after birds. The Eider of 1928 was a massive 45-litre V-12 with 170 × 165 mm cylinders, rated at 1,050 hp. The Courlis of 1929 was a W-12 with 145 × 160 mm cylinders (32.1 litres), rated at 600 hp. The Petrel of 1932 was a V-12 with 145 × 145 mm cylinders (29.5 litres), rated at 500 hp, but developed to 860 hp in the Petrel 12Hars of 1938 which drove a contraprop in the FK.55 fighter. Last came the Sterna of 1937, a V-12 with 30 litres and type-tested at 810 hp at 2,575 rpm, with 1,200 hp in prospect – in each case at 4 km (13,120 ft). Lorraine built small radials, such as the 120–125-hp P5 of 1933, but poor sales resulted in bankruptcy in 1940.

Lotarev (SOVIET UNION) Vladimir Lotarev was the General Constructor in charge of the KB at Zaporozhye previously directed by A.G. Ivchyenko. His obviously large team have produced some of the most advanced gas turbines in the Soviet Union, three of them being in production.

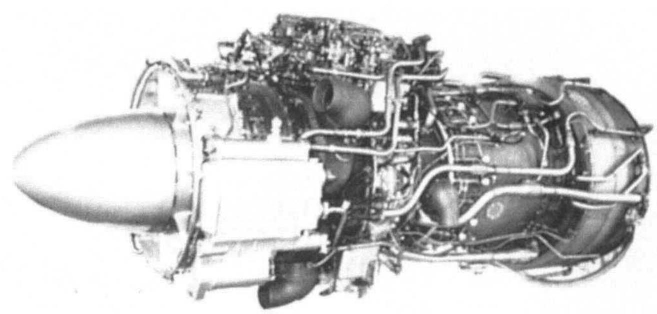
First came the smaller of two high-bypass turbofans, the D-36, developed for the Yak-42. This has three shafts, with a titanium fan, LP spool with variable inlet vanes and steel HP spool, giving overall pr of 20, bypass ratio being 5.6. The 28-burner annular combustor is fabricated with integral HP turbine entry vanes, inlet gas temperature being 1,177°C. The air-cooled HP turbine and the IP both have one stage, the LP having two. Normal take-off rating is 14,330 lb, with the competitive sfc of 0.36. It powers all Yak-42 versions except the 42M, and all versions of An-72 and An-74.

Next came the world's most powerful helicopter engine, the 11,400-shp D-136 for the Mi-26. This has a six-stage LP spool, six-stage HP, combustor scaled down from that of the D-36 single-stage HP turbine (1,205°C), single-stage LP and two-stage free power turbine. Construction is modular, take-off sfc 0.4365, and dry weight 1,050 kg. The D-236 is a modified D-136 coupled through a gearbox to contra-rotating propfans of 4.2 m (13 ft 9 in) diameter. The front propeller has eight scimitar-like blades and the rear has six. Turning at 960 rpm, propulsive efficiency at Mach 0.7 is 87 per cent. Full flight testing got under way in 1988.

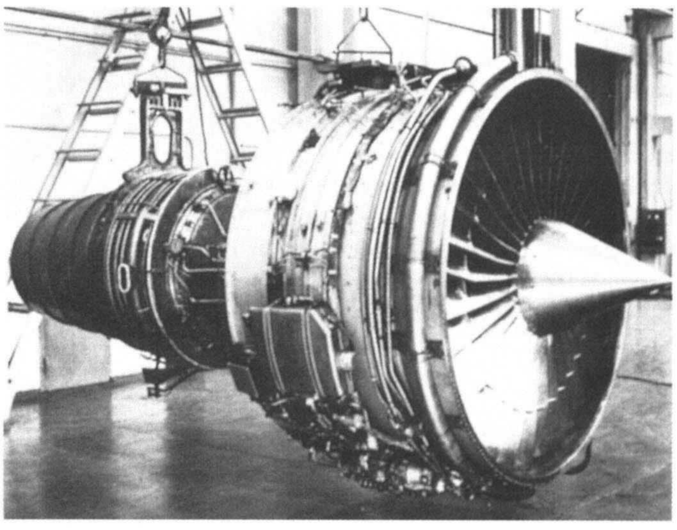
Subsequently Lotarev designed the much larger D-18 turbofan, and also a range of engines derived from the D-36. These are described under ZMKB Progress.



Lotarev's D-36 was the first three-shaft turbofan to be developed for service other than by Rolls-Royce. It powers the Yak-42 and has a good record.

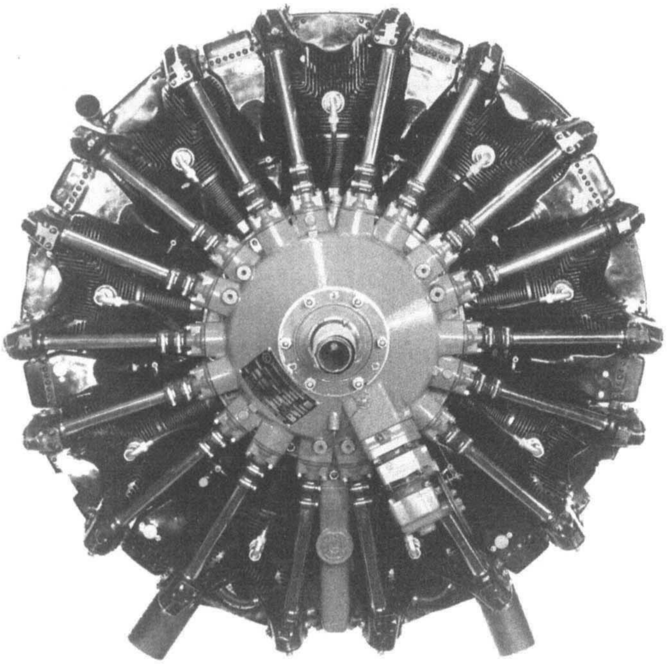


The D-136 turboshaft engine, rated at 11,400 shp, makes possible the big Mi-26 helicopter. The West has no engine in this class.



In May 1985 the giant An-124 visited Paris, powered by four D-18T turbofans. In this aircraft reversers are fitted.

Lycoming (USA) In numerical terms this is currently the world's No. 1 producer of aero engines. Founded in Williamsport, Pennsylvania, in 1908, it made car engines from 1910, by 1924 powering 57 makes of automobile. In 1929, as a subsidiary of E.L. Cord's Auburn Auto Company, it produced its first aero engine, the R-680 radial with nine cylinders 4.625 × 4.5 in, each with two valves, and a conservative design which soon produced outstanding reliability, at ratings



Lycoming's R-680 established the firm in the aero-engine business. This 300-hp wartime E3A model weighed 515 lb.

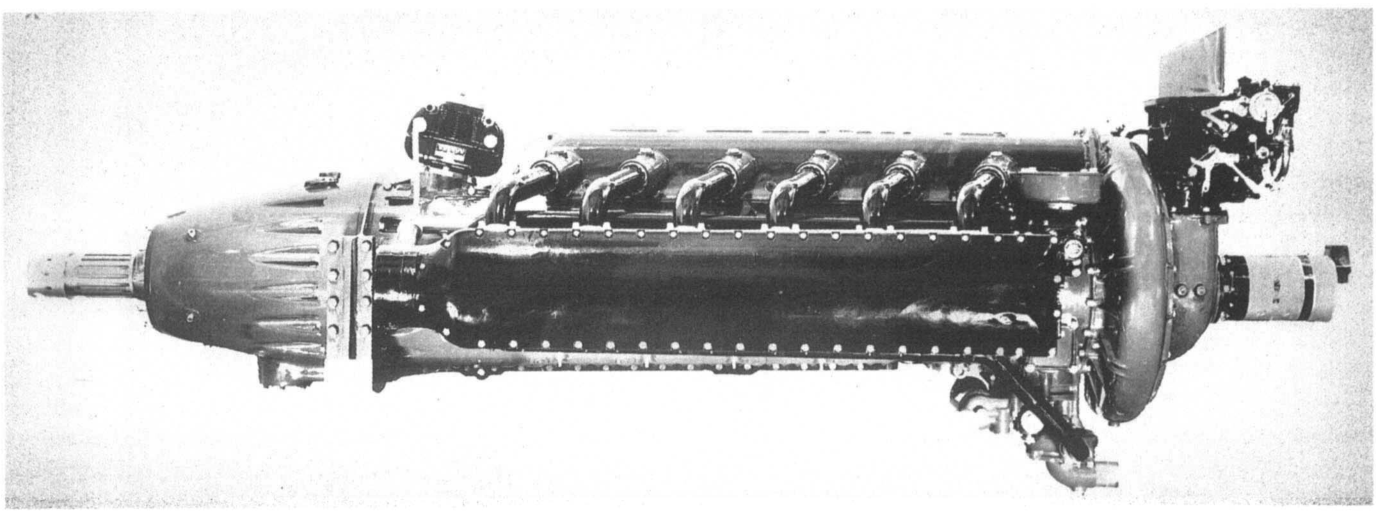
from 200 to 285 hp. In 1932 Lycoming Manufacturing became part of the conglomerate Aviation Corporation (from 1947 renamed Avco). Production of the R-680 continued until after the Second World War, to a total exceeding 26,000. In 1938 a new line of light-plane engines had been designed by Harold Morehouse starting with the O-145 flat-four. The left and right pair of 3.625 × 3.5 in cylinders was cast integral with half the mild-steel crankcase, the cast aluminium heads being held by studs. Opposite cylinders were staggered so that the crankshaft could have four throws. The O-145 started at 50 hp, weighing 152 lb, and at termination in 1950 had progressed to 75 hp in both direct-drive and geared versions. In 1939 Lycoming designed the O-235, with four cylinders 4.375 × 3.875 in, starting life at 104 hp, and the O-290 of 125 hp with bore increased to 4.875 in. This larger cylinder was also soon used in the flat-six O-435 family of 190–220 hp, and all these engines had an aluminium-alloy crankcase split on the vertical centreline to which the steel cylinder barrels were attached by studs. By 1950 this range had been joined by the eight-cylinder O-580 family of 320–400 hp, originally considered for buried wing installations. All these engines had many common parts.

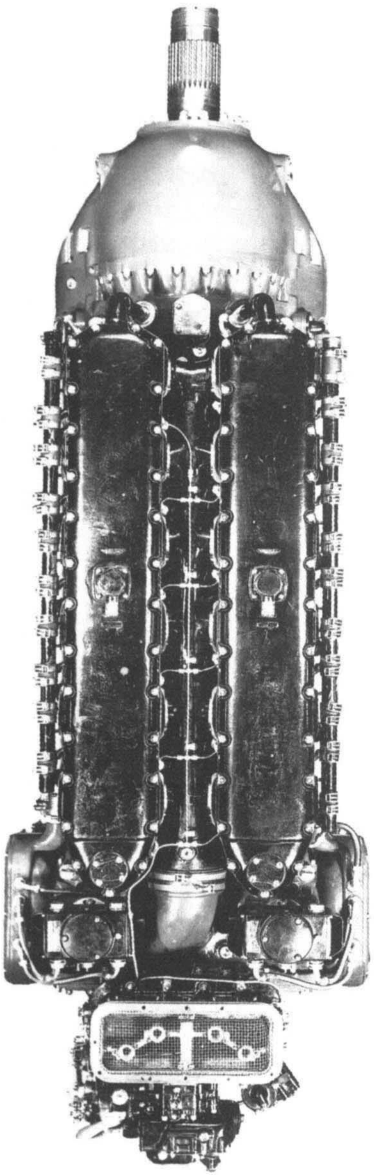
The flat-eight was almost a throwback to a major Army programme begun in 1935 to find an engine to fit inside wings. After a year testing a liquid-cooled 'hyper' cylinder, the O-1230 flat-12 was placed under contract and developed with speed and assurance, largely because Lycoming put more of its own money into the project. The 1,234 cu in engine ran in 1937, and flew in 1938 powering the XA-19A in a conventional nose installation. It was qualified at 1,000 hp in 1939, but more power was now needed, so Lycoming went ahead with the H-2470, a twinned O-1230. Navy funds supported it, and the first run in July 1940 was encouraging, so a production order was placed (for the F14C-1) in May 1942. In the event the only aircraft powered by this 2,200-hp liquid-cooled unit was the Convair XP-54.

Far more remarkably, in 1941 an Army contract launched the XR-7755, the biggest one-unit piston aero engine and one of the heaviest aero engines of all time (7,050 lb in contraprop form). With nine banks of four whopping 6.375 × 6.75 in cylinders (7,755 cu in) it gave 5,000 hp in 1944 and aimed at 7,000 hp, but no application was ever announced.

Today Lycoming engines are produced at Stratford, Connecticut (gas turbines), and Williamsport (general-aviation engines including small gas turbines). The company's best-selling piston engines comprise three flat-fours, the O-235

By late 1939 Lycoming's O-1230 flat-12 was giving 1,200 hp for a weight of 1,325 lb, and with a total height of 37 in. The Army wanted even more than this.

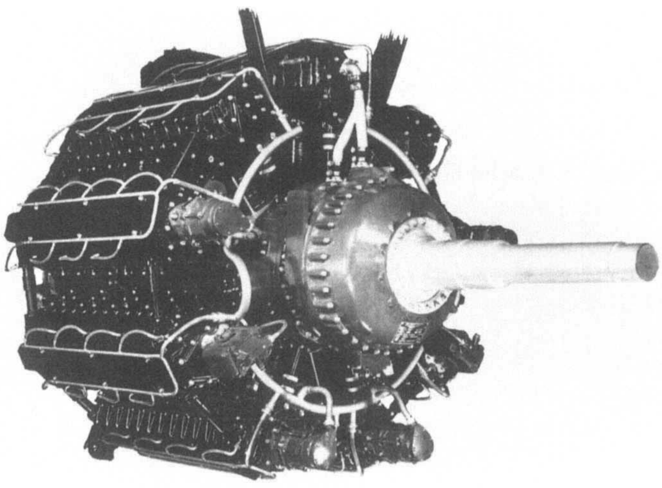




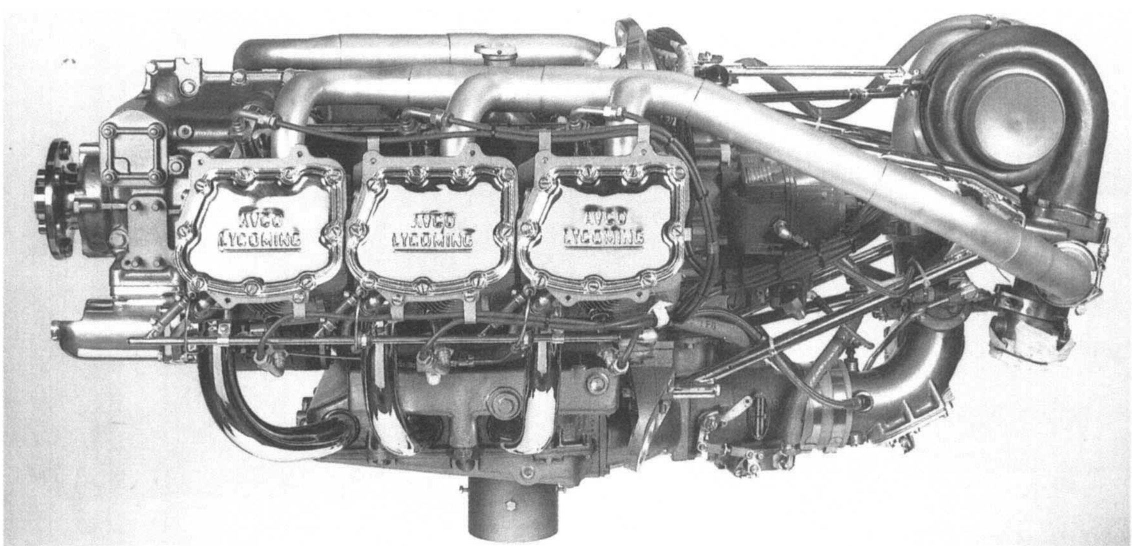
First run in July 1940, the Lycoming XH-2470 was two O-1230s superimposed. A special plant at Toledo, Ohio, was to build it for the F14C, the first liquid-cooled Navy fighter since 1925, but this potential 3,000-hp engine was cancelled in 1943 on grounds of too-late timing.

(4.375 × 3.875 in), O-320 (bore increased to 5.125 in) and O-360 (5.125 × 4.375 in), with ratings of 115–282 hp, two families of flat-sixes with O-360 cylinders, the O-540 and the redesigned O-541 range, and the corresponding flat-eight, the O-720. Almost all have direct injection and many are turbocharged. Piston-engine deliveries from Williamsport exceed 250,000.

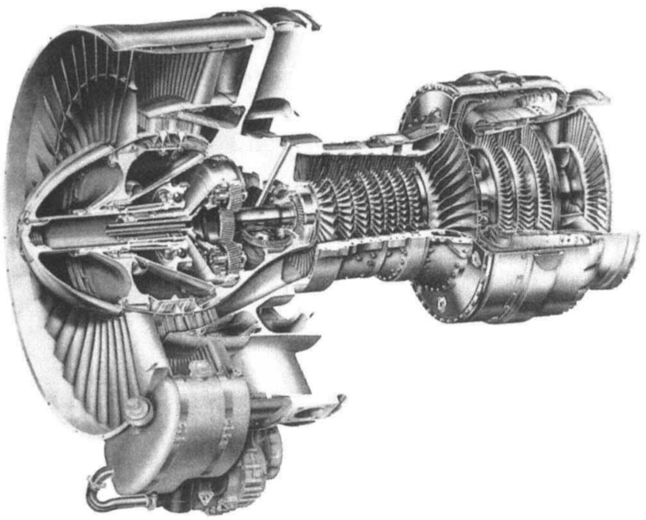
For nearly a decade Williamsport has watched the growth of previously absent competition, notably from derivatives of air-cooled and water-cooled car engines. A vice-president for new product development was appointed, and at last in 1985 a major new line of business was announced. In 1984 the last foothold that the once mighty Curtiss-Wright company had in complete aero engines was purchased by John Deere, the giant of agricultural machinery. The vast Wood-Ridge plant had from 1958 been developing Wankel-type RC (rotary combustion) engines, as also had NASA at Lewis Research Center. Deere planned to create advanced RC engines for many purposes, and in 1985 concluded a deal with Avco Lycoming under the



Lycoming's XR-7755 remains a mystery; what aircraft could have used this colossus among piston engines?



Today Williamsport builds them a bit smaller, an example of the world's biggest-selling range being this TIO-540, which weighs 450 lb and gives 250 hp up to 15,000 ft; other versions sustain up to 360 hp to this height, all cylinders exhausting through the single turbo.



Above: A cutaway showing the geared drive to the fan (and supercharging LP stage) of the Lycoming ALF 502R which powers the BAe 146. The axial/centrifugal core and reverse-flow combustor are taken from the T55 which powers the Chinook. Today this engine has been followed by the Honeywell LF507.

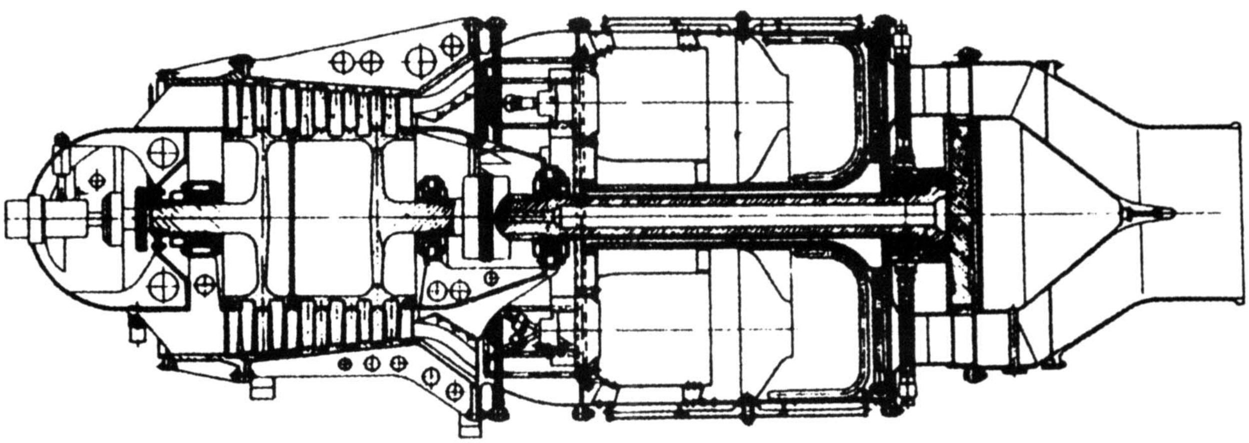
terms of which Lycoming would help fund development of advanced stratified-charge RC aviation engines and, paying a royalty on each engine, would have world rights to make and sell for aerospace applications. Termination of the whole project in 1986 does not cast doubt on the technology of the RC engine.

Gas turbines

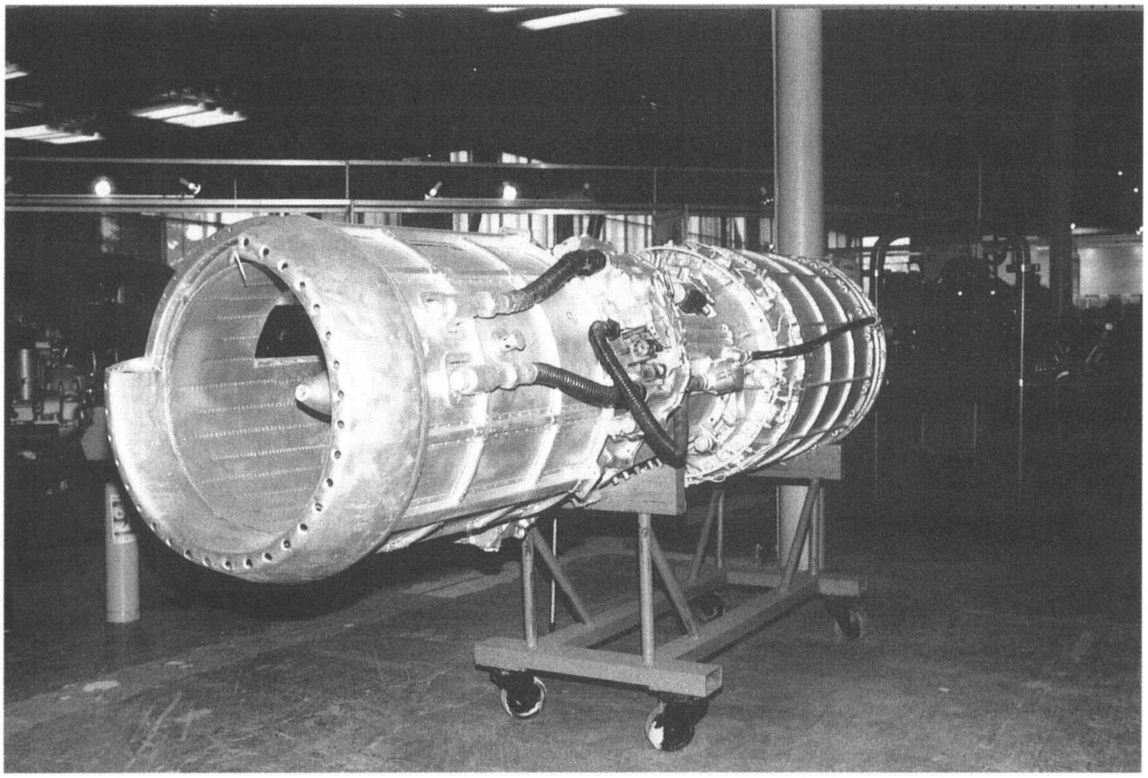
In 1951 Avco Lycoming hired Dr Anselm Franz, lead designer of the Jumo 004B in the Second World War. A year later he began work on the T53 turboshaft for Army helicopters, the prototype running in 1953 at 600 hp. Features included a five-stage axial and one-stage centrifugal compressor, folded annular combustor, and single-stage gas generator and free power turbines. Since then over 19,000 T53s have logged over 55 million hours in turboshaft and turboprop forms at powers up to 1,550 shp, some licence-made by KHD, Piaggio, Kawasaki or AIDC-Taiwan. In 1954 work began on the larger T55, with airflow raised from 10 to 20 lb/s (later models, from 12.2 to 27 lb/s). Some 8.2 million hours have been flown by 4,500 T55 engines, almost all in Chinooks. After building a few PLF1 and related engines, Lycoming Stratford's wish to launch a turbofan was realised in 1969 in the ALF 502, using the T55 core plus a single-stage geared fan. The 502R, for the BAe 146, has a single-stage core booster and is rated at 6,700 lb, while the 502L, for the original version of Challenger, has a two-stage booster and is rated at 7,500 lb; weight of all versions is about 1,330 lb. The 7,000 lb LF 507, for the Avro RJ, has many minor improvements. Stratford also developed a family of simple, robust, modular single-shaft engines in the 600-hp class known as LTS 101 (turboshaft) or LTP 101 (turboprop), military designation being T702. These have been assigned to Williamsport for production. With Army funding Stratford has developed the PLT 34 in the 1,200-hp class with technology intended for the next century.

In 1985 Avco Corporation became a subsidiary of Textron Inc. In 1987 the parent decided that Lycoming engines should in future be known as Textron Lycoming, but in 1994 negotiated to sell Lycoming to AlliedSignal. Five years later AlliedSignal merged with Honeywell, losing its separate identity.

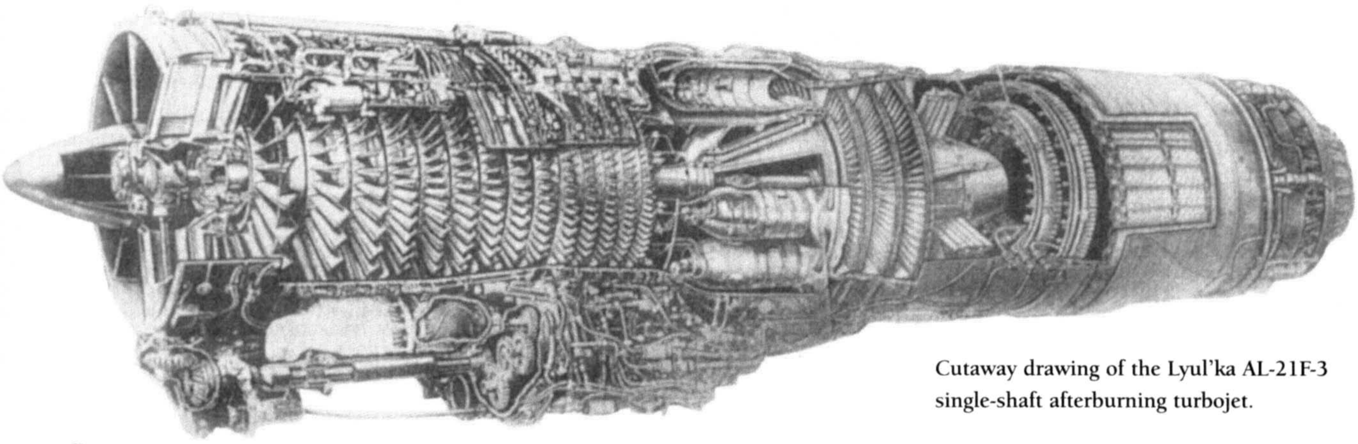
Lyul'ka (SOVIET UNION) Arkhip Mikhailovich Lyul'ka (the apostrophe replaces a Russian character that separates the syllables) was one of the greatest pioneers of the axial turbojet. His 1936 calculations at the Kharkov Aviation Institute met with scepticism, but, aided by famed designers Kozlov and



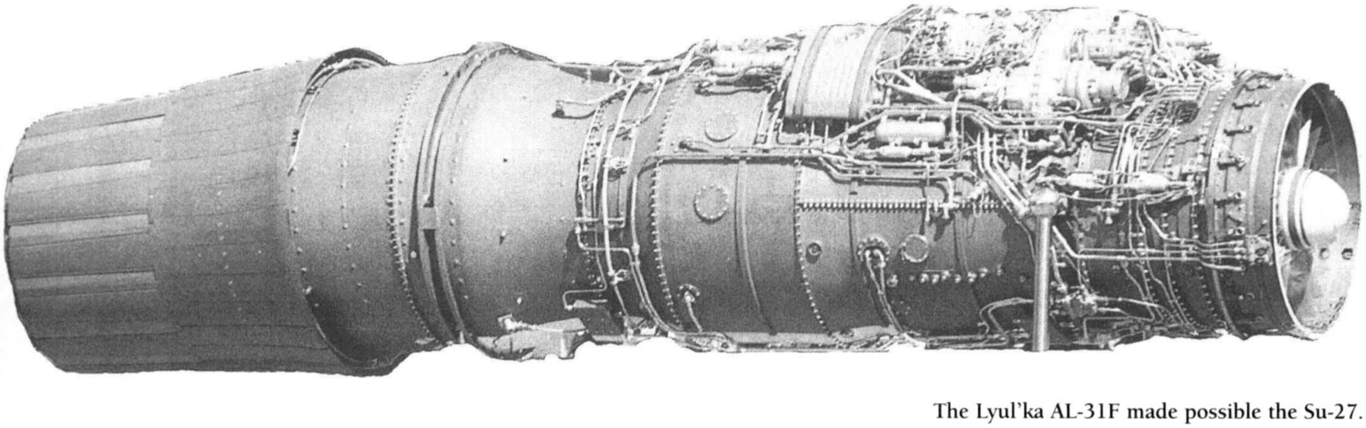
Designed in 1939–40, the Lyul'ka RD-1 was perhaps the best turbojet in the world at that time, with a thrust of 1.168 lb, pressure ratio of 3.2 and specific fuel consumption of 1.43. It was never able to be flown.



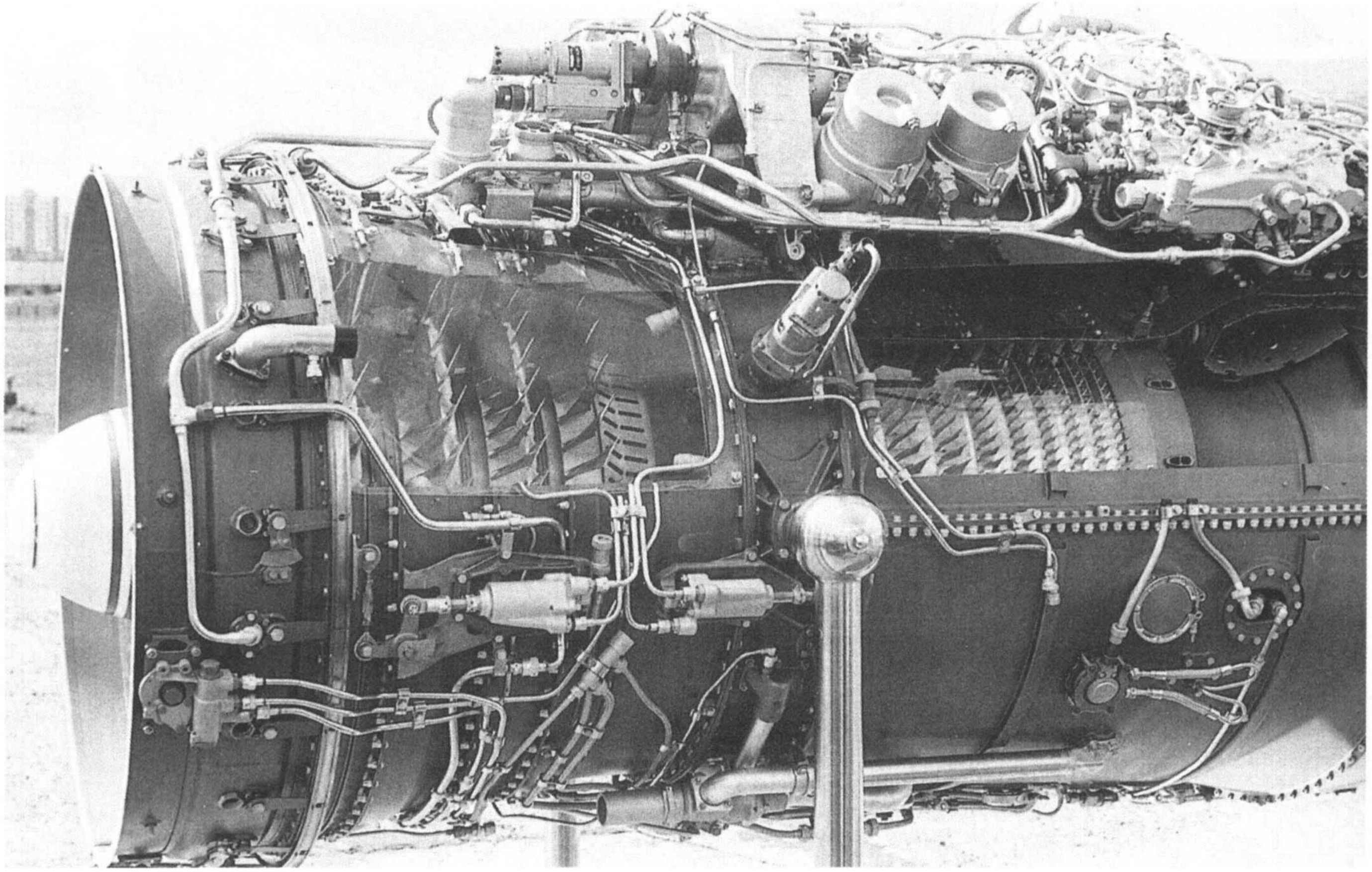
Lyul'ka was a pioneer of axial turbojets. This TR-1 is cut away on the far side.



Cutaway drawing of the Lyul'ka AL-21F-3 single-shaft afterburning turbojet.



The Lyul'ka AL-31F made possible the Su-27.



Close-up of the compressors of a cutaway Lyul'ka Saturn AL-31F fighter engine.

Shyevchenko, he was permitted in 1938 to begin work on the VRD-l turbojet in Leningrad. This eight-stage engine was to develop 1,322 lb thrust (a little more than its weight) at 700°C, but had to be shelved in 1941. In late 1942 Lyul'ka was able to return to the beleaguered city where he tested centrifugal and axial compressors, ran the VRD-2 axial at 1,543 lb in 1943 and late in that year headed a team that began design of the VRD-3, later called S-18 and finally TR-1.

This much better eight-stage engine had an annular chamber, single-stage turbine and many new features. In 1944 it was rated at 2,866 lb thrust at 6,950 rpm, and four powered the Il-22 bomber in July 1947. In 1946 work began on the TR-3 (VRD-5), with a seven-stage compressor and single-lever control, used in various prototypes at 19,140 lb thrust.

In 1950 Lyul'ka became a General Constructor, based in Moscow, the TR-3 being redesignated AL-5. Having been thwarted by failure of nine types of Lyul'ka-powered aircraft to be built in series, he then scored a smash hit with the AL-7, many thousands of which were made for the Su-7, Su-9, Su-11 and other types in 1955–75. It featured supersonic flow through the first two stages of its nine-stage compressor, an annular combustor, and a two-stage overhung turbine; in the Sukhois it also had an excellent afterburner. The AL-7 led to the AL-21, an impressive engine with a 14-stage spool, can-annular chamber and three-stage turbine. Mainly as the AL-21F-3, rated at 17,200 lb dry and 24,800 lb with afterburner, it has been made in large numbers for the Su-17 and -22, and all versions of Su-24.

Lyul'ka died in 1984, but his successor Dr Viktor Chepkin saw the AL-31F into production at the Ufa plant in the same year, as related under UMPO.

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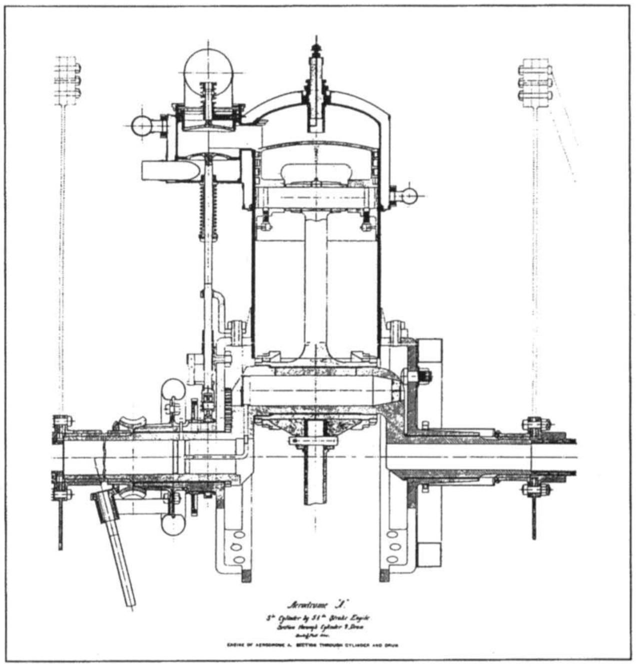
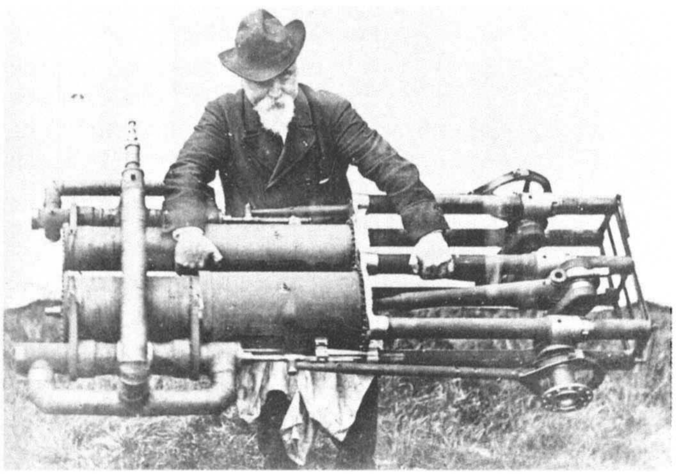
Manly (USA) On 1 June 1898 Charles Matthews Manly reported to the august Professor S.P. Langley of the Smithsonian Institution in Washington, DC, without even waiting to graduate from Cornell. From then until December 1903 he was engine designer and pilot of Langley's 'Aerodromes'. His engine was derived from the Balzer auto engine, but considerably redesigned. A static radial, it had five cylinders each 5 × 5.5 in (540.2 cu in), with closed-head steel barrels only 0.0625 in thick with shrunk-in cast-iron liners of the same thinness, the forged head and 0.02 in water jacket being brazed on. The master rod ended in a sleeve encircling the crankpin and fitted with a bronze liner, each split at 90° to the others to permit assembly. The outer periphery of the sleeve was truly cylindrical (except at the junction with the rod) and the other four rods all bore on this sleeve via bronze shoes. Pistons were cast iron, and a side extension to the combustion chamber contained an automatic sprung inlet valve opposite a pushrod-driven exhaust valve. This remarkable engine weighed 207.5 lb including water and gave 52.4 hp at 950 rpm, the weight/power ratio of 3.96 not being equalled until well into the First World War.



Cross-section of the Manly-Balzer, a remarkable engine for more than a century ago.

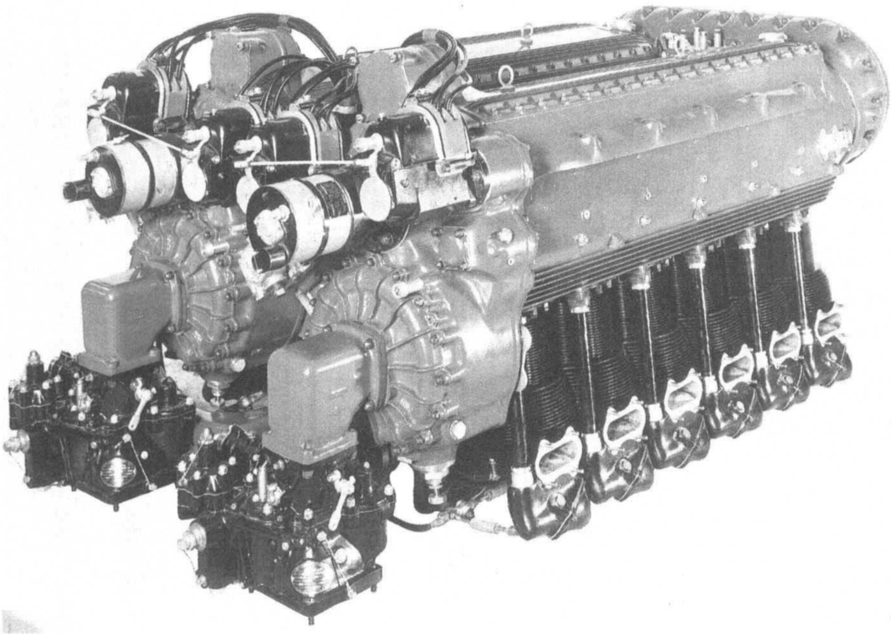
Mars (RUSSIA) *See* OMKB.

Maxim (UNITED KINGDOM) Sir Hiram Maxim, wealthy expatriate American, has been described as conceited, pigheaded and much more besides, and he certainly was one of the many 'chauffeur-minded' aviators who disregarded the problem of how to learn to be a pilot; but his giant biplane of 1894 had remarkable engines. Left and right steam engines drove handed (opposite-rotation) propellers, and it was all on a vast scale. High-pressure boilers burning naphtha fed the two compound engines, each with one HP (320 lb/sq in) and one LP cylinder, each engine weighing only 310 lb but putting out 180 hp (Maxim was sure 250 hp was ultimately attainable). Boilers etc. added 1,800 lb, plus 600 lb of water. Maxim finally concluded that the internal-combustion engine was better.

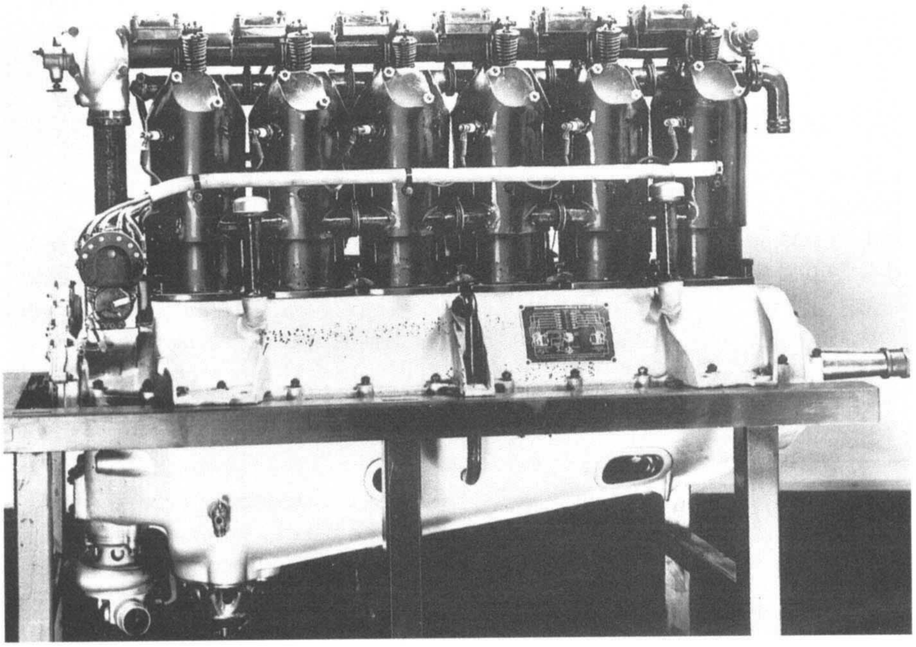


Sir Hiram Maxim is not seated but is actually lifting one of the remarkable 180-hp compound steam engines which powered his giant 1894 biplane.

Menasco (USA) Al Menasco established Menasco Manufacturing Corporation in Los Angeles in 1926, the first product being an air-cooled rebuild of a wartime Salmson radial. In 1929 he launched the 4-A inverted four-in-line with 4.5 × 5.125 in cylinders (326 cu in), with exposed valve gear operated from a camshaft in the crankcase. This engine was rated at 90 hp, but Menasco was an enthusiast for racing and by 1931 had brought out the 95-hp B-4, 125–150-hp C-4 (with bore increased to 4.75 in) and B-6 with six original-bore cylinders. Usually the 4s were named 'Pirate' and the 6s 'Buccaneer', but as the 1930s progressed there were numerous hot-rod versions. The ultimate baseline engine was the 6CS Super Buccaneer with large-bore cylinders (545 cu in), normally a 260-hp engine but in racing trim giving well over 300 hp. In 1938 the M-50 flat-four was launched but it was a marketing error, and the last news of the firm was its brief encounter with the complicated Lockheed XJ37 turbojet.



Menasco's Unitwin comprised two supercharged Buccaneers geared to a single propeller shaft. In an alternative scheme two Menascos were fitted flat, driving a pair of propellers side-by-side in the nose of the Alcor DUO-6.



Having in 1912 pioneered the welded-steel cylinder that later formed the basis of Rolls-Royce and Liberty engines, the Mercedes (Daimler Motorenwerke) was by a narrow margin the No. 1 German wartime engine. This is a Mercedes D III (D for Daimler) of 1915, with 140 × 160 mm cylinders rated at 160 hp.

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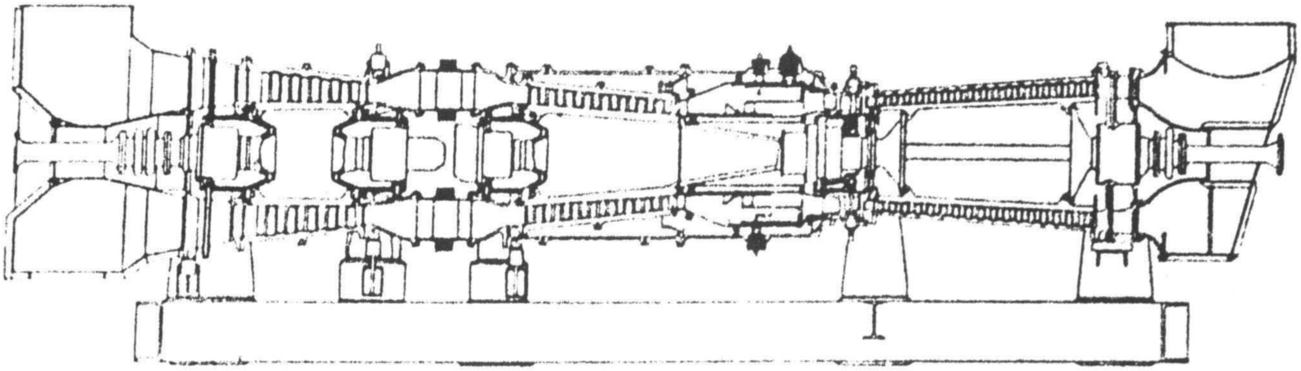
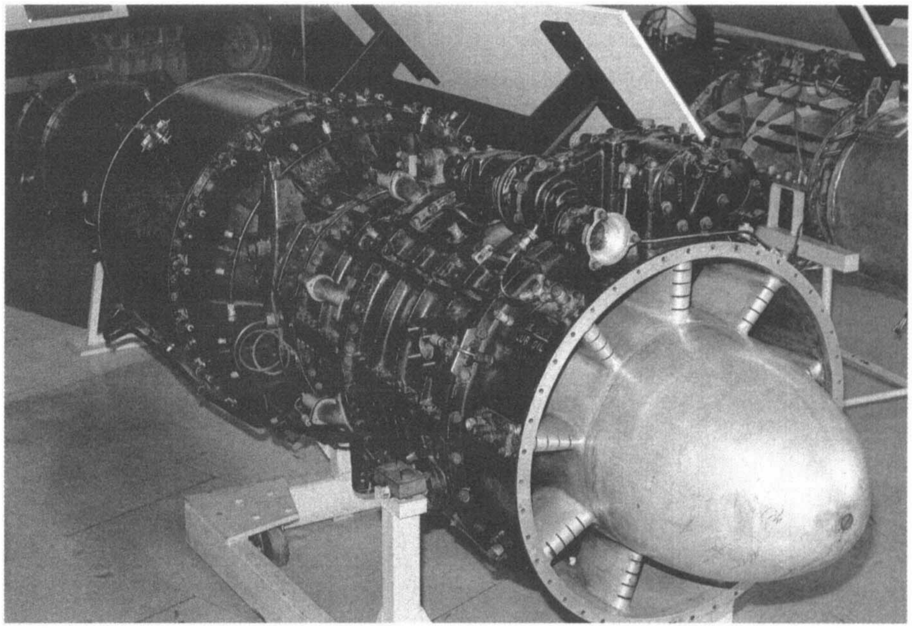
Mercedes (GERMANY) Strictly the name should have French accents because it was that of a wealthy Frenchman's daughter. It was originally a brand name of the famed Daimler company of Stuttgart, which built its first aero engine in 1910, a water-cooled four-in-line. Subsequently Daimler (Mercedes) produced an inverted four and a geared eight-in-line, but more than 99 per cent of its wartime output was of six-in-lines.

The Mercedes six-in-line of 1913 was at least as important as the Austro-Daimler in establishing such engines as almost standard for aircraft of the Central Powers, and they certainly were the first to make a success of the steel cylinder with welded water jackets. Like the Austro-Daimler there were twin carburettors and twin magnetos, but the valves were driven by an overhead camshaft which usually had a lever at the rear with which it could be moved axially to bring into action half-compression cams to facilitate starting. Almost all models had the cylinder barrel and head machined from steel forgings, screwed together and with valve pockets, guides and ports welded on. Jackets were three or four thin steel pressings welded together on each cylinder. Most cylinders comprised a



In 1940 the performance of axial blading was unimpressive. This shows the Royal Aircraft Establishment D.11. The inlet at right feeds the 17-stage compressor, driven by an eight-stage turbine, to supply gas to a five-stage power turbine at left.



First British axial turbojet, the Metrovick F.2 began at 1,750 lb thrust with a nine-stage compressor and two-stage turbine and by 1946 gave 3,500 lb with a 10-stage compressor and one-stage turbine.

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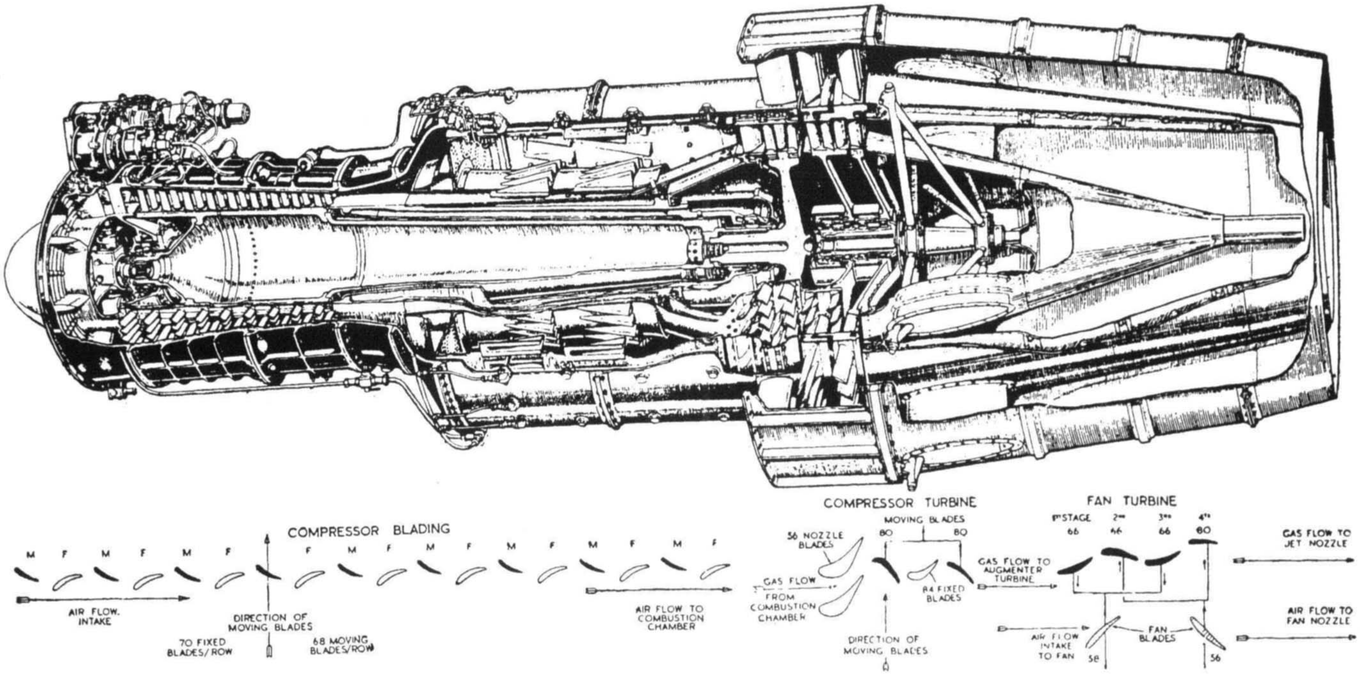
cast-iron skirt welded (often also screwed) to a domed steel crown. The sump sloped down to the rear, and all engines had scavenge pumps and separate oil tanks. The 1913 engine weighed about 209 kg and gave 100 hp at 1,300 rpm, with 14.78 litres from 140 × 160 mm cylinders. During the war this engine was increased in power in stages to 185 hp (Type IIIb), many thousands being made. The other mass-produced series (Type IVa) had 160 × 180 mm cylinders (21.7 litres) and was rated at 260 hp, usually for large bombers. Aero work ceased in 1919–26, subsequently being resumed as Daimler-Benz (*qv*).

Metrovick (UNITED KINGDOM) The Metropolitan-Vickers Electrical Company, of Trafford Park, Manchester, had a background of axial steam turbines when in August 1937 it was invited to build experimental gas-turbine parts by the Royal Aircraft Establishment. A.A. Griffith and Hayne Constant had pioneered axial compressors and turbines at the RAE from 1926, but real progress was made only after 1937 when – thanks to Whittle – the Air Ministry had at last begun to take gas turbines seriously. GEC and Parsons also received contracts for hardware, but Metrovick was the only non-aero firm to go on and produce complete engines. Its B.10 compressor first ran in December 1939, the drive turbine in May 1940 and the complete (clumsy) turbojet in October 1940. By this time the D.11 (Dora 11) shaft-drive engine had been tested, with a 17-stage compressor, but efficiency began to fall at pr above 2.02.

In July 1940 Metrovick put together a full design team under Dr D.M. Smith, with major roles taken by Dr I.S. Shannon and K. Baumann and helped by Constant. In July 1940 this team began development of the F.2 axial turbojet. Blading for the nine-stage compressor was designed at RAE; in 1941 this far outperformed the D.11 and in 1942 it maintained adiabatic efficiency of 88 per cent to pr of 3.2. The first F.2 ran in December 1941, and was the first non-German axial in the world. After many changes the third engine flew in the tail of Lancaster *LL735* on 29 June 1943. On 13 November



Above: The Metropolitan-Vickers F.3 aft fan was a pioneer engine based on Whittle concepts and Dr Smith's prowess with axial machinery. Note the interlinked turbine and fanstages. (Copyright Iliffe & Sons, 'Flight')

Below: The little Microjet 200 is powered by two Microturbo TRS 18 turbojets each of 247 lb thrust.

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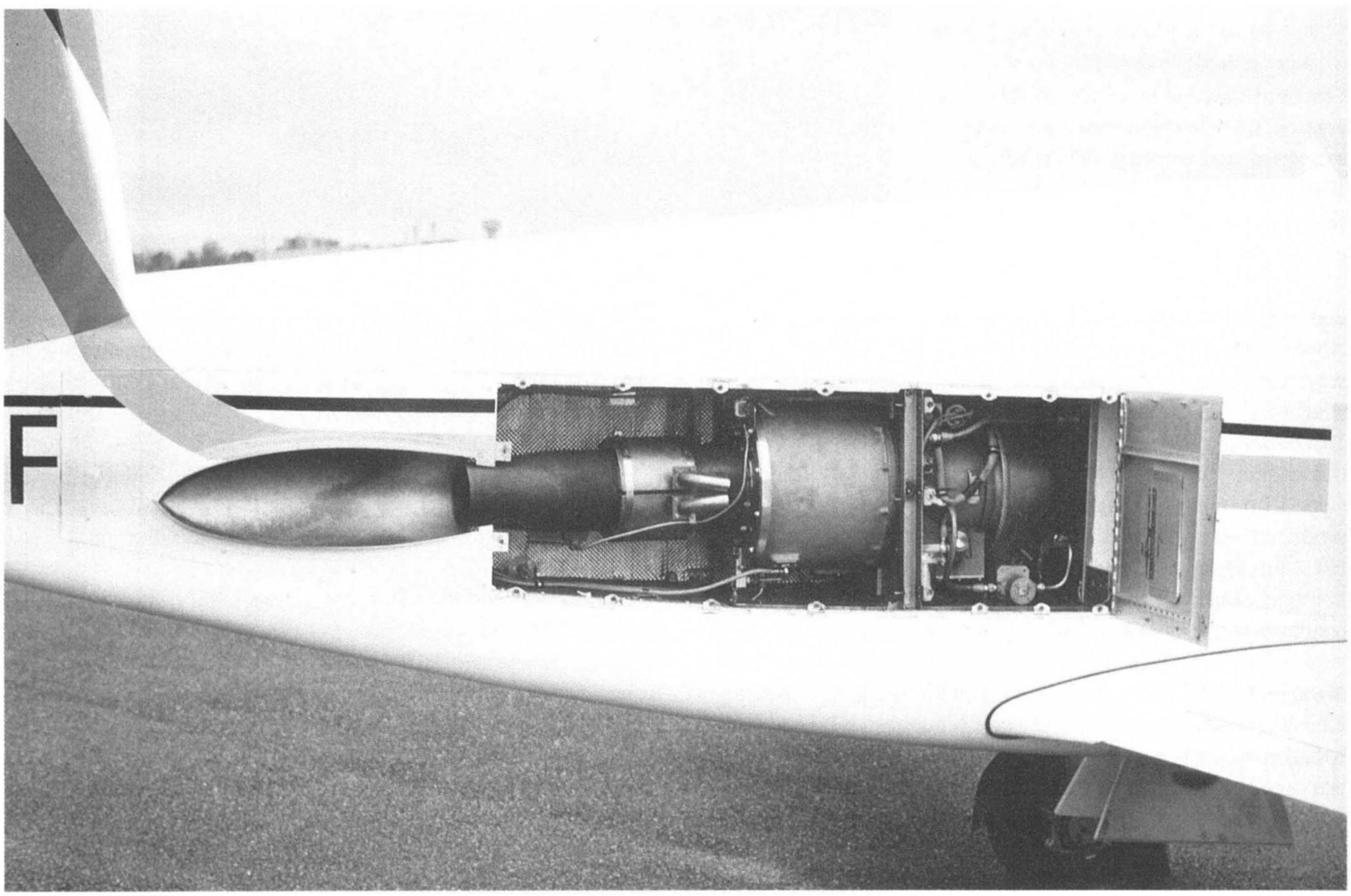


1943 two F.2s powered F.9/40 (Meteor) *DG204* on the first flight outside Germany of an axial-engined aircraft. Rating was then 1,800 lb, but after three redesigns the F.2/4 was built in small series in 1945 with a 10-stage compressor and thrusts of 3,500, 3,750 and 4,000 lb, weight being around 1,800 lb. The engine was named Beryl, first of a 'precious stone' series. Metrovick achieved promising results from August 1943 with the F.3, an F.2 with a thrust-augmenting ducted fan which boosted output from 2,400 to 4,600 lb. In 1945 the F.5 was run at 4,830 lb with a two-stage UDF (unducted fan), today reinvented by GE. In 1946 Smith began his masterpiece, the big F.9 Sapphire, with a disc-built compressor that was by a clear margin the best in the world at the time – the engine ran in April 1948. Perhaps short-sightedly the firm had decided in 1947, under Ministry pressure, to get out of aviation; the Sapphire was handed to Armstrong Siddeley.

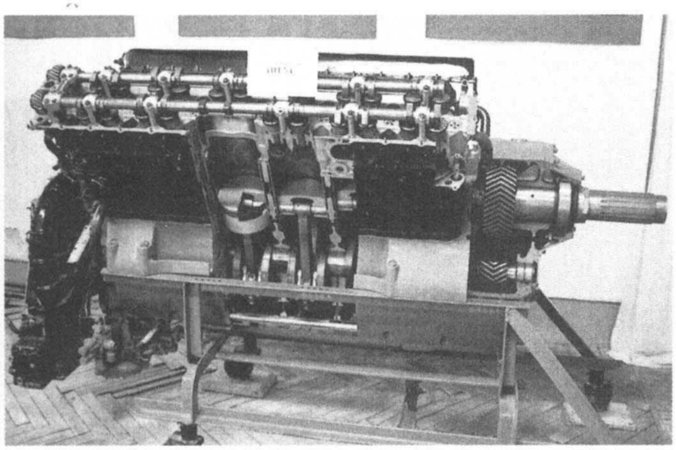
Microturbo (FRANCE) France appeared to have a near-corner in the market for small turbine engines with Turbomeca, but that company's engines are giants compared with Microturbo. Formed at Toulouse in 1960 to build tiny gas-turbine starters, this energetic firm has sold small gas turbines for almost every purpose. The TRS 18-046 was designed to give self-launch capability to gliders, but is also used in many twin-engined high-speed applications. A modular and very simple engine, it weighs 81.5 lb and gives a thrust of 225 lb at 45,000 rpm, but in 1991 Microturbo decided to pull out of manned-aircraft propulsion.

Mikulin (SOVIET UNION) Aleksandr Aleksandrovich Mikulin was one of the first engineers to work at NAMI (scientific auto motor institute), having been engaged in engine design since 1916. In 1925 he used Junkers techniques in the AM-13, a water-cooled V-12 qualified in 1928 at 880 hp at 2,150 rpm, and he collaborated with N.R. Brilling on the Soviet derivatives of the Jupiter, notably the two-row 18-cylinder M-18 which gave severe problems with the complex valve gear. More important was Mikulin's over-seeing the licensed BMW VI and its development into the M-17 family.

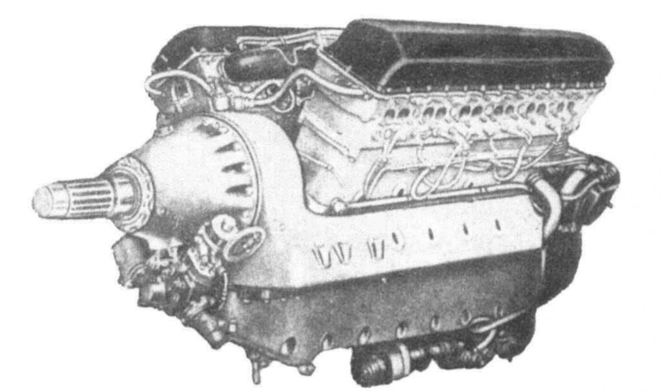
In parallel Mikulin studied available hardware and in 1930 obtained permission to design the AM-30 in an attempt to create the best V-12 possible. It used modified BMW VI cylinder blocks (160 × 190 mm cylinders, 46.7 litres), an HS12 rear wheelcase, Allison supercharger and RR Buzzard reduction gear. In 1931 it was qualified at 660 hp at 2,000 rpm. It was the starting point for a major series of large engines, the first production type being the AM-34 built in at least 14 versions between 1932 and 1939 with compression ratio 6.25, 6.6 or 7.0 and with powers 690 hp (34) to 930 hp (34R, F), 900 hp (FRN), 950 or 970 hp (R/RN) cr 7, 1,200 hp (FRNV) or 1,275 hp (RNF).

The AM-35 had a new cylinder head and improved supercharger, qualified in 1939 at 1,200 hp, the AM-35A reaching 1,350 hp. The AM-37 of 1940 reached 1,380 hp, or 1,400 as the 37F. Vast numbers were made of the AM-38 qualified in 1941 at 1,550 hp, later 1,665 hp, and the 38F of 1,700, 1,720 and 1,760 hp. In 1942 the AM-39 was qualified at 1,870 hp, followed by the FN-2 at 1,850 hp, the A at 1,900 and FB at 1,800. The family ended with the AM-42 of 2,000 hp, AM-43 of 1,950 to 2,200 hp, and AM-47 of 1946 of 2,700 to 3,100 hp (AM-47F).

Mikulin ended the war with great power, and opened a giant turbojet KB with Tumanskii as his deputy. Work began on the AM-01 (3,300 kg thrust) in 1948. The AM-2 was tested in 1953 at 4,600 kg. The AM-3 was a large but simple engine developed by P.F. Zubets' team, with an eight-stage compressor (135 kg/s, pr 6.4 at 6,500 rpm), thrust being 6,750 kg in 1952, 8,200 kg in AM-3M in 1954, 8,700 kg in AM-3M-200 and 9,500 kg in 3M-500; service designation is RD-3 and internal KB designation M-209. Many hundreds remain in use. The slim AM-5 was rated at 2,700 kg (3,040 with afterburner) but was not adopted. It was replaced by the improved M-205, or AM-9 (TsIAM designation), with nine-stage compressor (pr 6.3 rising in later versions to 7.14), annular combustor and



A cutaway Mikulin AM-34RN at Monino museum.



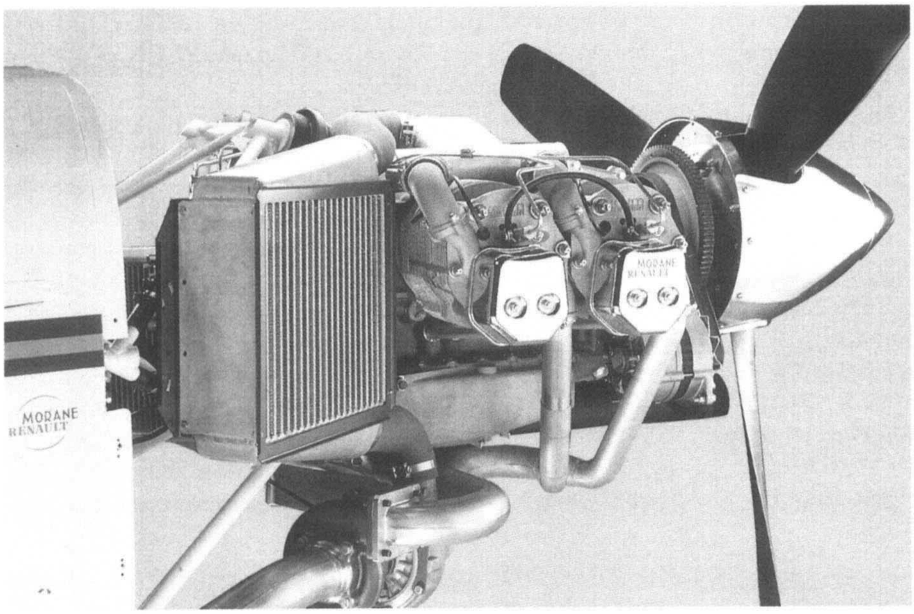
A.A. Mikulin became famous for his big and reliable V-12 liquid-cooled engines. This model, the AM-38F of 1,700 hp was one of the engines fitted to the Il-2 Stormovik, of which 36,163 were delivered.

two-stage turbine, diameter being 813 mm and thrust of production versions typically 3,300 kg with afterburner. This was picked for the Yak-25, and with afterburner for the MiG-19, but there was upheaval in the KB. Someone had 'informed' on Khrunichyev (aviation minister) and Stalin appointed a commission to investigate him.

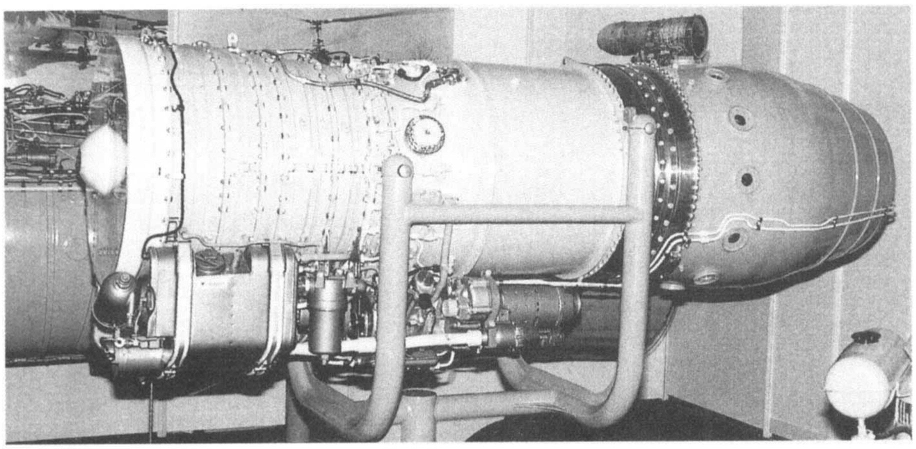
Mikulin did all he could do to incriminate the minister, who was arrested and might have been executed. Then Stalin died, Khrunichyev was set free and quickly settled the score by getting Mikulin blacklisted. The engines were all redesignated with RD numbers only, and the KB was led by Tumanskii from 1956 onwards.

Mitsubishi (JAPAN) This vast company was the first series producer of aero engines in Japan, and in the Second World War it ranked No. 1, with 38 per cent of gross national output of engines. Apart from a giant stillborn liquid-cooled unit, all were two-row radials with two-valve cylinders and very similar (and often interchangeable) features. In brackets are 1943 Army/Navy joint designations. The 14-cylinder engines were: Ha-6, 825 hp; Ha-26 of 900–950 hp and the related Zuisei and Ha-102 (Ha-31) of 875–1,080 hp; Ha-101 and related Kinsei MK8 and Ha-112 (Ha-33) of 1,280–1,560 hp; and the Kasei MK4 (Ha-32) of 1,460–1,850 hp. The 18-cylinder engines were the Ha-104 of 1,800–2,000 hp, the Ha-211 and related MK9 (Ha-43) of 2,200 hp and the Ha-214 and related MK10 of 2,400 hp. Some of the larger engines were developed in Ru (turbocharged) versions.

In 1952 MHI (Mitsubishi Heavy Industries) resumed aero work, supporting various US engines. It made modest numbers of JT8D and Allison CT63 engines, became a risk-sharing partner on the JT8D-200 and PW4000, and is a partner in IAE (*qv*). From 1987 MHI delivered 461 small turbojets to power missiles and targets. In 1993 testing began of the TS1 turboshaft engine. In August 1996 the Kawasaki XOH-1 helicopter began flight testing with two XTS1-10 engines each rated at 884 shp. The derived MG5 is a civil engine certificated at 800 shp in June 1997 to power MHI's own MH-2000 twin-engined helicopter.



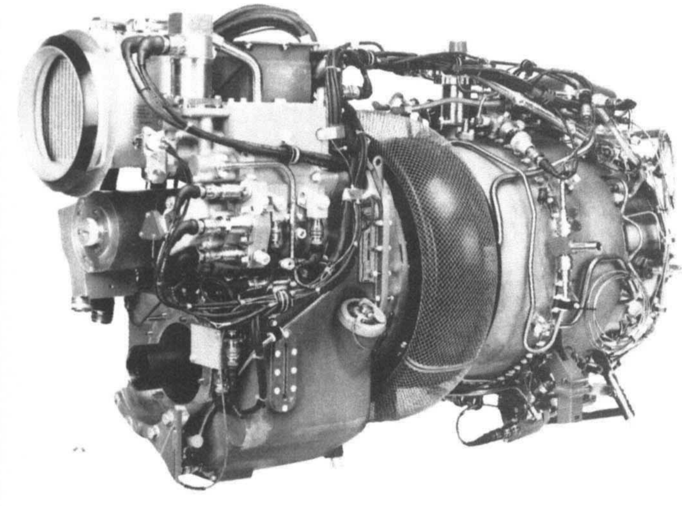
The Morane Renault is a new 5-litre piston engine with air/oil cooling and able to use jet fuel. Ratings are from 180 to 300 hp.



No other aero engine has ever been designed to keep running after suffering as much combat damage as Gavrilov's R-195, made by Motor, which powers later versions of the Su-25 attack aircraft.

The MTR390 turbo-shaft engine installed in the Eurocopter Tiger (in France, Tigre).

The MTR 390 is now in production for the Tigre, Gerfaut and UHU (an acronym, not German for owl). Air enters through the mesh screen round the centre, and the drive shaft is the black unit at lower left.



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Morane Renault (FRANCE) Developed by the SMA (Société de Motorisations Aéronautiques), this brilliant family of piston engines comprises the MR 180, MR 250 and MR 300. The figures denote take-off horsepower. All have four cylinders totalling 5 litres (305 cu in), the 250 and 300 having reduction gears. All give 70 per cent power at 25,000 ft, but their biggest advantage is that they can operate on jet fuel. All three have now been certificated.

Motor (RUSSIA) Based at Ufa, in Bashkortostan, alongside the vast UMPO production plant, GNPP Motor began by developing the R13 fighter engine designed by Sergei A. Gavrilov. Rated with afterburner at 14,300 to 14,550 lb, it powered MiG-21 and Su-15 versions, 12,500 being delivered in 1968–85. The R25 powered later versions of the same fighters, 3,200 being delivered. The R95 and R195 were simple turbojets in the 9,500 lb class designed to survive hostile fire in the Su-25.

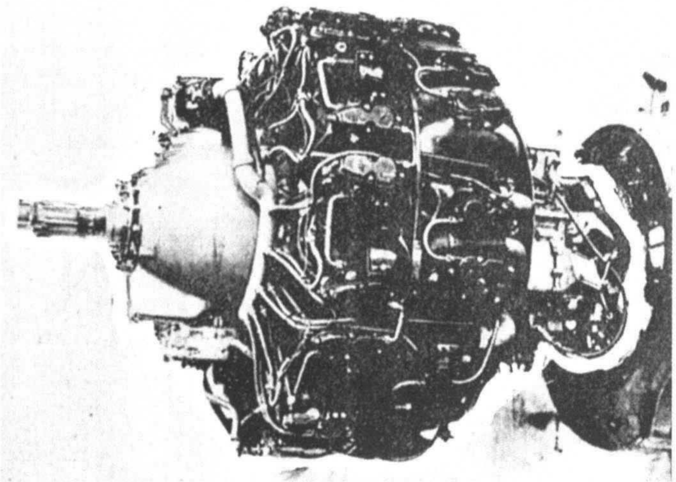
MTR (INTERNATIONAL) To power the Franco-German Eurocopter Tigre and Gerfaut armed helicopters, MTU of Germany, Turbomeca of France and Rolls-Royce of the UK are producing the MTR 390. This has tandem centrifugal compressors and has a contingency rating of 1,556 shp for a weight of 373 lb.

MWAE (UNITED KINGDOM) Mid West Aero Engines took over two engines designed by others. The MWAE75 is the former Hewland three-cylinder piston engine of 77 hp used in the Super2 light aircraft. The MWAE100R is the former Norton twin-rotor (Wankel-type) engine, rated at 100 hp for a weight of 115 lb.

N

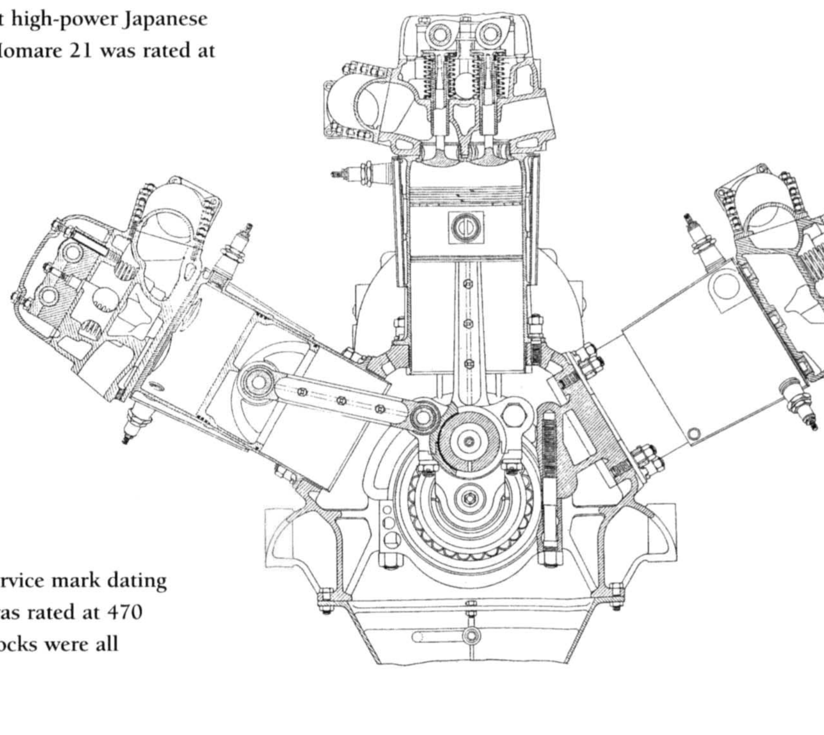
N

Nakajima (JAPAN) Established in 1914, Nakajima built large numbers of Bristol Jupiter and Lorraine engines in 1927–38 and developed the Ha-1 Kotobuki of 550–785 hp from the Jupiter. In the Second World War it ran a close second to Mitsubishi in engine production, and it was easily 'No. 1' in 1944–5. Main engines were: nine-cylinder radials, the Ha-1 already mentioned, Ha-8 and Hikari of 700–840 hp, Ha-20 of 730–820 hp and Ha-26 of 900 hp; 14-cylinder radials, Ha-5 of 950–1,080 hp, Sakae NK1/Ha-25/Ha-102/Ha-105/Ha-115 of 950–1,230 hp, Ha-109/Ha-34 of 1,300–1,500 hp, Ha-41 of 1,260 hp, Mamoru NK7 of 1,800–1,870 hp and Ha-117 of 2,420 hp; 18-cylinder radials, Homare NK9 (Ha-45), Ha-44/NK11 and Ha-145 (all with Sakae-size 130 × 150 mm cylinders, giving 32 litres) of 1,800–2.400 hp, and Ha-217/Ha-46 of 3,000 hp; and the Ha-505 with four nine-cylinder rows and rated at 5,000 hp. After 1945 the company became Fuji, building airframes only.



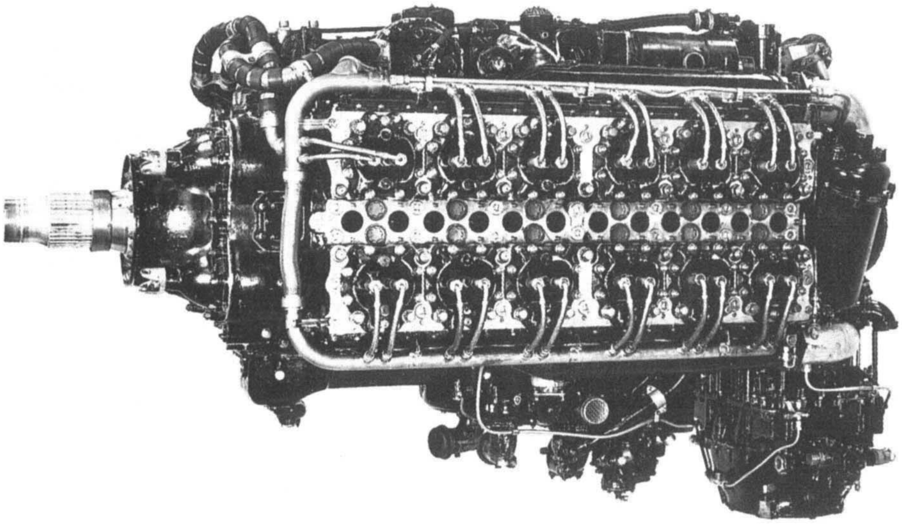
The Nakajima Homare was the most important high-power Japanese engine of the Second World War. This NK9H Homare 21 was rated at 1,990 hp.

Napier (UNITED KINGDOM) David Napier came from Scotland to London in 1808 to make printing machines. D. Napier & Son Ltd moved to Acton in 1903, became famous for its cars and from 1915 made RAF.3a and Sunbeam Arab engines. In 1916 Montague Napier began working with chief designer A.J. Rowledge on the design, at company expense, of a completely new engine. The result was the Lion, a masterpiece. First run in April 1917, it was a water-cooled W-12, or broad-arrow engine, with three banks of four 5.5 × 5.125 in cylinders (1,461 cu in) spaced at 60°. The closely spaced steel cylinders were spigoted and flange-bolted into the aluminium crankcase, with integral combustion heads and steel water jackets welded on. Each row of four cylinders was capped by a monobloc aluminium head secured by screwing into it the seats for the two inlet and two exhaust valves for each cylinder, each head containing the inlet/exhaust ports, water passages and five bearings for the twin overhead camshafts. The vertical cylinders had master rods, working on the short and almost unbreakable crankshaft, the other cylinders having auxiliary rods pivoted to the masters by tapered wrist pins. From the start it was a magnificent engine,

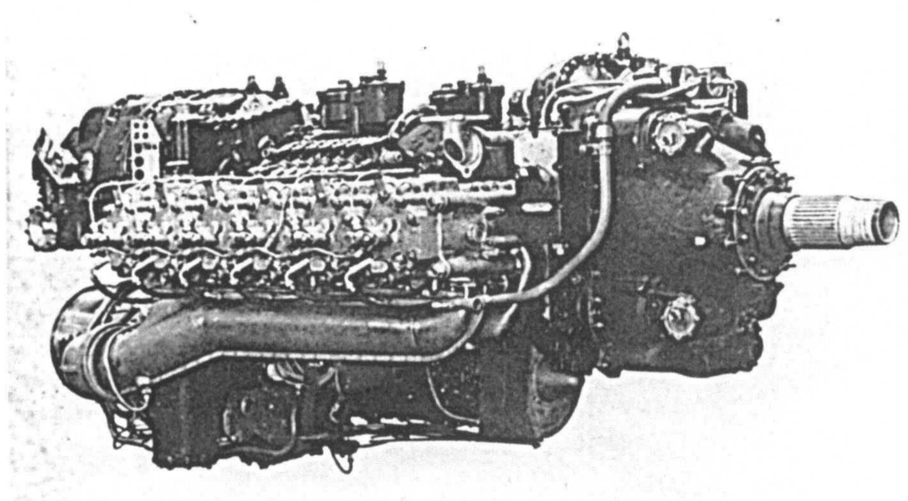


Cross-section of a Napier Lion IIB, a typical Service mark dating from December 1923. It weighed 966 lb and was rated at 470 hp at 2,000 rpm. Cylinders in the three 60° blocks were all aligned, though one has not been sectioned.

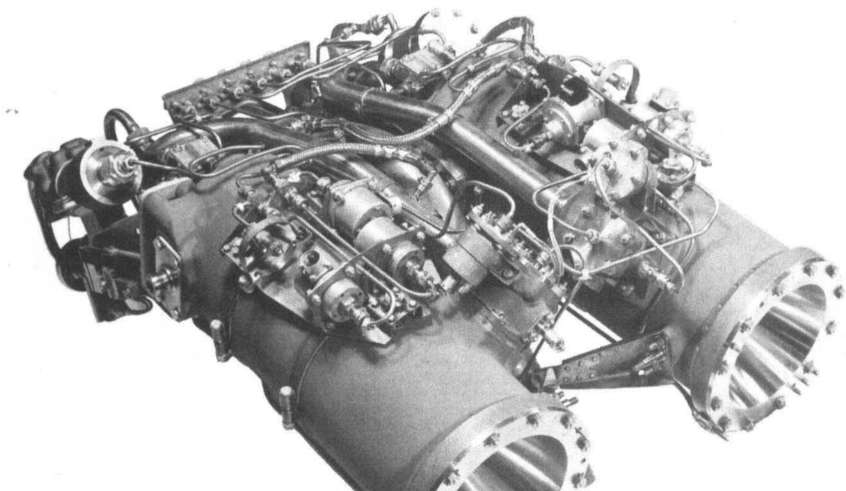
N



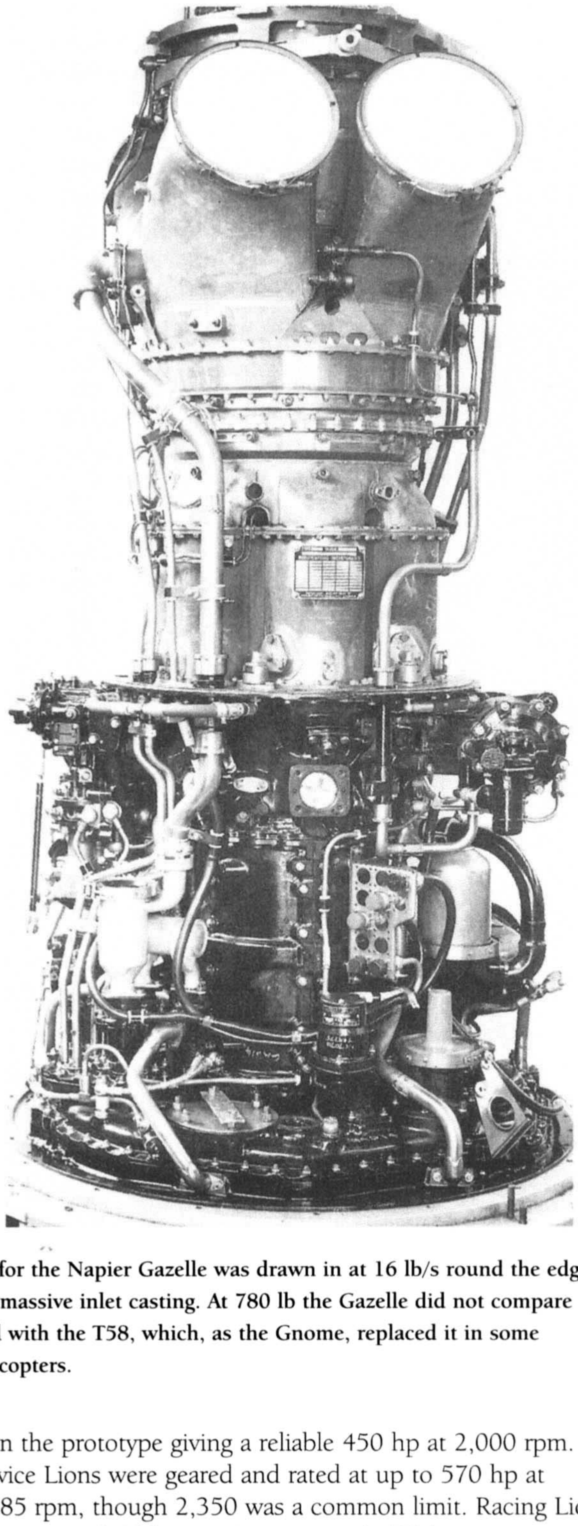
The author never flew with a Napier Sabre but will never forget the sound of Typhoon squadrons. As sheer packages of engineering this engine was impressive. This was the initial production Mk II of 2,400 hp.



The Napier Nomad passed through two very dissimilar development stages. This was the second, simplified version, with the diesel and gas turbine both geared to the same propeller shaft.



Napier's Double Scorpion was one of many rocket engines that never got into production, though this peroxide/kerosene package did thrust a Canberra to 70,310 ft in August 1957.



Air for the Napier Gazelle was drawn in at 16 lb/s round the edge of the massive inlet casting. At 780 lb the Gazelle did not compare very well with the T58, which, as the Gnome, replaced it in some helicopters.

even the prototype giving a reliable 450 hp at 2,000 rpm. Most service Lions were geared and rated at up to 570 hp at 2,585 rpm, though 2,350 was a common limit. Racing Lions ran at up to 3,900 rpm, giving up to 1,400 hp.

The company's utter complacency sapped the morale of its few designers, and inevitably the Lion became uncompetitive after 1930, though Sea Lions for RAF rescue launches stayed in production to 1943. In 1923 there was a stillborn attempt to get the Lioness, an inverted Lion, into RAF fighters because of the improved pilot view it offered. In 1919 Montague Napier – at that time actually looking beyond the Lion – got Air Ministry backing for an engine of 1,000 hp, the Cub. This had four banks of four cylinders bigger than the Lion's arranged in the form of an almost flat-bottomed X. Six were built, but the market was not ready.

To try to reverse its decline Napier got Halford in 1928 to design a range of small-cylinder engines of only 404 to 718 cu in capacity. The result was a series of unusual engines of H configuration. These began with the Rapier, with 16 air-cooled cylinders of 3.5 × 3.5 in size (538.8 cu in) arranged in four vertical rows driving side-by-side crankshafts, output of production engines being 340 hp. The Javelin inverted six-in-line of 160–170 hp hardly penetrated the market, but the Dagger almost saw major production. An enlarged Rapier, with 24 cylinders 3.8125 × 3.75 in (1,027 cu in), it ran at 635 hp in 1934 and was cleared for production in 1936 at 1,000 hp at 4,200 rpm, though for reasons of reliability and maintainability it soon faded from the scene. All these air-cooled engines were fully supported by the Air Ministry, though none was needed.

In 1935 the Air Ministry fell for a proposal that Napier should build a 'Hyper' engine running at high rpm with many small but highly rated cylinders, the output being 2,000 hp. Halford thus created the Sabre, adopting the flat-H configuration with liquid-cooling and sleeve valves. The engine comprised upper and lower light-alloy blocks each with 12 opposed cylinders 5 × 4.75 in (2,238 cu in) each with three inlet and two exhaust ports, and four-port sleeves based on Bristol practice. At the rear was the two-speed supercharger and a four-choke updraught carburettor which in most Sabres was of the injection type. On top was the Coffmann cartridge starter and other accessories. A compact engine distinctive for its thrilling high-rpm sound, the Sabre ran in 1937 and was type-tested at 2,200 hp in 1940, but suffered many prolonged problems. In retrospect the gigantic effort put into it would have been better applied elsewhere, but by 1944 it was becoming reasonably reliable with ratings up to 3,055 hp at 3,850 rpm for a weight of 2,540 lb.

By this time chief engineer Ernest Chatterton was busy with the ultimate in economical engines for long-range operation, the Nomad. As first run in 1950 the E.125 Nomad comprised a liquid-cooled flat-12 diesel with big 6 × 7.375 in cylinders (2,508 cu in) with valveless two-stroke operation, supercharged by an axial and centrifugal compressor in series, with inter-cooler. The crankshaft drove half a contraprop and an exhaust gas turbine the other half, and for maximum power a reheat chamber and auxiliary turbine were brought in. With much flame and backfiring the power was 3,125 ehp (3,000 shp) for a weight of 4,200 lb. By 1953 the engine had been simplified into the E.145 with the centrifugal compressor, reheat chamber and auxiliary turbine eliminated, drive to a single propeller being by the crankshaft, the gas turbine being linked through a variable-ratio Beier gear. Power went up to 3,135 ehp (with water injection, 4,095 ehp) and weight fell to 3,580 lb. Though sfc set a new low at only 0.345 this engine remained a near miss, and the Shackleton stayed with the Griffon.

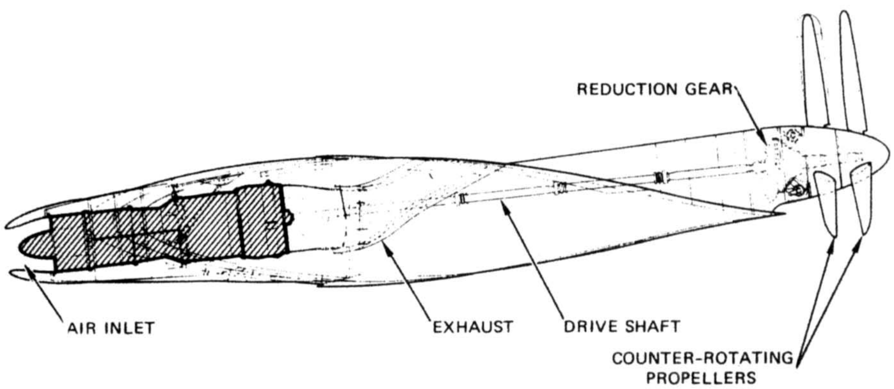
N

Gas turbine

Meanwhile, Napier had got into gas turbines under A.J. Penn and Bertie Bayne. The 535-hp Nymph was dropped, and so after years of work was the l,600-ehp Naiad and its coupled version, but the Eland ran on for nine years (1952–61). Its 10-stage compressor had blades of aluminium-bronze (DTD.197) as did the other Napier gas turbines, and it was on the same shaft as the propeller gearbox, all driven by a three-stage turbine. Starting at 3,000 ehp (2,690 shp) it grew in 1955 to 4,200 ehp with air-cooled blades, and the E.151 (NEl.3) with auxiliary compressor powered the Rotodyne convertiplane. Of the Oryx gas generator for the Percival P.74 tip-drive helicopter the less said the better, but the Gazelle did at last find a real market as an any-attitude free-turbine engine for helicopters. First run in December 1955 at 1,260 shp, it had an 11-stage compressor, six flame tubes and 2 + 1 turbine stages, production engines giving up to 1,790 shp. D. Napier & Son also produced ramjets and rockets, but in 1960 was divided, Napier Aero Engines Ltd becoming a subsidiary of Rolls-Royce in 1962 and soon losing its identity.

Northrop (USA) When John K. Northrop founded his own company in August 1939 his head of research was Vladimir Pavlecka, a Czech, who managed to convince Northrop that in the long term gas turbines would replace piston engines. After much in-house study an Army/Navy contract was obtained in June 1941 for design plus tests of the compressor for an engine of 2,400 hp. In 1942 Pavlecka had a row with the great aerodynamicist Von Kármán and left. His replacement was an Englishman from General Motors, Art Phelan, who pointed out that to drive the compressor needed 7,000 hp and that it made sense to build the whole engine. On 1 July 1943 two engines of 3,800 hp were contracted for, and one of these was the first US turboprop to run complete with propeller in December 1944.

Named Turbodyne, the engine was then scaled up to meet Army needs, and the XT37 was designed in 1945 for 4,000 hp at 35,000 ft for future bombers. Three engines were running in 1947 and achieved sea-level power rising from 5,150 to 8,000 hp in six months. By 1949 the XT37 with 14-stage compressor (pr 7.5) and two-stage turbine was giving 10,400 hp at only 815°C, developed by the Northrop-Hendy partnership owned 50-50 with the Joshua Hendy Iron Works. Perhaps short-sightedly the USAF cancelled the EB-35B testbed in October 1949, effectively terminating the project, entirely because Pratt & Whitney had shown that the B-52 could be a jet.

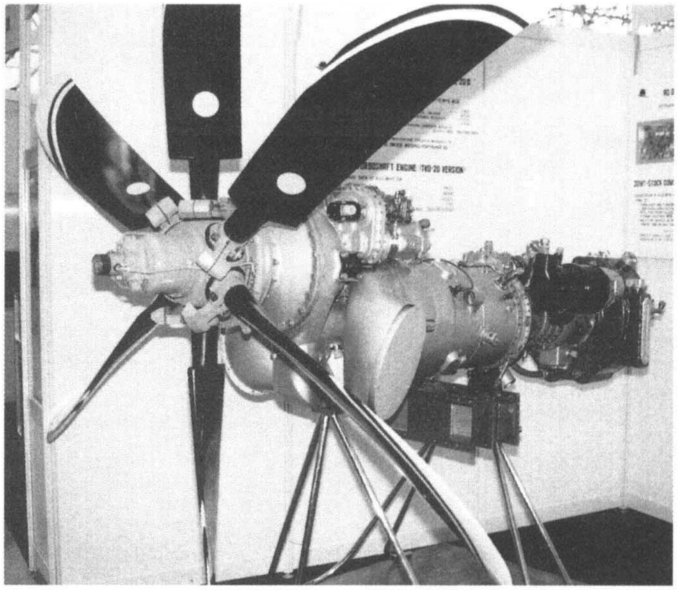


Had the Northrop B-35 flying-wing bomber gone into production it would probably have been powered by the Turbodyne in the installation seen here.

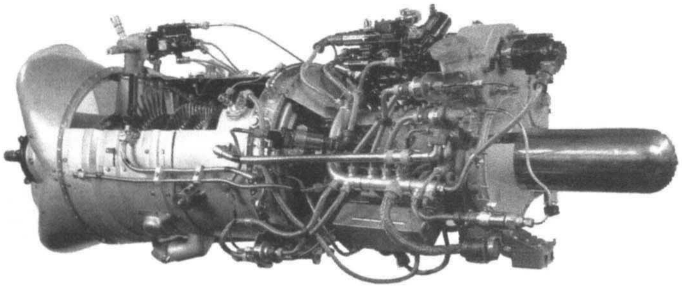
O

O

OMKB (RUSSIA) The Omsk Engine Design Bureau opened in 1956. Headed by V.A.Glushenkov, followed by P.I. Baranov, its first task was to produce the GTD-3, a robust turboshaft initially of 900 shp, to power the Ka-25 family of helicopters. The derived TVD-10 turboprop was made under licence by PZL-Rzeszów in Poland as the PZL-10W. In the 1970s the 1,450-shp TVD-20 appeared, retaining the reverse-flow layout with air entering at the rear and flowing forward through seven axial stages and a centrifugal. Production of thousands to convert An-2s into An-3s never happened. Again, mass markets have eluded the all-new TV-O-100, turboshafts and turboprops in the 700-shp class, developed jointly with AMNTK Soyuz.

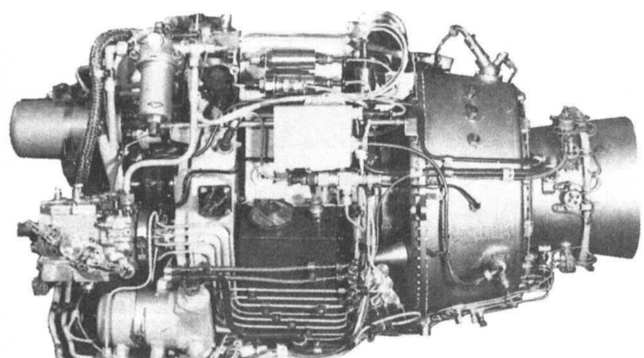


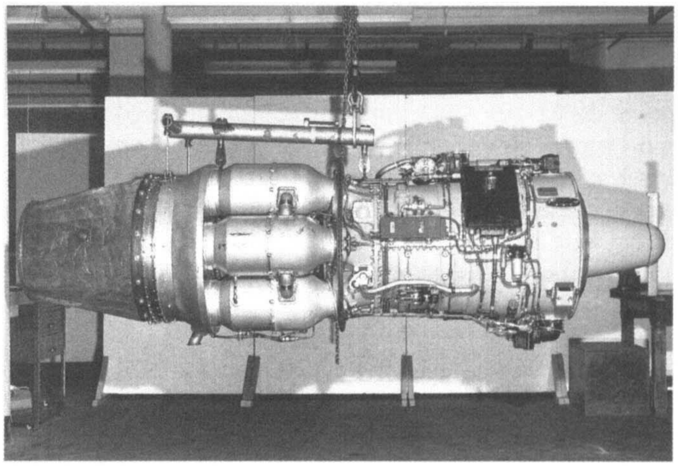
A display model of the Mars (Glushenkov) TVD-20, complete with AV-17 propeller.



A cutaway Polish-built PZL-10W helicopter engine.

Designed by Kobchyenko (Soyuz), the OMKB TV-O-100 is later expected to reach 830 shp.

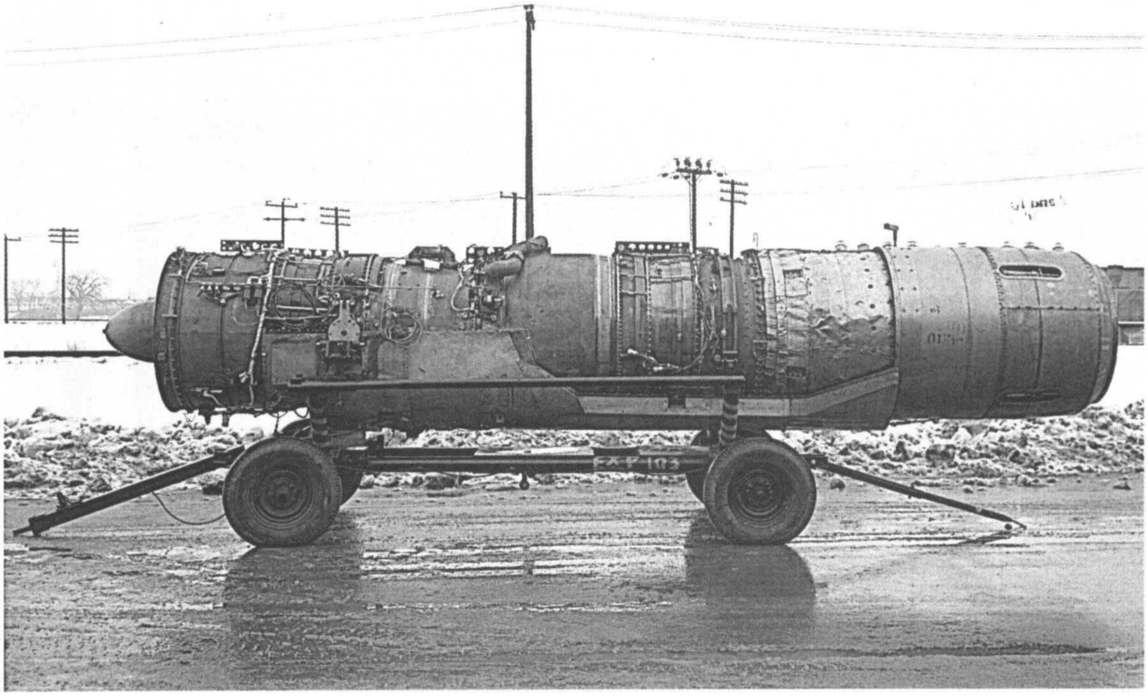




The Orenda 11 powered the main run of CF-100 all-weather interceptors, the Mks 4 and 5. Note the free-spinning alcohol de-icer windmill on the bullet nose.

Orenda (CANADA) In 1945 Hawker Siddeley purchased the wartime Victory Aircraft plant at Malton, Toronto, and formed Avro Canada, which in 1946 took over Turbo Research, a nearby government gas-turbine laboratory. Under chief designer Winnett Boyd the Chinook axial turbojet was designed, and run on 17 March 1948. This had a nine-stage compressor, six cans and one-stage turbine, and gave 2,600 lb thrust, later 3,000. It assisted design of the Orenda, under chief engineers Paul Dilworth and then C.A. Grinyer. The Orenda, which gave its name to the vastly expanded Orenda Engines Ltd in early 1956, was an enlarged Chinook with a 10-stage compressor.

The Orenda 1 ran in February 1949, leading through various marks to the Orenda 9 and 10. These had airflow of



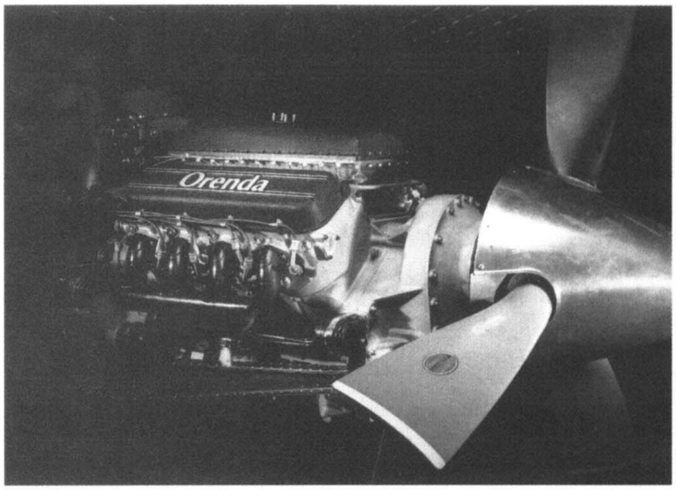
Outside the Soviet Union the Orenda Iroquois was perhaps the greatest turbojet of the 1950s. This 1958 development engine, complete with afterburner, is seen en route to the testbed.

First run in 1995, the Orenda OE600 is the most powerful aircraft piston engine recently under development. Sadly it has been shelved.

106 lb/s, pr 5.5 and thrust 6,500 lb. The Mk 9 had an alcohol spray fan on the nose bullet and could be installed in a CF-100 in either left or right position; the Mk 10 fitted the Canadair Sabre. The Orenda 11 and 14 were the corresponding versions with a new two-stage turbine, reducing weight to 2,430 lb and increasing thrust to 7,500 lb at 7,800 rpm.

In 1953 design began on the totally new PS.13 Iroquois to power the CF-105 Arrow. An outstandingly advanced two-spool supersonic engine, this had 300 lb/s airflow, was made largely of titanium (long before any other engine) and housed accessories in a pressurised sealed box. Many aspects of the design were far in advance of normal practice. First run was on 15 December 1954, and first flight (B-47 rear fuselage pod) in 1956. Ratings then were 19,250 lb dry and 27,000 lb with full afterburner, weight being 4,120 lb. This superb engine was cancelled along with the Arrow on 20 February 1959. Orenda practically vanished, until 1966 when Orenda Ltd was formed, owned 60/40 by Hawker and United Aircraft.

For many years Orenda's main aero work was to support General Electric J85 turbojets, which it had made under licence to power CF-5 fighters. In 1996, as Orenda Aerospace Corporation, the company celebrated its 50th anniversary (of Avro Canada, see above). By this time work was well advanced on an impressive new aluminium-block V-8 piston engine with dual turbochargers, the OE600. With liquid-cooled cylinders 4.433 in bore and 4 in stroke, capacity is 495 cu in (8.11 litres). Dry weight with accessories is 750 lb, and output is 600 hp at 4,400 rpm, with propeller speed 2,075 rpm. The only evident shortcoming of this outstanding engine is that it uses 100LL gasoline. Estimated fuel burn at 325-hp cruise is 25 US gal/h. The engine first flew in a King Air on 11 July 1997, giving dramatic gains in performance. Later that year both the OE600 and normally aspirated OE500 entered production at a refurbished plant at Truro, Nova Scotia. There were numerous applications, mainly replacing turboprops and older piston engines, but in 2005 the work was halted because of 'a market downturn'.

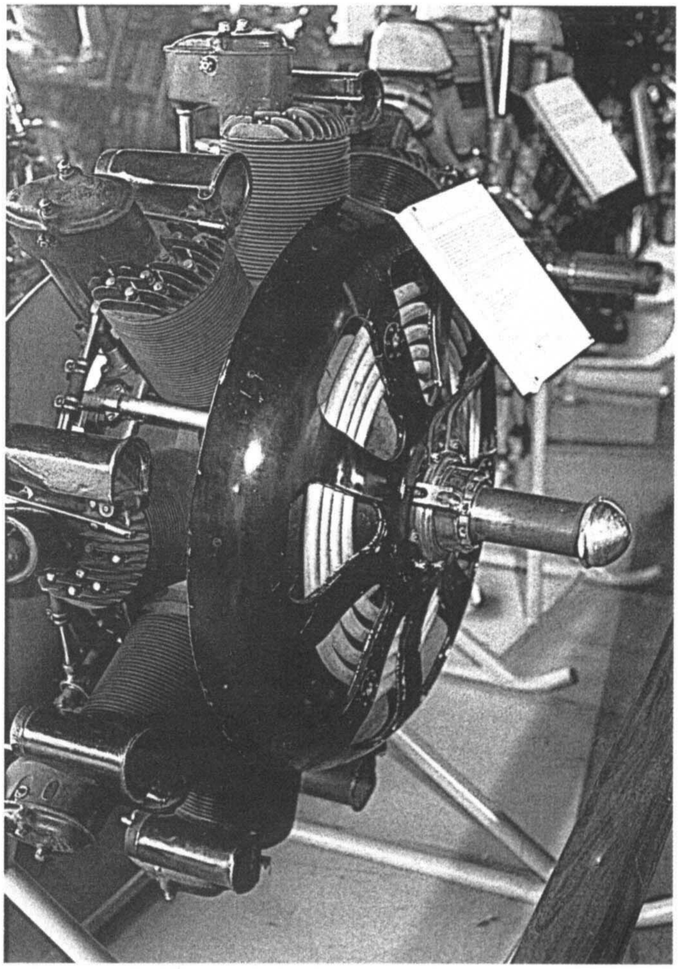


P

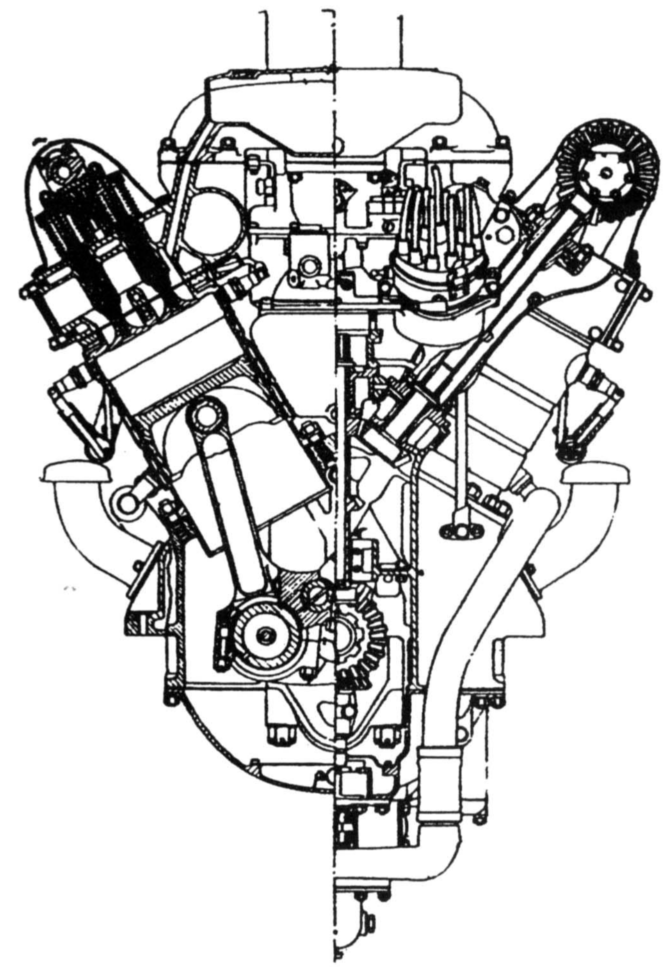
P

Packard (USA) Jesse Vincent built a 905 cu in V-12 of 250 hp in 1917 and used features of this in the Liberty. After the war his company naturally used the Liberty as starting point for its A-1500 and A-2500 V-12s, the designations giving the displacements in cubic inches, with typical ratings of 520 and 750 hp. In 1926 two X-2775s (basically an X-24 using 1,500 cu in cylinders with shorter stroke) were built on Navy contract for the Schneider Trophy, giving over 1,250 hp, but aircraft float trouble prevented them from reaching the start line.

In 1927, partly motivated by the Wasp, the US Navy said it would henceforth buy air-cooled engines exclusively, and Packard then fell out with the Army as well on matters of policy. The company abandoned the military market and got chief engineer Captain Lionel Woolson to develop a nine-cylinder radial diesel, the DR-980. In 1930 this was certificated at 225 hp at 1,950 rpm for a weight of 510 lb, but its smell and vibration proved insuperable drawbacks. It did, however, set an unrefuelled duration record of 84 h 32 min (Bellanca, 28 May 1931). In the Second World War the company mass-produced the Merlin as the V-1650, one of which, very carefully uprated, holds another record – for piston-engine speed at 517.06 mph.



Captain Woolson and a German engineer, Prof Herman Dohner, designed the world's first practical aircraft diesel engine, the Packard DR.980, first run in 1928. The arrangement of direct air inlets on one side of the cylinder head with exhaust to the rear on the other side, was followed in the Guiberson of two years later. The DR-980 established a fuel cost of 1 c/mile in many aircraft; sadly Woolson was killed (in a diesel Verville Air-Coach) through no fault of the engine.



Transverse section through the Packard 3A-2500. With a capacity of 2,540 cu in, and weight of 1,425 lb, this geared version was rated at up to 800 hp.

Perm (RUSSIA) The Perm Engine Company makes engines designed by neighbouring Aviadvigatel, except for the D-30KU which was made at Rybinsk.

Piaggio (ITALY) This company obtained licences to build the Jupiter in 1928 and Gnome-Rhône radials in 1930, using these as the basis for a family of radials with 7, 9, 14 and 18 cylinders. Most had Mercury-size cylinders 146 × 165 mm, and all were named Stella. Examples were the P.VII (seven-cylinder) of 400–510 hp, the P.IX, P.X and P.XVI (nine-cylinder) of 625–700 hp, the P.XI and P.XIUV (14-cylinder) of 700–1,100 hp, and the P.XII and P.XXII (18-cylinder) of 1,500–1,700 hp. Since 1953 the company has made Lycoming and Rolls-Royce engines under licence.

Pobjoy (UNITED KINGDOM) Douglas R. Pobjoy was perhaps the only proprietor in the jealousy-ridden British industry between the wars to be liked by everyone. He designed a series of beautifully engineered small radials from 1926, forming Pobjoy Airmotors & Aircraft Ltd in 1930. All his production engines had seven cylinders and ran at high rpm, with spur gears to a propeller shaft above the crankshaft. First came the Pobjoy P, run in 1927 and type-tested in 1928. Of only 25 in diameter, it had cylinders 2.385 × 3.425 in and gave 65 hp at 3,000 rpm. Next came the R, later named Cataract, with bore increased to 3.0625 in, giving 75 (later 80) hp at 3,300 rpm. In 1934 came the Niagara, with enclosed valve gear and other refinements, rated at 95 hp at 3,650 rpm (Niagara III), followed in 1937 by the Niagara V with bore further increased to 3.21875 in (192 cu in) to give 130 hp at 4,000 rpm. Pobjoy went public in 1935, Short Brothers buying a controlling interest in 1936. Pobjoy designed the world's first APUs and auxiliary gearboxes, made by Rotol, and was designing his first postwar engines when he was killed in an air crash in 1947.

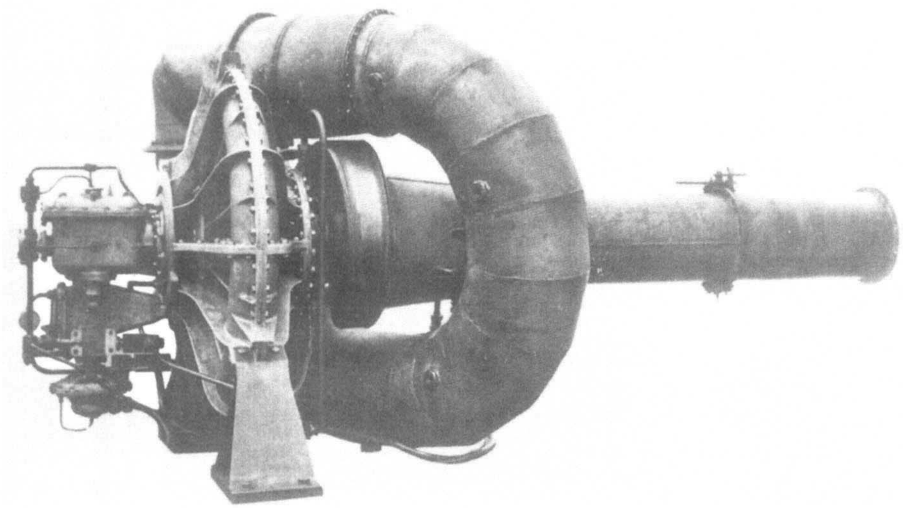
One of the first major applications for the Pobjoy R (Cataract) was the Comper Swift, made, like the engine, at Hooton Park, Cheshire. Extremely quiet, the engine was geared down to a big (78 in) propeller.

Porsche (WEST GERMANY) While ordinary 911S engines power Airship Industries Skyships, driving ducted reverse-pitch propellers, the great Dr Porsche's company has in recent years spent much money developing a derived engine purely for aircraft. A four-stroke flat-six with air-cooled cylinders of 74.4 mm stroke and 95 mm bore, giving capacity of 3.2 litres, the PFM 3200 was marketed in several versions rated at 212–41 hp, but in 1988 the company cancelled its plans to power aircraft.

Potez (FRANCE) This prolific aircraft company formed an LEM (engine design laboratory) in 1928, subsequently producing a range of three-, six- and nine-cylinder radials originally derived from Anzanis. In 1935 Henri Potez planned a range of four-, eight- and 12-cylinder inverted engines all using the same air-cooled two-valve cylinder of 125 × 120 mm. The 4-D ran before the war, but marketing did not begin until the company was reformed in 1949, with works at Argenteuil. The 12-D never went into production but a 6-D was added, this being the first with direct injection (305 hp supercharged, the supercharger lying flat on top of the engine). Biggest of the range, the 8-D 30 was geared and rated at 500 hp at 2,650 rpm. In 1963 the company was acquired by Avco and its dwindling aero-engine business terminated.

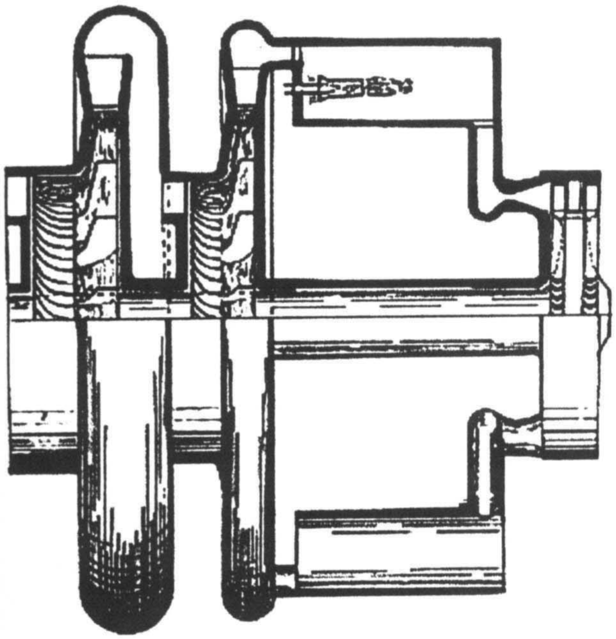
PowerJet (INTERNATIONAL) In 2000 Snecma of France and Saturn of Russia began discussing how they could create an entirely new turbofan in the 16,000-lb class to power the planned RRJ (Russian Regional Jet). At first called Smartec, the firm was renamed in July 2004, the engine becoming the SaM146. Boeing is assisting with marketing, though the RRJ is pretty close to early 737s. RRJ certification has slipped from 2004 to 2008.

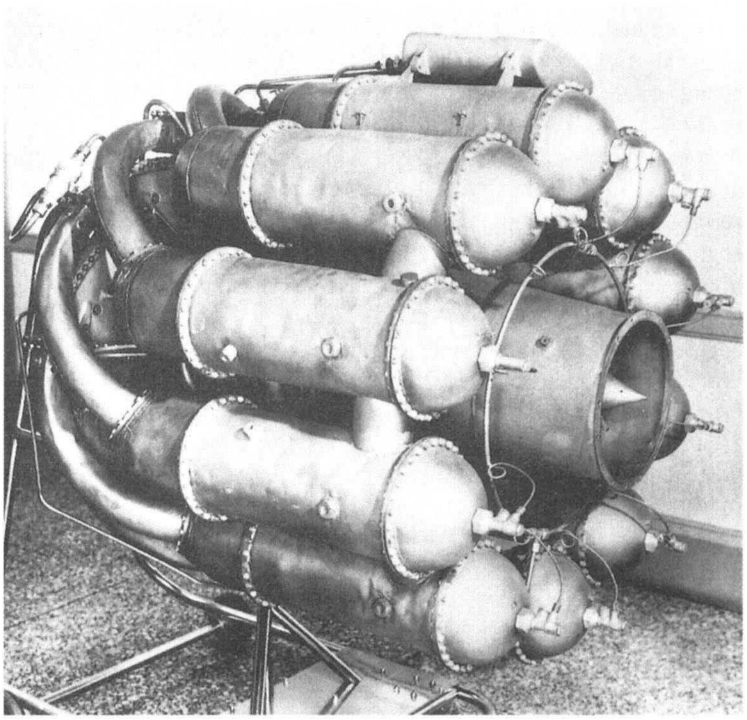
Power Jets (UNITED KINGDOM) In 1928 Flight Cadet Frank Whittle wrote a thesis at the lately opened RAF College in which he described how gas turbines and jet propulsion would free aircraft from the existing limitations on flight performance. In January 1930 he was awarded the first patent for a turbojet, but despite his reasoned pleading neither Air Ministry nor British industry showed the slightest interest. In May 1935 he was approached by former Cadet R.D. Williams and



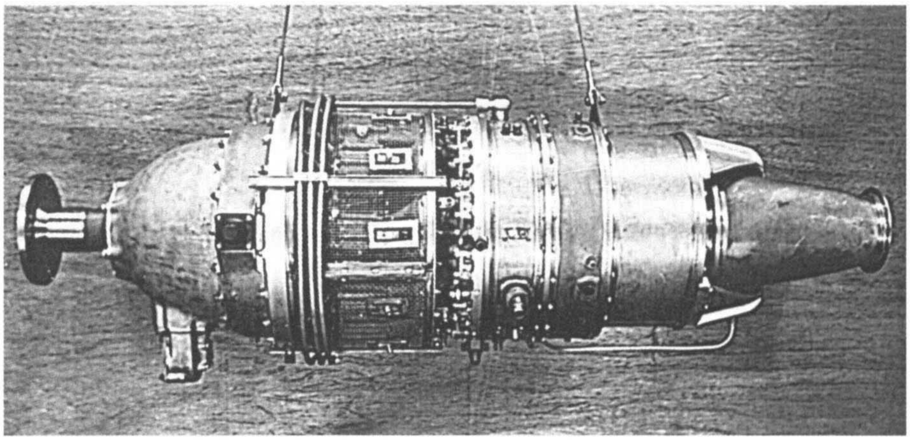
Left: Known as the WU, from Whittle Unit, this famous engine was the first true aero gas turbine in the world to run. To Britain's shame it no longer exists, even in a much-rebuilt form.

Below: This was the actual Power Jets W.1X which was shipped to the USA on 1 October 1941. It was the only bench engine Whittle had at that time. Inlet out of sight at left, reverse-flow cans fed by long curved pipes, and jetpipe attached on right.





Above: Whittle's 1929 patent drawing.



Right: Britain threw away this Power Jets turboprop because 'nobody wanted it'; later an almost identical engine (the Canadian PT6) found 6,000 different customers.

J.C.B. Tinling, who got bankers O.T. Falk & Partners (after a favourable independent assessment by M.L. Bramson) to put up capital for Power Jets Ltd, formed in March 1936. BTH (British Thomson-Houston) were contracted to produce sets of drawings, and in June 1936 a contract at cost plus was placed for most parts of the WU turbojet. Ideally many sets of major components would have been made and tested individually, but with practically no money or resources all that could be done was build a single complete engine. Even then, while the double-sided centrifugal compressor and single-stage axial turbine were far beyond all previous experience, the requirements for the combustion chamber exceeded normal practice by a factor of more than 25. Whittle visited the British Industries Fair and was practically laughed off every stand until he found in Laidlaw, Drew & Company a firm at least prepared to tackle the colossal problem.

The first engine was ready on 12 April 1937, after total expenditure of about £3,000. On the first run Whittle opened the main fuel valve at about 2,300 rpm. At once the unit accelerated away violently out of control, the combustion chamber suddenly glowing bright red in places and the engine emitting a giant rising shriek like an air-raid siren. This happened persistently, each time causing a rapid exodus by all save Whittle, who finally realised that overnight pools of kerosene were collecting in the chamber and on each test the engine ran away until this pool had been consumed. This and hundreds of other problems progressively reduced the U engine to 'a running heap of scrap', but it was the only Whittle engine in existence until the first run of the greatly improved W.1X on 14 December 1940, this time with a little Air Ministry money. The incredibly myopic official view changed in summer 1939 to a surprised belief that Whittle might have the basis for a practical engine, and a contract was placed for a flight engine, the W.l, and the Gloster E.28/39 aircraft. The W.1 ran on 12 April 1941 and the E.28 flew on 15 May, the engine giving 850 lb at 16,500 rpm, for an installed weight of 623 lb.

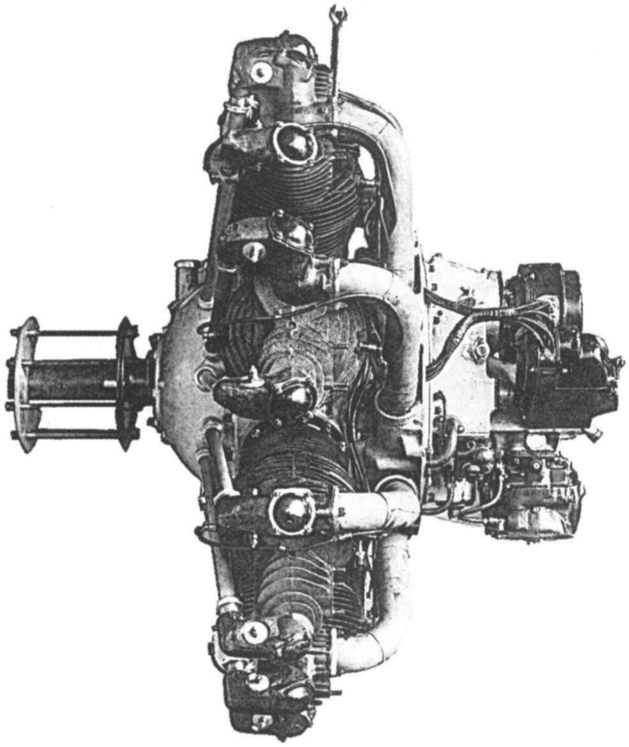
In 1940 Gloster was given a contract for prototypes of the F.9/40 (later Meteor) twin-jet fighter and Power Jets was authorised to design its W.2 engine to be made under direct Ministry contract by the Rover Car Company. This led via the W.2 Mk 4 to the W.2B, slightly differing examples of which were made by BTH, Rover and Power Jets themselves, which by this time (late 1941) was a substantial organisation with over 500 personnel. In retrospect it would have been far better had Power Jets been allowed to grow normally until it could take its place as a full member of the British industry and war effort. Sadly, once it could be seen that Whittle's engine was actually going to work, there arose strong feelings of jealousy and animosity whose seeds were planted at the most crucial period of the war. In the case of Rover it was not so much fear of competition as a progressive deterioration in personal relationships, originally triggered by Rover's long delays (they blamed Whittle) and refusal to abide by their agreement not to undertake redesign, the culmination being Rover's unauthorised redesign of the W.2B into the W.2B/26 with straight-through instead of reverse-flow chambers. By November 1942 the two parties were hardly speaking. S.G. Hooker of Rolls-Royce, appalled at the situation, got his company to replace Rover (see RR).

On 22 July 1941, when just two Whittle engines existed, Colonel (later General) A.J. Lyon USAAF and D. Roy Shoults of GE visited MAP to discuss gas turbines. The result was that on 1 October 1941 the W.1X and a complete set of W.2B drawings were flown to Washington, and what happened next is recorded under GE. Power Jets themselves continued with the W.2B/500 with longer turbine blades, typically giving 1,850 lb thrust at 16,750 rpm, followed by the W.2/700 with a new compressor diffuser with cascade-assisted 90° bends, and later with a more reliable compressor rotor from GE in the first reverse flow of gas-turbine technology. The W.2/700 was by 1944 giving 2,485 lb with airflow 47.15 lb/s from the same size engine as the 1941 W.1. Power Jets also carried out pioneer testing of afterburners (including duct augmentation for the proposed M.52 supersonic aircraft), variable nozzles, thrust spoilers and reversers, and even a ducted fan run behind a W.2/700.

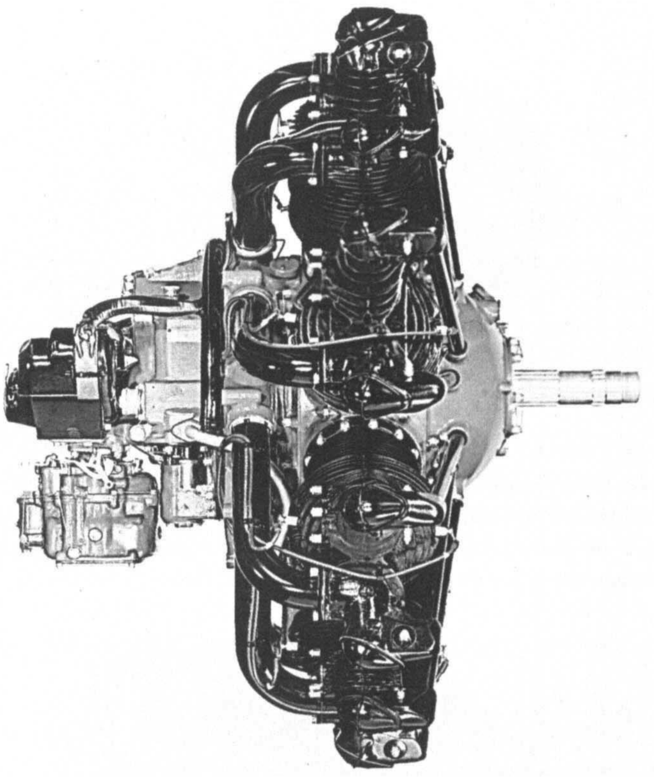
P&W Canada had a struggle to get started with the PT6 in 1958, but 14 years earlier Power Jets designed almost the same engine, to give an initial 250 hp and later twice this amount. According to former PJ designers it was Hayne Constant who 'threw it on the scrap heap', claiming nobody wanted such an engine. It was picked up by Coventry Climax Limited, which was eager to get into gas turbines, and called the C.P.35, but no real effort was put behind it. This neat turboprop had an amidships inlet to the double-sided first-stage compressor; the second impeller was single-sided, and the jetpipe was split on each side of the free-turbine optional rear drive.

In April 1944 the Ministry of Aircraft Production under Sir Stafford Cripps nationalised Power Jets, took over its assets and thereafter turned it into the National Gas Turbine Establishment. It was replaced by Power Jets (R & D) Limited which, forbidden to make anything, merely administered the Power Jets patents. Whittle was showered with honours and told not to rock the boat.

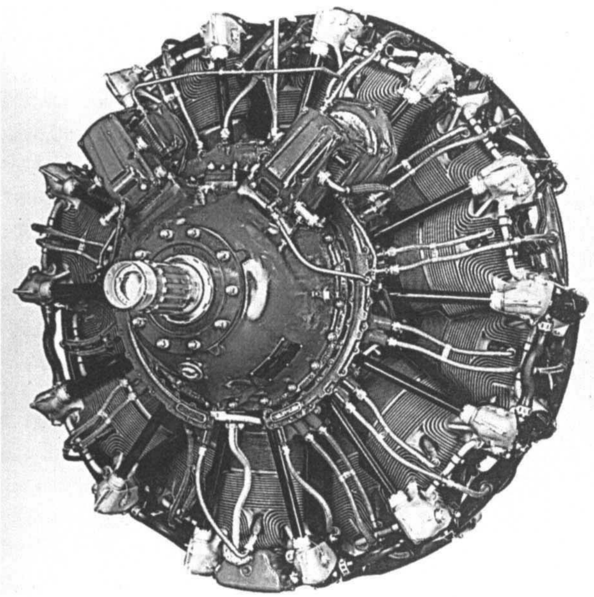
Pratt & Whitney (USA) In many respects the world's biggest aero-engine company, United Technologies' Pratt & Whitney was formed in 1925 as Pratt & Whitney Aircraft Company. More than a year earlier the president of Wright Aeronautical, Frederick B. Rentschler, had begun to see serious danger signals in the bland indifference of the company board to proper engineering research and development to keep the products competitive. In fact, Wright was in a very strong position, and there was no immediate problem. But Rentschler talked with General Patrick, Admiral Moffett and Chance Vought about the prospects and decided that, despite a gloomy general picture, there would be a significant near-term market for a superior engine if one could be created. Such an engine, a nine-cylinder air-cooled radial, could indeed be created, and Wright chief engineer George Mead and chief designer Andy Willgoos were the men to do it.



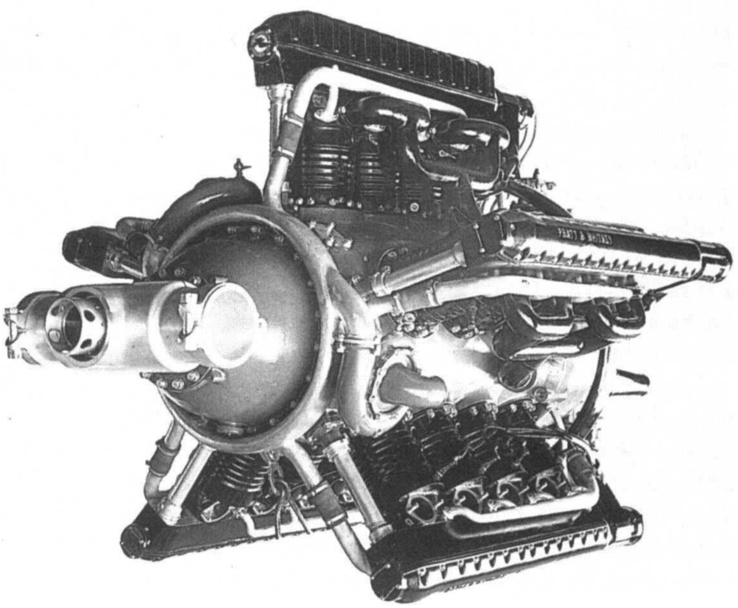
The first Pratt & Whitney Wasp, photographed at Christmas 1925.



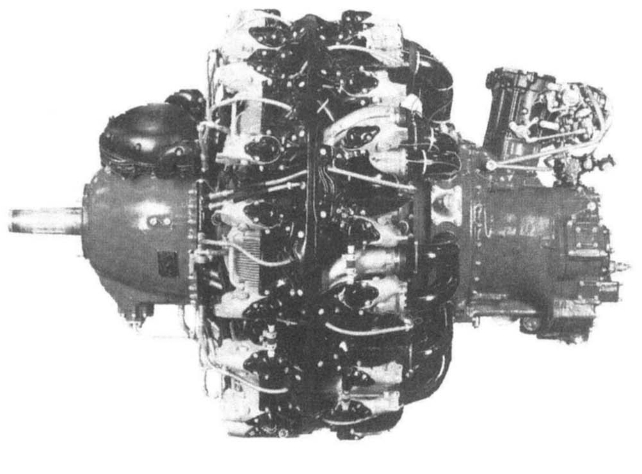
The first production A-series Wasp, now in the National Air and Space Museum, Washington. The author spent 683 hours behind later R-1340 Wasps, and they never missed a beat.



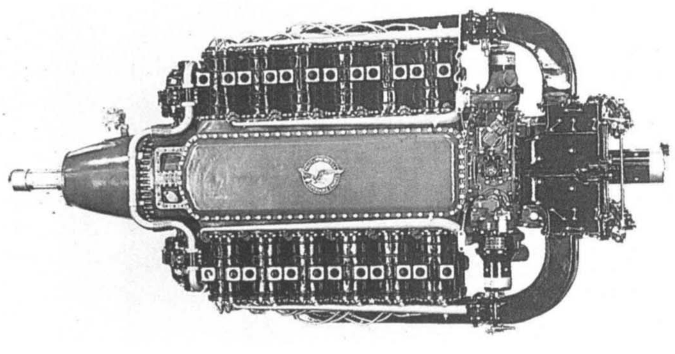
The R-1830 Twin Wasp was one of the great engines of all time. Two applications alone – 19,000 B-24s and 10,000 C-47s – took a fair number, and it went into 87 other types as well.



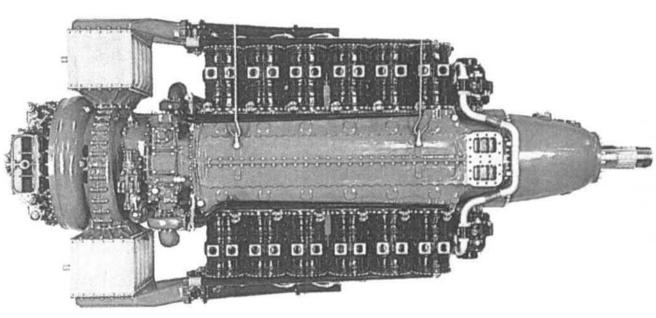
First of the oddballs was the R-2060 of 1931, with 20 liquid-cooled cylinders. Results were so poor that the company went off liquid cooling until 1935.



One of the greatest wartime Double Wasps was the R-2800-59, used in later P-47Ds. The Dash-63 was a -59 with Scintilla instead of GE ignition. The small black unit projecting at far right, under the carburettor, is the water injection regulator.



Army pressure forced a return to liquid cooling, but the XH-3130 gave way in 1939 to the much more powerful X-1800 with 24 sleeve-valve cylinders. This is an X-1800-SA-G without aftercoolers.



For comparison, this is an H-3730, basically an X-1800 with bigger cylinders and two-stage superchargers and aftercoolers. It was potentially a 4,000-hp engine.

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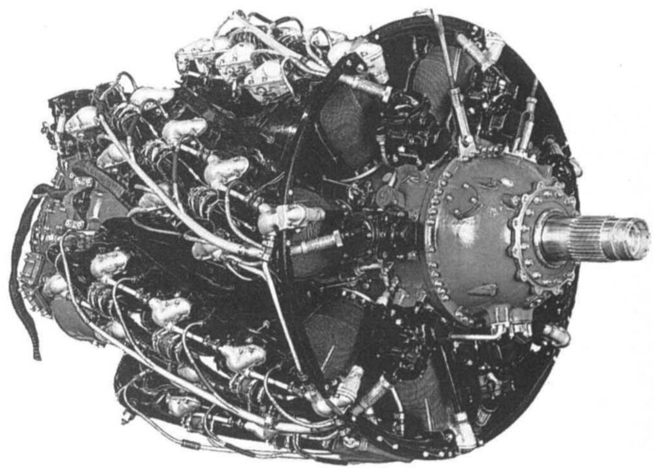
Rentschler resigned from Wright on 21 September 1924. Six months later he took his battered briefcase to see the Pratt & Whitney division of the Niles-Bement-Pond company, of Hartford, Connecticut. As a boy Rentschler was familiar with P&W machine tools and other engineering products. Now he was simply asking them for $¼million to build a prototype engine, plus a further full million should that prototype lead to production.

Most investors at that time would have thought the proposition laughable, but Rentschler got his backing, and Pratt & Whitney Aircraft was incorporated on 23 July 1925. Rentschler became president, Mead vice-president and Willgoos chief engineer. They had to move fast to beat the Wright Simoon for promised US Navy orders. There was never any doubt about how the new engine would be arranged, though the only numerical demands were for 400 hp within a weight of 650 lb. Willgoos bent over the drawing board in his garage in Montclair, New Jersey, and by 3 August tons of tobacco had been cleared from a building on Capitol Avenue, Hartford, and the P&W executives moved in to set up an experimental machine shop. Work went on round the clock, and at last the first Wasp engine was ready on Christmas Eve. It took a whole day to get it rigged for testing; then on 29 December 1925 it was started for the first time, and within a few days was delivering 425 hp, for a weight just under 650 lb.

Its cylinders were 5.75 × 5.75 in, giving 1,344 cu in. Each barrel was machined from a steel forging with exceptionally thin close-pitch fins. The cast aluminium head was screwed and shrunk on, and contained integral rocker boxes for the enclosed single inlet and exhaust valves, with telescopic covers over the pushrods. The crankcase was assembled from identical front and rear halves joined on the centreline of the cylinders, each an aluminium forging. The two-piece crankshaft ran in two roller bearings sharing the load evenly, and was fitted with vibration dampers; it also permitted the use of a one-piece master rod. Mead devised a rotary induction system with a low-pressure blower giving good distribution from a single



To Luke Hobbs' relief the liquid-cooled engines were cancelled and replaced by the R-4360 Wasp Major. This was still no small challenge, but one that could be mastered before the end of the war. All 28 cylinders got proper cooling.

carburettor, and Willgoos added a fully accessible rear cover for the auxiliaries. Later the Wasp design was described as 'clean as a hound's tooth'.

The first Wasp romped through the Navy 50-h test in March 1926, the final reading being 415 hp at 1,890 rpm, and in fact never flew. The second Wasp flew on 5 May 1926 in a Wright F3W-1 Apache, in the hands of BuAer test pilot Lieutenant C.C. Champion Jr. The result was dramatic, and soon Wasps were flying in Curtiss, Boeing and Vought aircraft with startling improvements in every aspect of performance. Production engines were delivered from December 1926, output by February 1927 reaching 12 per month. Meanwhile, back in January 1926 Mead and Willgoos had completed the design of the 1,690 cu in Hornet, which the Navy wanted to replace the heavy Packard in torpedo and bomber aircraft. The first Hornet ran in June 1926 and the Navy picked the direct-drive version for the T4M torpedo-bomber whose installed powerplant weight was exactly halved in comparison with the Packard (a matter of 3,000 lb in total aircraft weight) while having a top speed 15 mph higher. It was at this point that the Navy announced it would buy no more water-cooled engines.

At the 1928 National Air Races Major-General Fechet, Army Air Corps chief, was so impressed by Boeing's new XF4B fighter that he ordered it on the spot (ahead of the Navy), getting his P-12A version in the summer of 1929. By this time Wasps and Hornets had set many world records, were in massive production for the Army and Navy and powered 90 per cent of American commercial transports, adding up to an amazing 60 per cent by value of the total business reported by the nation's 25 leading engine firms. So on 16 July 1929 Mrs Rentschler dug the first spadeful for a totally new plant out in East Hartford, costing $2 million. With 400,000 sq ft under one roof and 30 test cells it seemed fabulous; little did anyone think P&W would soon expand to 6 million sq ft.

By 1930 P&W had enlarged the Hornet to 1,860 cu in and offered a whole family of Wasps and Hornets including versions with supercharging and geared drive. This had taken the Wasp up to 500 hp, and to compete in the 300/400-hp market the Wasp Junior was born, with cylinders 5.1875 in bore and stroke (985 cu in). In 1927 Leonard S. 'Luke' Hobbs had been hired as a research engineer, and one of his first jobs was to study the prospects for twin-row engines. Use of existing parts led to the R-2270 (cu in), run in May 1930 but used for research only. But in 1932 two production engines appeared, the R-1535 Twin Wasp Junior with 14 Junior cylinders, and the R-1830 Twin Wasp with 14 cylinders of a new size 5.5 in square. The 1535 began at about 600 hp and gradually developed to 825 in the Second World War. Compared with a Hornet it gave similar power, was heavier and more expensive but had lower installed drag, and in single-engined aircraft offered better pilot view. It was never important, though Hughes picked a standard example for his privately funded racer which in 1935 gained the world absolute landplane speed record. The 1830 was a different case, starting life at 750 hp and by 1936 with improved fuel giving 1,000 hp. This was a splendid engine, made possible by the company's policy of using only two valves per cylinder, and it opened a market unreachable with a single-row engine.

This was the bright side. Conversely, the company's still quite small engineering team had produced the R-2180 Twin Hornet, which gave 1,400 hp on test in 1935, and from 1931 had expended masses of nervous energy on the R-2060, a totally different engine with five banks each of four small liquid-cooled cylinders which developed up to 1,116 hp for the Army. Moreover, in 1928 Rentschler, Boeing and Vought had created the giant United Aircraft and Transport Corporation, adding Hamilton (propellers), Sikorsky (chiefly for Igor Sikorsky's talent), Stearman (small aircraft) and Standard Steel Propeller (to buttress Hamilton).

Later the airlines had to be hived off under a new 1934 Act to leave United Aircraft; but the still enormous group took most of Rentschler's time, and his efforts to find a successor as P&W president from within the company proved troubled.

In 1936 Mead and Hobbs set the company on course again, concentrating on the R-1830 with single-stage and two-stage or turbosuperchargers, and embarking on the big R-2800 Double Wasp with 18 cylinders 5.75 × 6 in (2,804 cu in) to replace an 18-cylinder project of 2,600 cu in. They dropped the Hornet and R-1535 and also the R-2180, even though it was ready for production. Against Hobbs' belief that they were nowhere near the limits of the engine they knew – the air-cooled radial – the pendulum then began to swing the wrong way again with pressure from the Navy, which wanted 2,300 hp, and the Army, which saw the XP-37 pursuit prototype as indicating lower drag from liquid-cooled engines. For the Navy P&W started the air-cooled X-3130 but found they were on the limits of air cooling and substituted the liquid-cooled XH-3130 in April 1937. In the same month Mead visited England and returned full of enthusiasm for the high-speed multi-cylinder liquid-cooled sleeve-valve engine. He persuaded Douglas to fit such engines buried in the wings of a new high-speed bomber, and then contracted with the Army for the X-1800, with H-24 twin-crankshaft layout, the 1800 denoting the power (capacity was 2,240 cu in). Work began in 1938. In November of the same year the XH-3130 was terminated and replaced by the H-3730, an even bigger sleeve-valve H-24 engine aimed at 3,000 hp.

By 1939 Mead, a sick man, was directing the troubled liquid-cooled programmes from his home. Rentschler viewed the situation with disquiet, and Hobbs, who in nine months had brought the R-2800 to 2,000 hp and readied it for production, decided to investigate the cooling and installed drag of a 3,000-hp engine with four rows of seven conventional radial air-cooled cylinders. The results were surprisingly encouraging. In mid-1939 Mead resigned, and Luke Hobbs took over responsibility for engineering. A year later, by which time the orderbook had been multiplied by 10 (half of it British and French orders), the XF4U-1 prototype, powered by an early R-2800, reached 405 mph in level flight, a world record for a military aircraft. Soon afterwards General 'Hap'

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Arnold visited Hartford. Rentschler told him bluntly the liquid-cooled engines would be too late for the war, but that P&W could build an equally powerful conventional engine that could make it. Arnold reputedly said, 'Now we're getting somewhere.' The R-4360 Wasp Major team was formed the next day, and the liquid-cooled engines were cancelled.

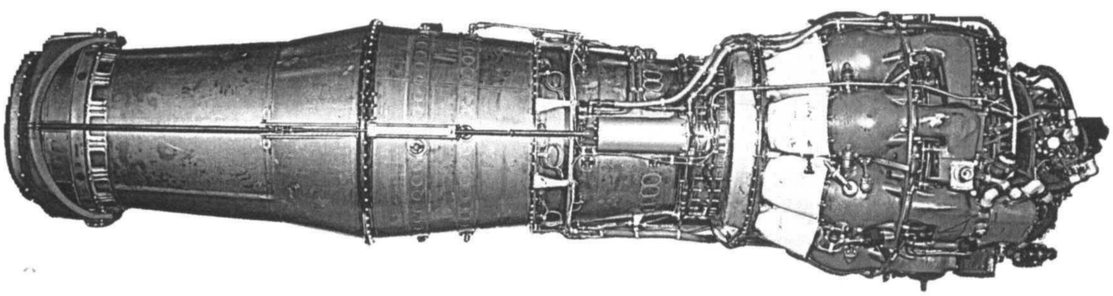
Back in 1939 business had actually been depressed but then the French orders had paid for a plant addition of 280,000 sq ft. Then 'The British Wing', paid in sterling, added 425,000 sq ft from June 1940. US funds added another 375,000 sq ft, and this was just the start. In late 1940 Ford, the first licensee, began a process which duplicated not only the R-2800 but also the complete Hartford plant. Buick built the R-1830 and the R-2000 Twin Wasp (for the DC-4/C-54, with 5.75 in bore); Nash-Kelvinator, the R-2800; Chevrolet, the R-1830 and later the great R-2800 C-series fighter engine with wet ratings up to 2,800 hp; and Continental and Jacobs built, under licence, R-1340s and R-985s, respectively.

Meanwhile, Hartford grew to 3 million sq ft, another 2 million was added in satellites in Connecticut, and finally in 1943 a new plant was built outside Kansas City, Missouri, even bigger than Hartford and put to making the new C-series Double Wasp, a colossal challenge because the workforce had to be trained from scratch and much of this largely new engine had never been mass-produced anywhere and involved new techniques. The mighty R-4360 had already passed its first tests by June 1942, and later in the year was qualified at the unprecedented rating of 3,000 hp. An unusual feature of this engine, apart from its 'corn-cob' layout, was that it had a one-piece crankshaft and split master rods. By VJ-Day it had been qualified at 3,500 hp.

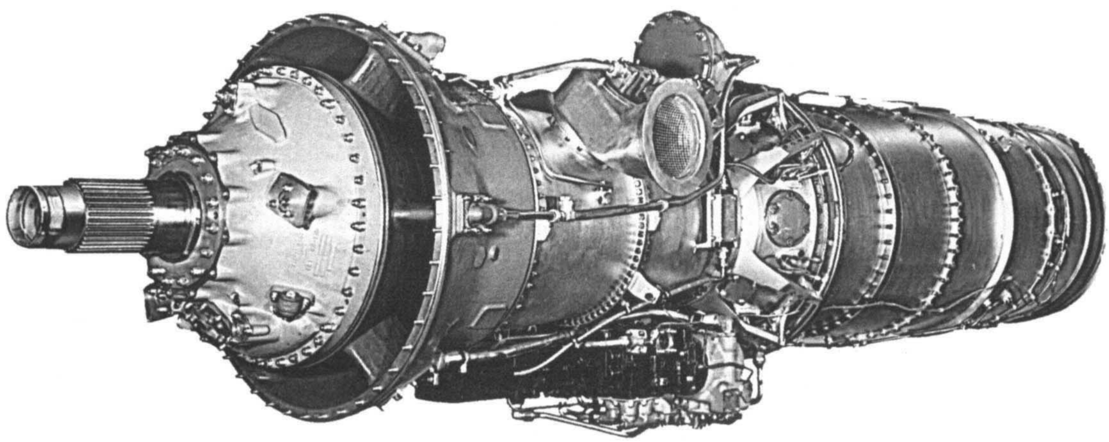
On that day P&W's giant order-book was slashed close to zero. Thousands took a vacation, the first for four years, while in the boardroom Rentschler, 'Jack' Horner and general manager Bill Gwinn added up the horsepower of the wartime engines and found it came to 603,814,723 from 363,619 engines. No other company has ever come anywhere near this. But on Gwinn's office wall there soon hung a cartoon: Gwinn, aboard a battered sailboat, asks 'See anything, Jack?' Skipper Horner, looking to the horizon, replies 'Nope'. In fact, the traditional engines were to go on for a long time, with even the R-2180 being designed as a new replacement for the Twin Wasp, with 14 Wasp Major type cylinders. Called Twin Wasp E, it was certificated as a bolt-on power egg (a first for P&W) for the DC-4; but by this time nobody wanted DC-4s and the only application was 18 Saab Scandias. The last throw was the R-4360 compound, which exceeded 4,000 hp with a VDT (variable-discharge turbine), but the B-36C was cancelled.

Gas turbines

Hobbs had studied turboprops in 1939, and from 1940 collaborated with MIT on the PT1 in which the propeller was driven by a turbine fed by eight two-stroke free-piston diesel gas generators. Effectively the giant firm had nothing in this new field, and it set 1950 as the time by which it must learn

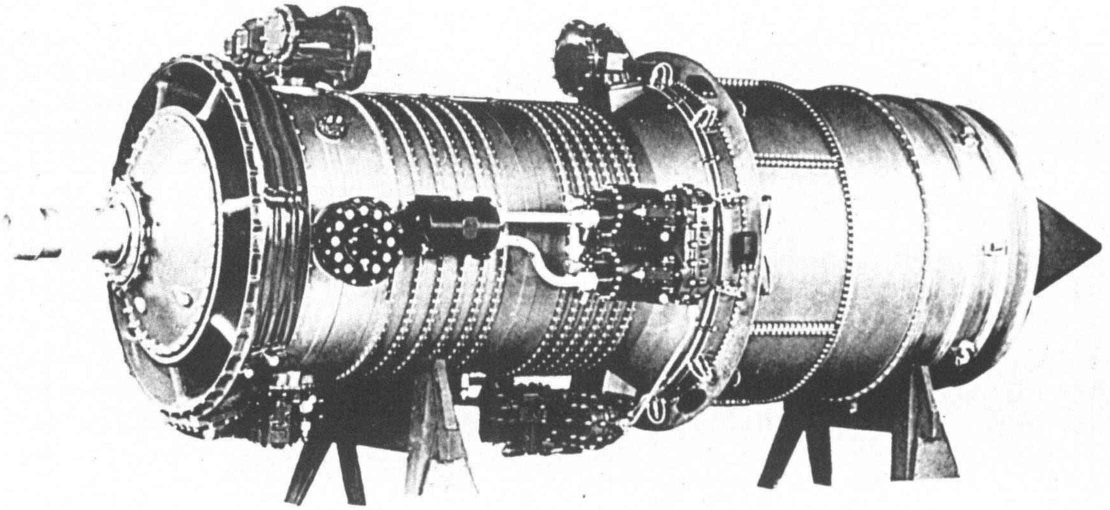


Britain ignored the potential of the Nene and Tay, but the Hartford engineers took these engines to 8,300 lb with afterburner in this J48-P-5A. Airflow was 130 lb/s.

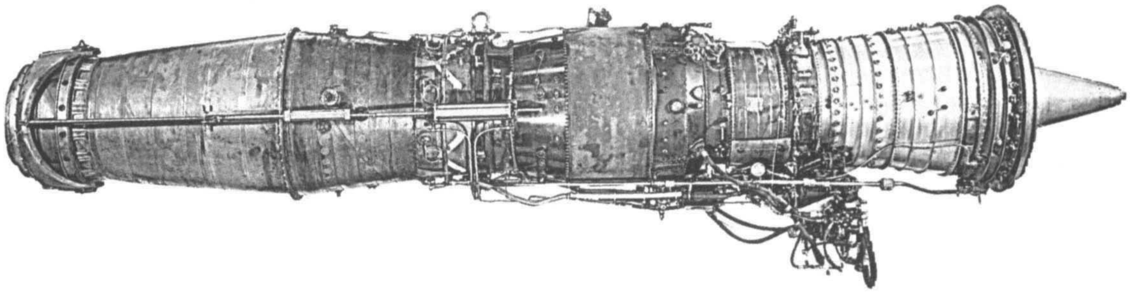


A production T34-P-3, the 5,700 shp (6,000 ehp) turboprop which powered the C-133A. Weighing 2,670 lb, it was the company's first gas turbine.

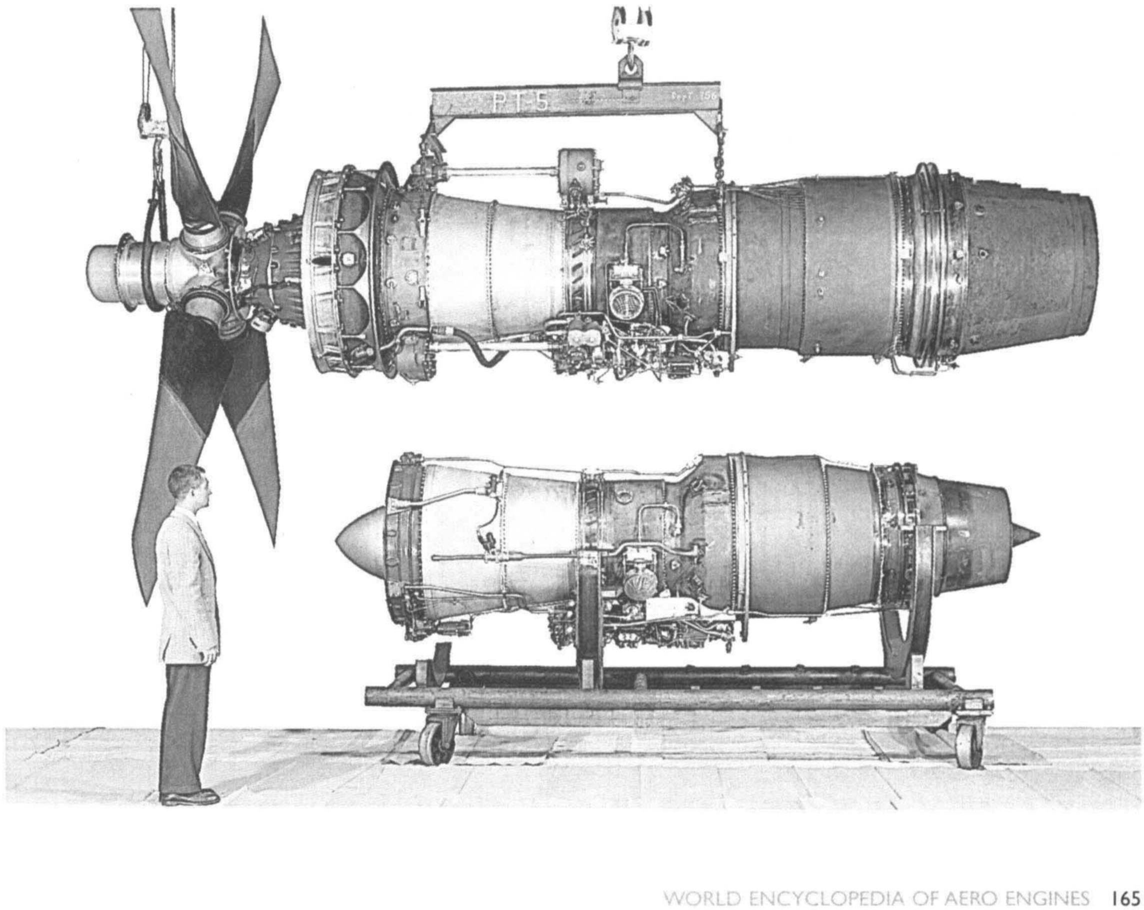
The XT45 led to the original J57, the 'barrel-type' X-176, which differed mainly in having no reduction gear. Those familiar with the J57 would find little to recognise.



One of the first wasp-waisted (JT3A) engines, X-185 is seen coupled to an adapted J48 afterburner in December 1951.



The 15,000-hp PT5 (XT57) turboprop compared with a J57 bomber engine. The XT57 was flown in the nose of a C-124C Globemaster II.

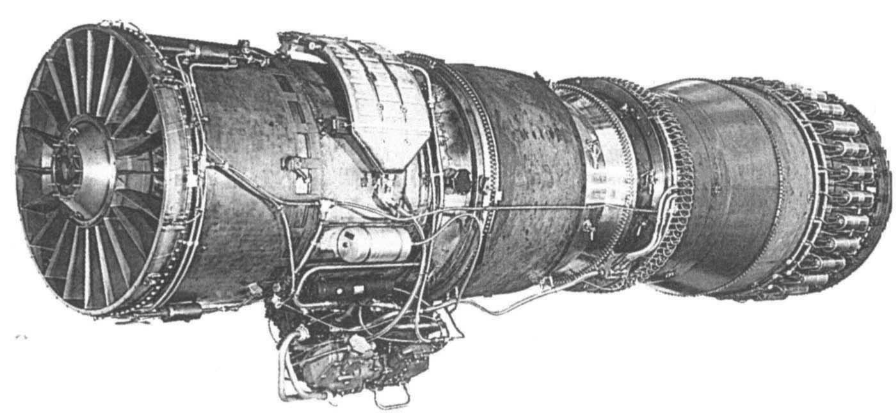


all about it and then leapfrog past its rivals. It learned a little immediately after the war building 130 Westinghouse J30 turbojets, but the big project that tided P&W over the hard pre-1950 period was the decision of the US Navy to buy the British Nene turbojet.

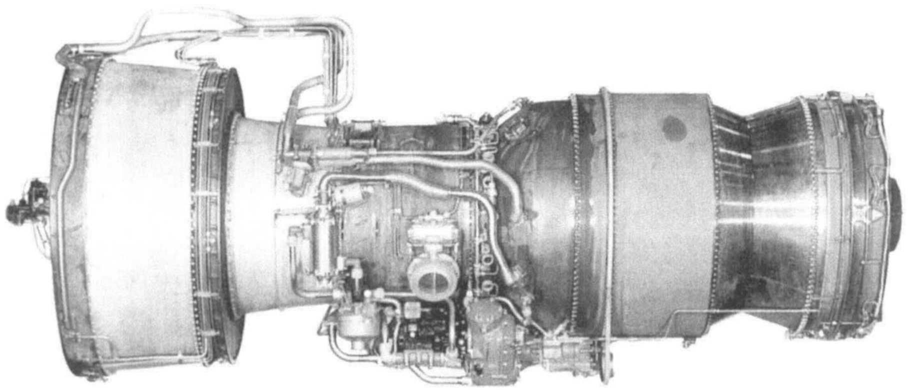
The Navy stipulated the first J42 must roll off the Hartford line in November 1948, in time for the F9F programme. It also had to be Americanised, be engineered for mass production (it was not being made in quantity in England) and be able to come from a US source. Gwinn headed a delegation to Derby in August 1947, the first J42 (a Nene with US accessory systems) was running in March 1948, and it was in production with a wet rating of 5,750 lb by October. Hobbs had insisted on the need for future development, as a result of which the two firms jointly produced the Tay and J48, the latter following the J42 with ratings up to 6,250 lb, or 8,750 lb with afterburner.

In June 1945 Hobbs had begun development of a large single-shaft turboprop, the PT2, funded by the Navy as the T34. Made largely of stainless steel, it had a 13-stage compressor handling 65 lb/s at pr of 6.7, a cannular combustor and three-stage turbine. It entered service in modest numbers in 1958 at ratings of 6,000 and later 7,500 ehp. Once design of this engine was complete, in March 1946, studies were begun for a successor. Hobbs was determined to start the leapfrog process, and the choice fell on an axial turbojet of 8,200 lb thrust, the JT3. By May 1947 the JT3-6 was in detail design, with a compressor of 6 pr with a constant diameter of 36 in. The Navy rejected it – ironically, because Westinghouse offered the J40 sooner and cheaper. In January 1947 a study for a related 10,000-hp turboprop showed that with the desired high pr of 8 the cranking power needed to start the engine would be exorbitant, and flow through the compressor would be very poor. This led in July 1947 to the idea of splitting the compression between two spools, each turned by its own turbine via concentric shafts (an idea investigated by P&W's R.G. Smith and W.H. Sens in spring 1946, though by this time the Rolls-Royce Clyde was a mature engine). The two-spool turboprop was launched as the PT4, funded by the Air Force as the XT45. Components were made in late 1947, while parallel studies were made of the two-spool JT3-8 turbojet, which by March 1948 was supercharged by adding two stages at the front, giving 10,000 lb thrust. During 1948 Air Force interest hardened on a high-compression turbojet for long-range bombers, and the XT45 was terminated in September 1948. Instead the J57-P-1 specification was written, and the shops began building two actual engines, the X-176 (JT3-8) and X-184 (JT3-10). Even as they were being built, rig testing indicated poor performance, mainly because of the very small HP compressor blades, poor turbine disc design and excessive weight.

Mechanical design came under Willgoos (it was his last engine, for he died after shovelling snow in March 1949) and aerodynamic design under Perry W. Pratt. In February 1949



One of the two JT9A-20 (J91-P-1) engines tested in summer 1957. The high design Mach number is reflected in the nozzle diameter of 65.6 in, compared with 55.0 in maximum for the engine. Airframe-mounted nozzle ejector flaps were bigger still.



The prototype JT3D-1 turbofan of December 1958, which was just preceded by the USAF-funded TF33 version. This can claim to have been the first big turbofan, and it transformed the 707 and DC-8.

The JT8D has been described as 'the world's most profitable engine' (a cynic might say because the spares cost so much). JT8Ds have logged over 600 million hours, probably an all-time record for any engine. This is a Dash-200.

they worked out a scheme to redesign the JT3 in a wasp-waisted form, the rotor discs having a constant diameter but the casings tapering towards the HP end amidships, to give higher efficiency, better sealing and cut 600 lb off the weight, besides improving the arrangement of accessories to give a more compact installation in fighters or in bomber pods. Pratt got the go-ahead to redesign in May 1949, but it was decided to complete both the barrel engines, the X-176 running on 28 June 1949 and the X-184 in February 1950. Both confirmed the poor performance. The wasp-waisted design threw up its own problems, notably with bearings and compressor-blade vibration, but with massive effort these were 'trampled to death'. The first redesigned JT3 ran on 21 January 1950, flew under a B-50 in March 1951, completed a 150-h test in J57-3 production configuration in November 1951, powered the eight-jet YB-52 on 15 April 1952, and with afterburner took the YF-100A beyond Mach 1 on its first flight on 25 May 1953.

This was probably the most important engine in the world since 1945. It initially gave 10,000 lb dry or 15,000 lb with afterburner yet, because of its pr of 12.5, it set totally new standards in jet fuel economy. Almost certainly its use in short-range fighters was mistaken: they would have done better with a less-economical engine of half the J57's weight of about 5,000 lb with afterburner. For the B-52 and many other long-range aircraft the J57 opened up possibilities previously only dreamed of, not least being the design of the 707 and DC-8 commercial jets using civil JT3C engines. The latter entered scheduled service on 26 October 1958 with TBO (time between overhauls) of 800 h, and were developed later to a dry thrust of 13,000 lb for a weight of 3,495 lb, almost 1,000 lb lighter than the original B-52 engine, and with TBO of 14,120 h. The JT3/J57 was made of steel (later versions had a titanium LP compressor), with nine LP and seven HP stages, eight flame tubes in a cannular chamber and 1 + 1 turbine stages; airflow was 164–187 lb/s, pr 11 to 13.8, and highest rating 13,750 lb wet (P-43s and P-59s in B-52F/G and KC-135As) or 19,600 lb with afterburner (P-420 in F-8J). In 1951–60 P&W made 15,024, and Ford in Chicago a further 6,202.

The JT3 fulfilled every hope in overcoming P&W's late start in gas turbines, and fortuitously the failure of the rival J40 gave it the US Navy market which had not been expected. Obviously it was not an end but a beginning, and from a host of possibilities the first derived engines were the T57 and JT4. The former still remains the most powerful turboprop built outside the Soviet Union, rated in the 15,000-hp class. It added extra LP turbine stages driving a front reduction gear to a giant HamStan B48 single-rotation propeller with four hollow-steel blades; its application, the C-132 military airlifter, was cancelled in 1957. The JT4, funded by the military as the J75, was a JT3 scaled up to 249–256 lb/s airflow, retaining similar pr despite having only eight LP stages. Bulk and weight were increased by only some 10 per cent, but typical ratings were 17,500 lb dry and 26,500 lb with afterburner. Though heavier and less fuel-efficient it far outsold the Rolls-Royce Conway in 707s and DC-8s, and as recently as 1984 former afterburning fighter J75s were being rebuilt to power TR-1s.

In 1951 work began on an indirect-cycle nuclear powerplant based on a PWR (pressurised-water reactor) driving a ducted fan

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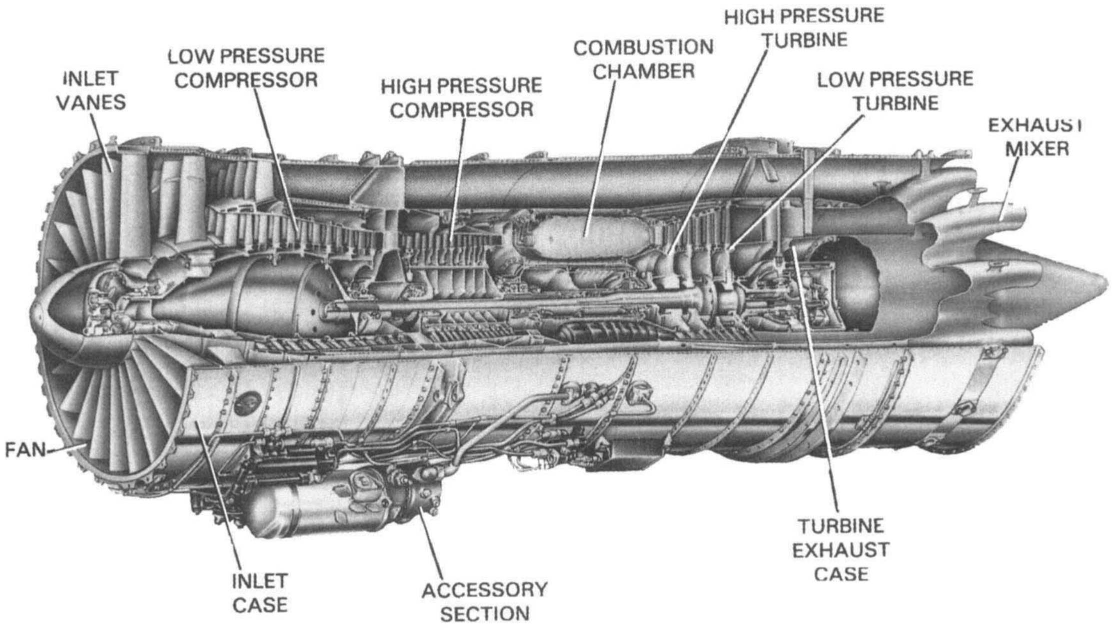
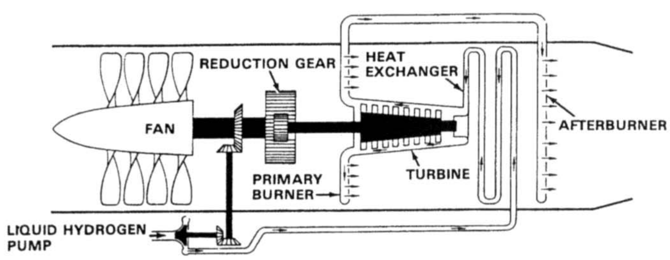


This cutaway shows internal features of the world's most common airline engine, the JT8D, seen here in its latest JT8D-200 form, used in the MD-80 family.



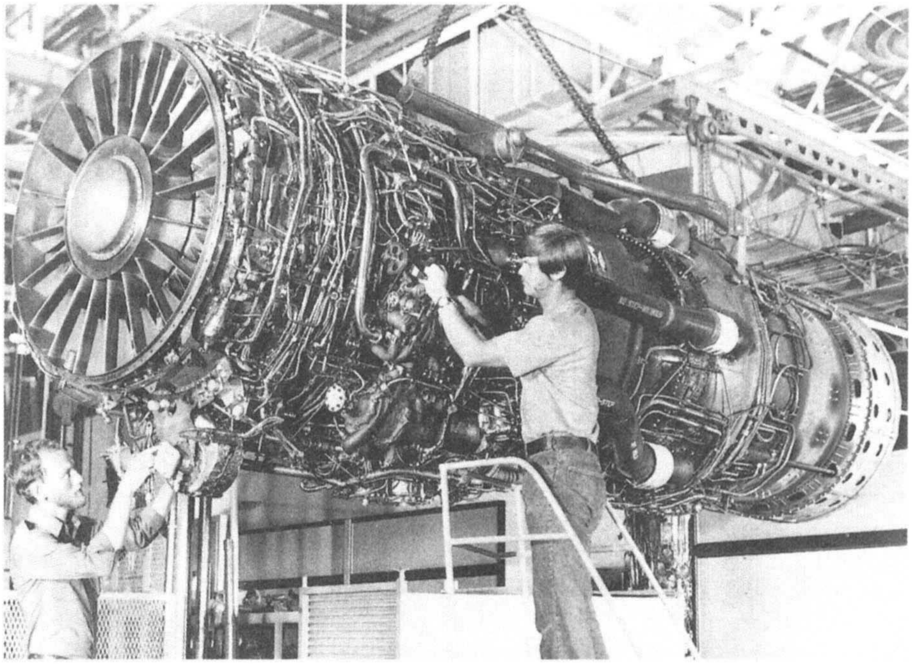
The Hartford engineers were probably better fitted to tackle the highly secret Project Suntan engine than any other team anywhere, but the liquid-hydrogen pump and heat exchanger were new challenges. The 23,500 rpm pump had oil lubrication! The heat exchanger, of 71.6 in diameter, transferred heat at a rate that would 'heat 700 six-room houses'.

of 13.1 ft diameter and 67.6 ft long. In 1953 this was replaced by a powerplant based on a single molten-salt circulating-fuel reactor providing heat for six J91 turbojets each of almost 6 ft inlet diameter. When the WS-125A nuclear-powered bomber was cancelled in 1957 the indirect-cycle powerplant went with it, though P&W then turned to a new scheme with four J58s modified to higher pr and fed from two or even four reactors, to fly in a 500,000-lb Convair testbed in 1965. This aircraft, the NX-2, was finally abandoned in 1961.

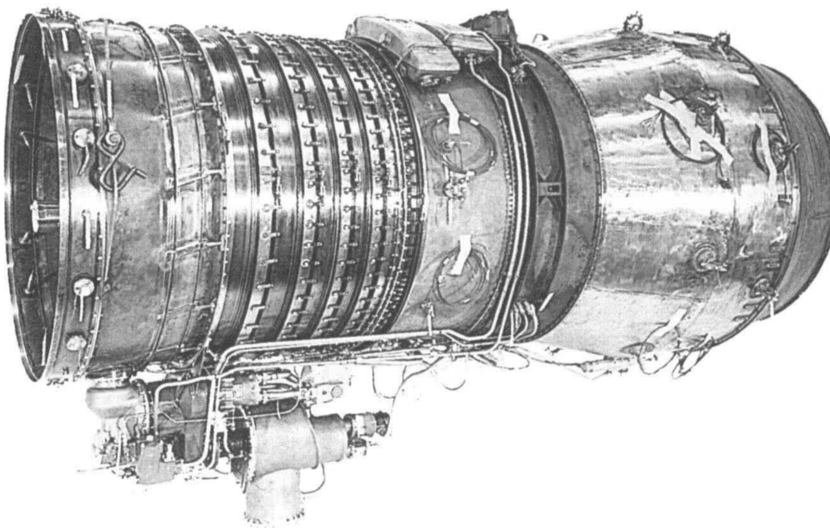
The J91 was a major programme for the USAF aimed at the CPB (chemical-fuel bomber) WS-110A and then the NPB WS-125A. It had to be a big single-shaft turbojet stressed for Mach 3, fed from a variable inlet and with a giant convergent/divergent nozzle with ejector flaps of 72.5 in diameter. The chemical-fuel engines were a series of JT9s, 9Bs and 9Cs (J91-P-1 variants), all with a nine-stage compressor of pr 7, annular chamber with eight ring cans each with six burners, and a two-stage turbine. Only two experimental engines, X-287 and 291, were built (in spring 1957). They were run at 24,500 lb dry and 35,000 lb with afterburner. The JT9-5A series had dual-fuel afterburners burning either JP-5 or HEF-3 boron fuel, ratings being 28,700 lb dry, 41,500 lb with afterburner and 44,000 lb with water injection as well. In the event, GE won the CPB contract, but the JT9 provided a valuable basis for the later (but mainly unrelated) JT9D commercial engine and, especially, the J58 as noted later. The nuclear J91, the JTN9, was never built, though a quarter-section of the heat-transfer radiator was tested.

The X-287, JT9A-20, had proved on test to be aerodynamically brilliant. Its first two compressor stages, with long transonic blades, were then scaled down to 53 in diameter, handling 450 lb/s airflow, and substituted for the first three LP stages of the JT3 turbojet. Almost the only other modifications were to add a third LP turbine stage and a new fan duct which in the B-52H was bifurcated at the rear to discharge supersonic air from left/right nozzles, having a cross-section resembling a banana. The result was the JT3D turbofan, funded by the USAF as the TF33, which almost overnight in 1960 not only fended off all competition from the Conway (which had a bypass ratio far lower than the JT3D's 1.4) but did it with a simple modification to the existing turbojet which could be carried out by the operator using a kit sent from Hartford. The conversion had only marginal effect on weight but increased thrust by over 35 per cent, reduced fuel burn by 15–22 per cent and cut 10 dB from take-off noise. (Despite this, today operators of JT3D airliners are faced with costly modifications to meet severe new FAA Stage-2 noise rules.) Production of this pioneer turbofan ended in 1985 at about 8,600, most of them not conversions. Late (P-7 and PW-100) models have seven LP stages and rating of 21,000 lb thrust.

At Mach 3.2 almost all the thrust pulling the SR-71 'Blackbird' along came from the inlet system, a little being added by the white-hot nozzle. In between came this J58, which just got in the way (but you needed it for take-off).



The Pratt & Whitney '304' looked almost normal, but a fitter dismantling it would soon be amazed. The six variable stators show this to be the first 304-2 (June 1958) with five-stage fan geared from the 18-stage hydrogen turbine. Two were to power the 164 ft 10 in Lockheed CL-400 at 99,500 ft.



The next spin-off was a scaled-down turbojet, the JT8/J52, funded by the US Navy in 1954 and produced for missiles and Navy aircraft at 7,500–11,200 lb thrust. Compressor and turbine stages were 5 + 7/1 + 1, and though the planned commercial JT8 never found a market, development continued for the EA-6B ADVCAP until 1986, with the 12,000 lb J52–409. In sharpest contrast the derived JT8D turbofan, produced in 1960–1 to power the 727, has had hardly any military sales (apart from the Volvo Flygmotor RM8) (*qv*), yet it has probably been the most profitable gas turbine in history, with 11,845 having logged 575 million hours at the time of writing. Compared with the JT8 the LP spool was changed to have two fan and six LP stages, driven by a three-stage turbine, airflow being roughly doubled from 136–143 lb/s to 315–331 lb/s, pr being around 16. From 1970 the nine cans and burners were modified to reduce smoke, and subsequently a refanned JT8D-200 series was marketed (for the highly successful MD-80 series) which takes thrust from the 14,000–17,400 lb bracket up to 20,000–21,700 lb, with reduced sfc and noise. The 2,856 engines of this type have brought the JT8D total to 14,701, which by late 2006 had flown 680 million hours. Noise legislation has now resulted in mass production of several kinds of 'hushkit' for the 727, 737 and DC-9. Though these increase cost, weight and fuel burn, more than 1,700 shipsets have been ordered, representing over half the surviving active JT8D-engined fleet.

In the story of Garrett on an earlier page, reference is made to Randolph Rae and his attractive proposal to use liquid hydrogen to fuel highly supersonic, ultra-high-flying aircraft. On 15 June 1955 a parallel contract was awarded to United

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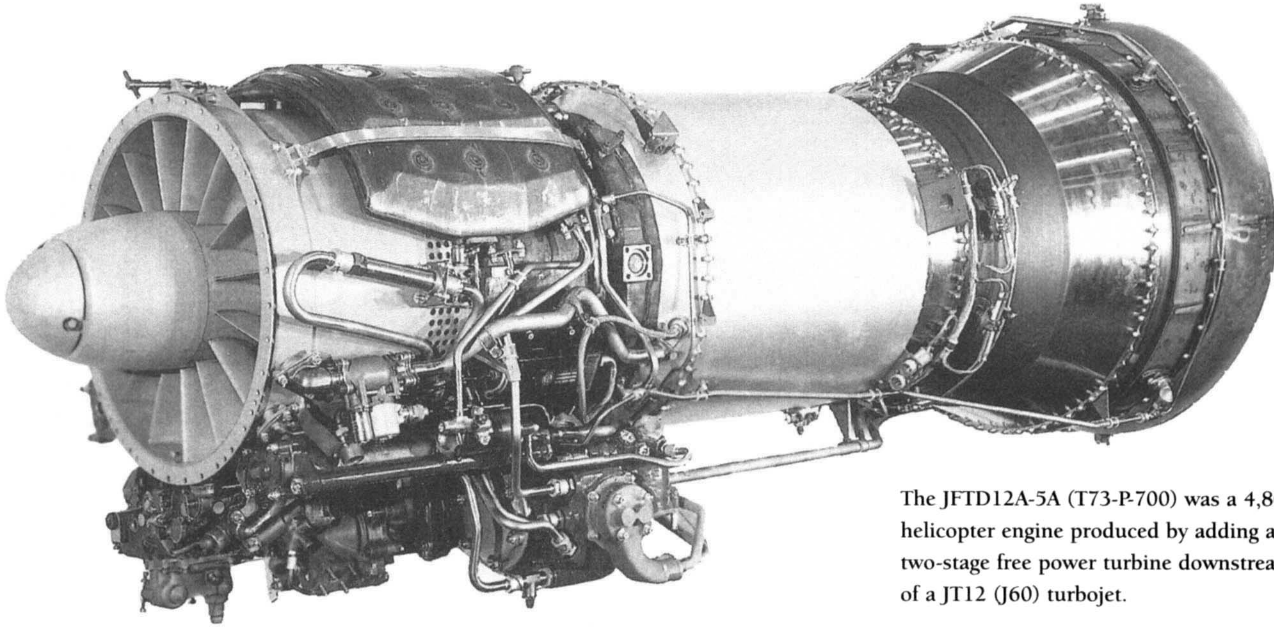


The JFTD12A-5A (T73-P-700) was a 4,800-shp helicopter engine produced by adding a two-stage free power turbine downstream of a JT12 (J60) turbojet.

Aircraft's research division. Before the year was out the USAF was well into its gigantic Suntan project; Colonel Appold, who headed it (and later ran the C-5A on behalf of the Air Force) reckons the cost was not less than $250 million, but it was so disguised and super-secret there is no way of getting an 'accurate' figure. On 17 February 1956 P&W chief engineer, Perry W. Pratt collected current hydrogen knowledge and began talking with Lockheed's 'Kelly' Johnson about a U-2 successor. William Sens, who accompanied Pratt, outlined an engine cycle in which the gas was burned downstream of the turbine, figures being: thrust 4,500 lb at 100,000 ft; diameter of nacelle 61 in; and sfc 0.75. One of the young J75 engineers, Richard J. Coar (later president of Pratt & Whitney), was pulled out to organise a hydrogen deal with the Air Force; it took just one day, and one sheet of paper. Suntan multiplied, the next development being a J57 rebuilt to run on the intensely cold liquid; it was dramatically shorter than before. By August 1956, with Coar as project engineer, the world's first 'clean sheet of paper' liquid hydrogen engine was being built. It could not receive a legitimate designation, so P&W looked at the Engine Order No. (703040) and extracted the digits 304. The diagram on page 168 shows how the fuel, at 18K (minus 255°C), was pumped at high pressure through a heat exchanger containing over five miles of stainless tube with 2,240 furnace-brazed joints. Here a heat-exchange rate of 21 MW (21,000 kW) heated the hydrogen from 18K to just over 1,000K, at which temperature it expanded through a remarkable turbine with 18 small stages putting out 12,000 hp. This drove through a reduction gear to the multi-stage fan. Downstream of the turbine some hydrogen was burned, to give 1,500K; the rest was burned downstream of the heat exchanger. Nacelle weight was 6,000 lb, and thrust at 100,000 ft was 4,800 lb, with sfc of 0.8. The 304 began testing on 11 September 1957, running successively on nitrogen, gaseous hydrogen and liquid hydrogen. Later engines had five instead of four compressor stages, with sea-level thrust of 13,500 lb. But Suntan, like its name, faded. It encountered opposition from many quarters, and even Kelly Johnson became convinced this fuel was a non-starter (though since he retired Lockheed-California has published hydrogen-powered TriStars and similar studies). The lasting benefit was a vast national capability in the technology and supply of liquid hydrogen.

Johnson himself re-embraced petroleum, and in 1958 P&W accepted the challenge of providing propulsion for his A-12/SR-71 family at up to Mach 3.35. The resulting JT11B turbojet, funded as the J58 – an out-of-sequence Navy even number – is a single-spool engine made of refractory materials, with much of the supersonic compressor delivery bypassed through six large pipes; special JP-7 low-volatility fuel is used, with chemical-reaction ignition of the afterburner, and lube oil must be preheated before each engine start. HamStan provided the advanced control system for the engine, afterburner, inlet, nozzle and complex arrangements of secondary airflow doors.

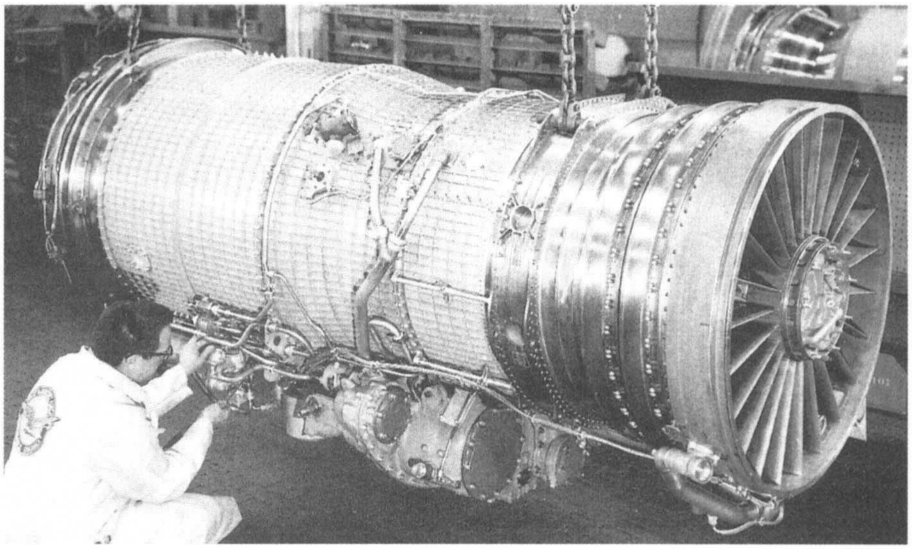
In 1957 what is now P&W Canada began design of the JT12 (J60) small turbojet with nine-stage compressor (*c.* 50 lb/s, pr 6.4) rated in the 3,000-lb class. This was taken over by the parent firm, about 1,900 being delivered. From this the JFTD12 (T73) helicopter engine was derived by adding a two-stage free turbine giving an output of 4,500 or 4,800 shp.

Chronologically the next step forward was selection by the US Defense Department of the GD/Grumman F-111 version powered by the JTF10A. If one includes work on derived engines by SNECMA this was the first afterburning turbofan, with three fan stages rotating with six LP, seven HP, eight flame tubes, and 1 + 3 turbines. The initial production version, the TF30-P-3, had airflow of 233 lb/s at 17.1 pr, thrust being 10,750 lb or 18,500 with full afterburner. Severe problems were experienced in matching the engine and aircraft, the inlet system needing redesign. Later the F-111 engine was developed into the P-100 version rated at 25,100 lb, yet at 4,022 lb marginally lighter than the P-3. Unaugmented versions rated at 11,350–13,400 lb powered early A-7s, the final model (P-408) in this series transferring the third fan stage to the LP compressor. In the F-14A the P-412, with a different afterburner nozzle, suffered prolonged trouble requiring repeated redesign and various 'fixes' such as armour to contain burst compressors. The final P-414A version achieved a TBO of 2,400 h, but the TF30 damaged P&W's reputation, and opened the way for the F-14 to be re-engined by GE.

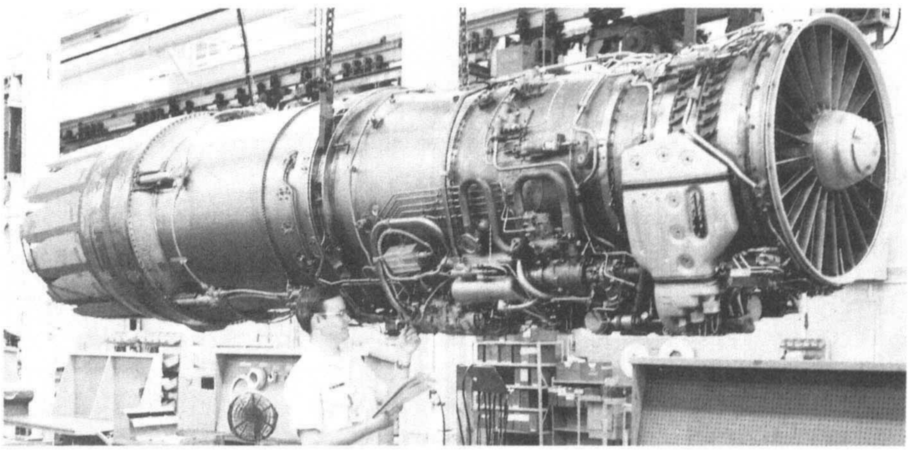
The company also suffered its share of problems with the next-generation fighter engine, the JTF22, designed and developed as the F100 by the Government Products division at West Palm Beach, one of the four divisions of the 1976-restructured Pratt & Whitney Group of UTC (United Technologies Corporation), which previously had been the Florida R&D Center. With this engine steel suddenly took a back seat, the dominant materials being titanium, high-nickel alloys and even more exotic materials. There are three fan stages, a 10-stage HP spool with three variable stators at the upstream end, an annular combustor and 2 + 2 turbines with directionally solidified blades. Airflow is 228 lb/s at 24.8 pr and dry and augmented ratings are 14,670 and 23,830 lb respectively. To some degree the problems stemmed from the arduous operating conditions and the USAF wish for very long service life with reduced ownership costs. A fairer picture of F100 performance is the fact that current engines fly 1,800 mission cycles without even hot-section refurbishment.

The F100 is the basis for three derived engines: the PW1115 (basically an unaugmented F100) of 15,000 lb thrust, the PW1120 (a turbojet of 20,600 lb thrust with the original fan replaced by an LP compressor driven by a single-stage turbine) and the PW1129 or F100-229. The latter is a bolt-on replacement engine for F-15s and F-16s, giving thrust in the 29,000 lb-class (so GE did not have it all their own way). The PW1120 powered the Israeli Lavi prototypes and is flying in an Israeli Phantom, but whether hundreds will be sold for upgraded Phantoms looks doubtful.

In 1961–3 P&W fought and lost the propulsion contract for the aircraft that became the C-5A. Undaunted, it was selected by Boeing to power the 747, the resulting JT9D being



This TF30-P-6, for an A-7A, shows the distinctive ribbed casing that was also a feature of the related SNECMA TF306.



The F100 almost had a corner of the market with the F-15 and F-16, but caused headaches almost as prolonged as those of Navy TF30s. Today it is one of the most reliable fighter engines in the world.

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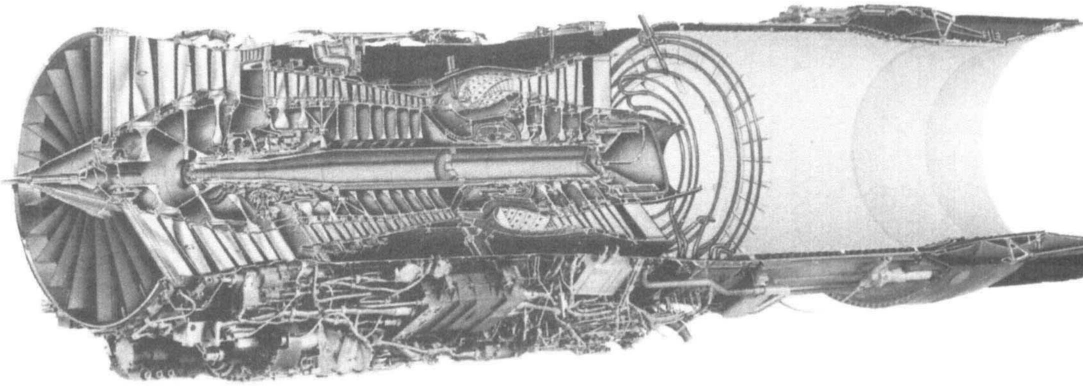
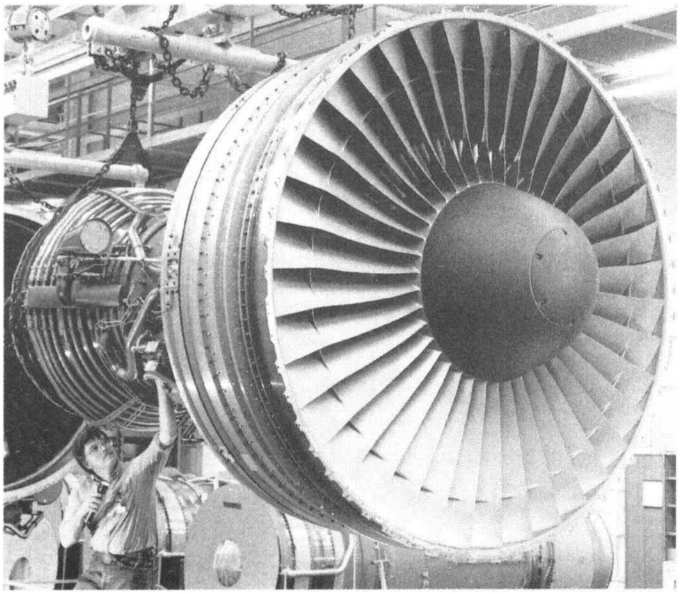
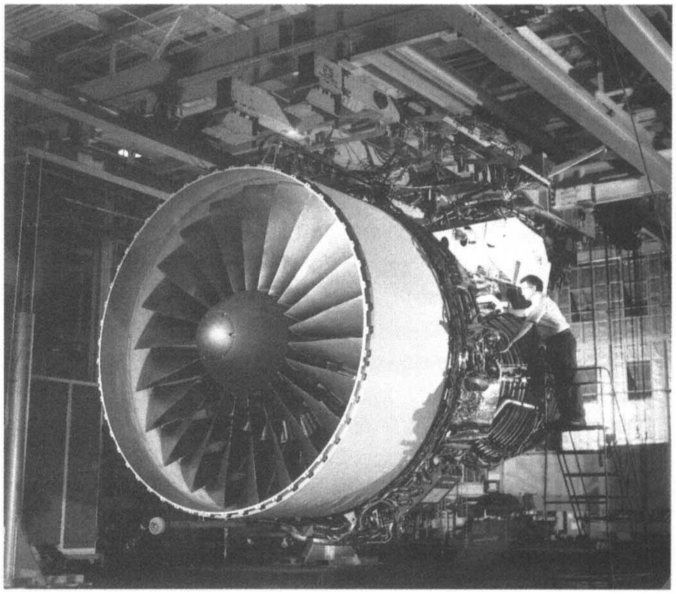
This cutaway shows the latest and best of the F100 fighter engine family, the Dash-229. Rated at 29,100 lb with afterburner, even the hottest parts have a 4,300-hr inspection interval, equivalent to over nine years of fighter operation.

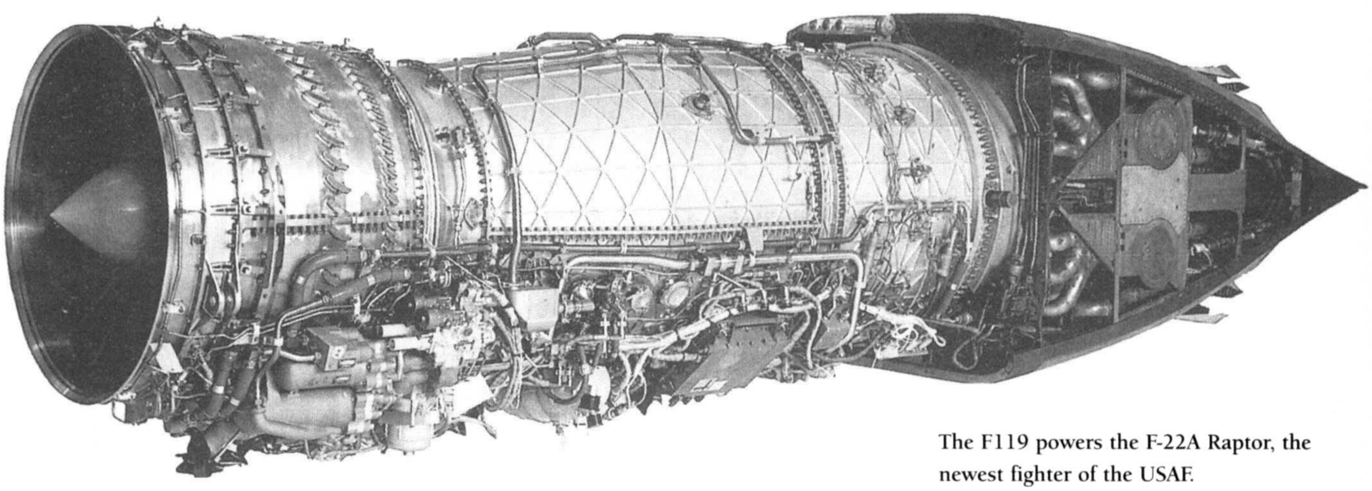




The PW4000 has been built in large numbers with three different sizes of fan. The engine illustrated has the smallest.

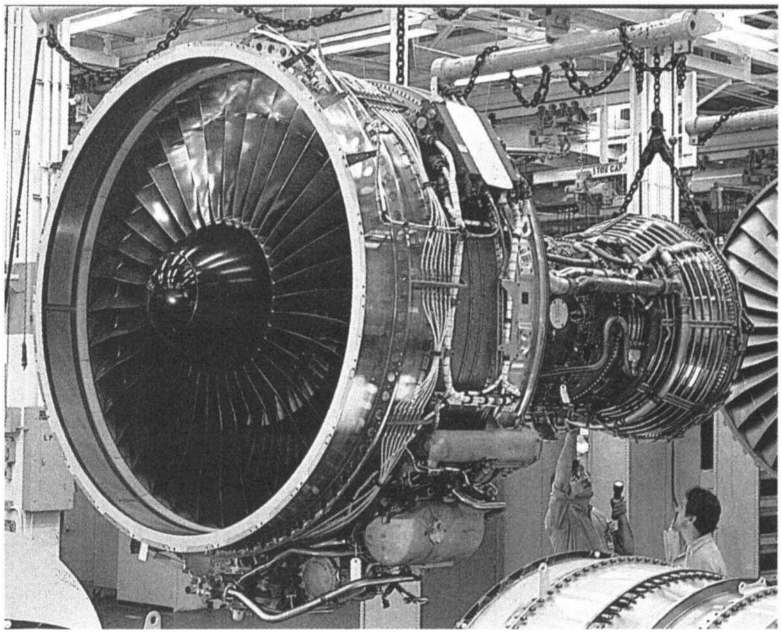


The most powerful member of the PW4000 family is the PW4098, with a 112-in fan driven by an LP turbine with no fewer than seven stages, supplied by partner MTU of Germany.



The F119 powers the F-22A Raptor, the newest fighter of the USAF.

Pratt & Whitney unexpectedly failed to beat the competition in powering the 757 with the PW2000, but it has got the engine into the C-17 Globemaster III airlifter and the Russian Ilyushin 96M.



the first of today's giant commercial turbofans. First run was in December 1966, first flight (B-52E) in June 1968, and maiden flight of the 747 followed on 9 February 1969. The JT9D is made of titanium, high-nickel alloys, stainless steel and other advanced metals, and in the latest models the HP turbine blades are single-crystal. The original JT9D-3 which entered service on 21 January 1970 had a one-stage fan (1,510 lb/s), three LP, 11 HP, annular combustor and 2 + 4 turbines, weight being 8,608 lb and thrust 43,500 lb. Since then 3,265 JT9Ds have flown 187 million hours with ratings up to 56,000 lb, the latest models having 4 LP compressor stages and weighing about 9,100 lb.

On paper the PW4000, announced in December 1982, reads like an advanced JT9D, but in fact this is a near-total redesign at company expense to reduce the number of parts by more than 50 per cent, improve economy and promise extended life at lower cost.

The PW4000 is produced in partnership with companies in Belgium, Germany, Italy, Japan, Netherlands, Norway and South Korea. There are three fan sizes: the PW4052/4062 series has a 93.6-in fan to give 52,000–62,000 lb thrust to power the A300/310, 747/767 and MD-11; the PW4164/4168 have a 99.8-in fan to power the A330; and the PW4084/4090/4098 have a 112-in fan with wide snubberless blades to give 84,000–98,000 lb thrust, to power the 777.

In 1972 P&W began work on the JT10D to fill the gap between the JT8D and JT9D with a modern engine. A demonstrator ran in 1974 at 23,000 lb, and in 1977, following long collaboration, MTU and Fiat (now Avio) joined as risk-sharing partners. Since then the engine design has been largely started again, in the 37,400 lb bracket as the PW2037, pulling out all the stops to compete against the Rolls 535. The PW2037 has a single fan stage (78.5 in, 1,340 lb/s) rotating with four LP, 12 HP (all with controlled-diffusion aerofoils), an annular combustor and 2 + 5 turbine stages with active clearance control. P&W has claimed the PW2000 to be the most fuel-efficient in the world, but over 80 per cent of 757 customers picked the rival engine. Pratt & Whitney have fought back with reliability improvements, and have also sold the engine for the much-delayed Ilyushin 96M and, with military designation F117, for the USAF C-17.

In 1987 a partnership was formed with Allison to develop propfans, and this did get as far as flying an engine with geared pusher propellers. P&W is now working with other partners on what they call Advanced Ducted Propulsors, in other words turbofans of about 15 bypass ratio.

In the early 1990s P&W discussed the prospects for an engine to replace the JT8D with GE, MTU and SNECMA, but in 1995 went ahead on their own with a family of PW6000 engines. Northrop Grumman and Hispano-Suiza supply the nacelle and reverser. The PW6000 is to cover the thrust range from 15,000 to 24,000 lb. Features of all versions include a 56.5-in fan, three-stage core booster, six-stage HP compressor, single-stage HP turbine and three-stage LP turbine. Above 21,000 lb there will be improved materials and/or coatings in the hot parts. The PW6000 succeeded in being selected to power the Airbus A318, but the early test compressors did not perform as predicted. Eventually a new compressor had to be adopted, designed and made by German partner MTU, and the redesigned PW6000A at last entered service at the end of 2005, five years late.

An even bigger blow was failure to be selected to power the 787, but at least P&W has a half-share in the GP7200 (*see* Engine Alliance).

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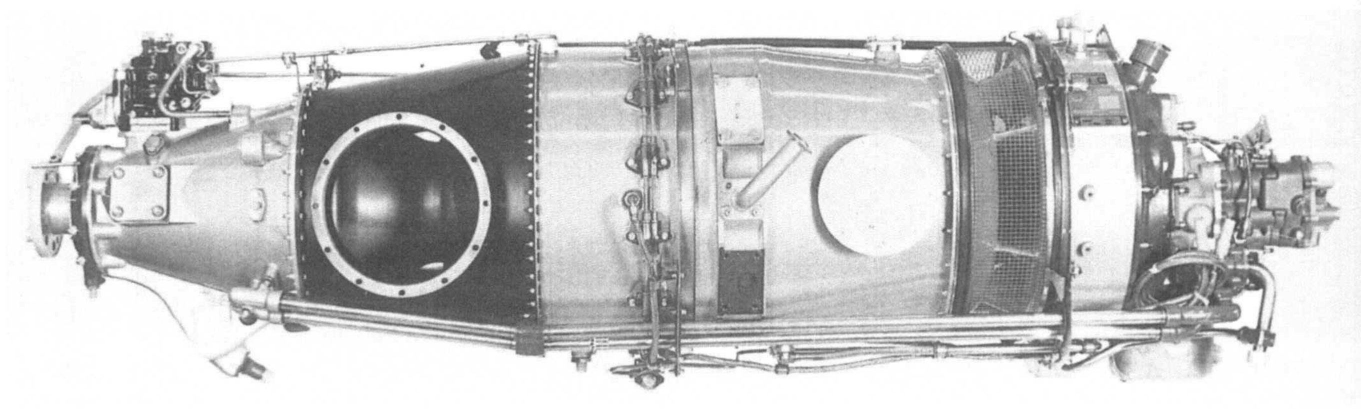
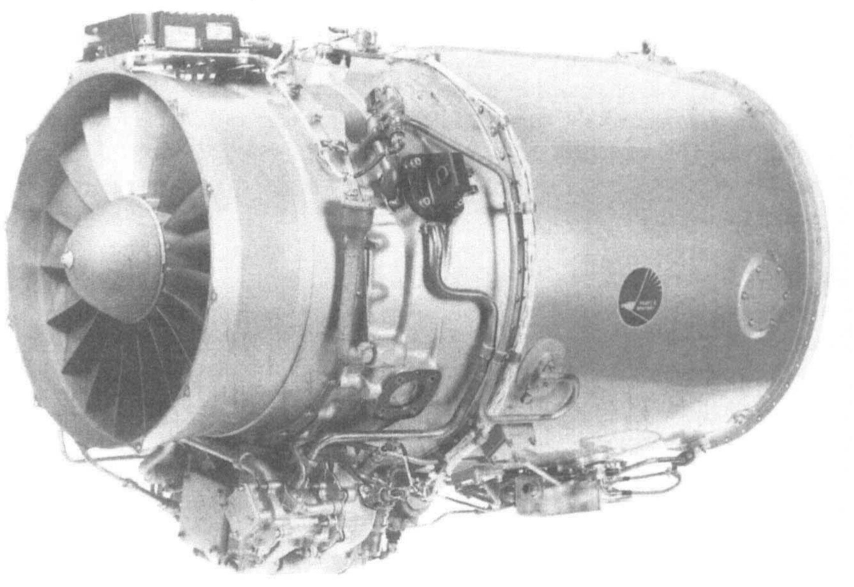
In April 1991 P&W scored a big win over GE by having its F119, in the 35,000-lb class, picked to power the Lockheed Martin F-22 Raptor. Features include a fan with three widely separated stages, rotating in the opposite direction to the six-stage compressor, both being driven by single-stage turbines. The digital control system also controls the 2DCD (two-dimensional convergent/divergent) nozzle, which can vector ±20°, rotating over the full 40° range in one second. The F-22A entered full USAF service in late 2005, by which time the F119's derivative, the F135, had logged hundreds of hours on test. It was intended to compete with the General Electric Rolls-Royce F136 to power the F-35 Joint Strike Fighter, but this newer and more powerful rival was cancelled by President Bush in 2006, leaving the F135 as sole engine of all versions of F-35. The F135-PW-600 incorporates the Rolls-Royce LiftFan, roll posts and vectoring nozzle for the F-35B, intended to replace the Harrier.

Pratt & Whitney Canada (CANADA) In 1927 the RCAF was so excited by the P&W Wasp that it suggested to a group of Montreal businessmen that it should be built in Canada. James Young responded, and Canadian Pratt & Whitney Aircraft was organised in 1928. Most of its effort was devoted to service support, but in 1951 sudden demand for new R-1340 Wasps resulted in the parent company at East Hartford deciding to build a major new plant at Longeuil, Montreal, to handle all future piston production and spares. Longeuil prospered, but studies showed the business would decline. In talks with the parent United Aircraft Corporation it was decided to make Montreal the P&W company handling turbine engines for general aviation. On 1 January 1957 the first six 'new hires' for this endeavour joined the firm and formed the nucleus of a new team.

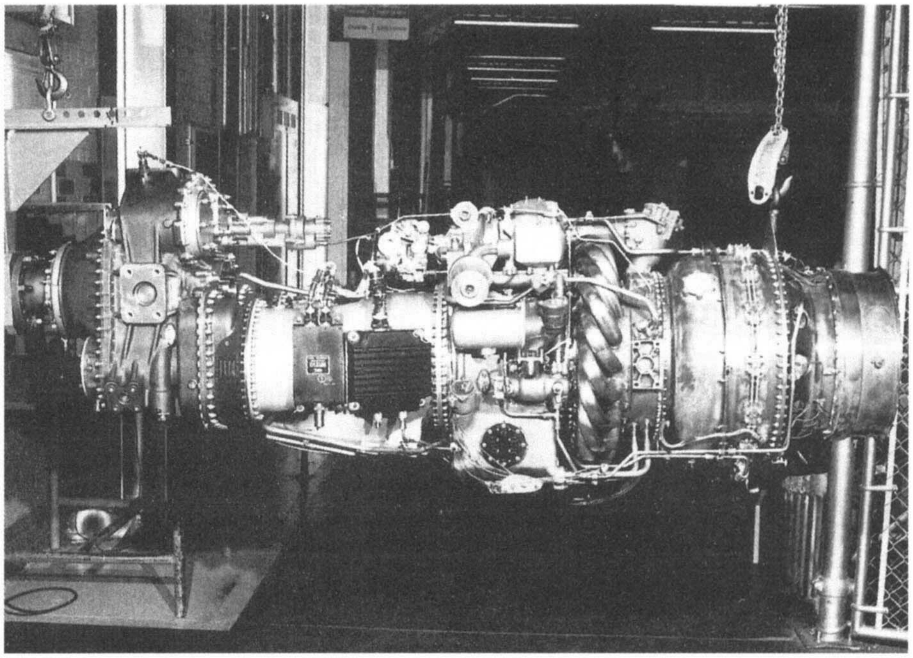
Though small turboprops were obviously the most likely replacement for the Wasp, there was the prospect of an immediate jet market in Canadair's proposed new military trainer, the Tutor. This was being designed to use the J83 or J85. The new team began designing the JT12 turbojet in the 3,000-lb class, but prospects looked interesting and with the Canadian company not yet big enough to handle it, the design and marketing team moved to Hartford, where the JT12 went ahead (see Pratt & Whitney). The team then returned to



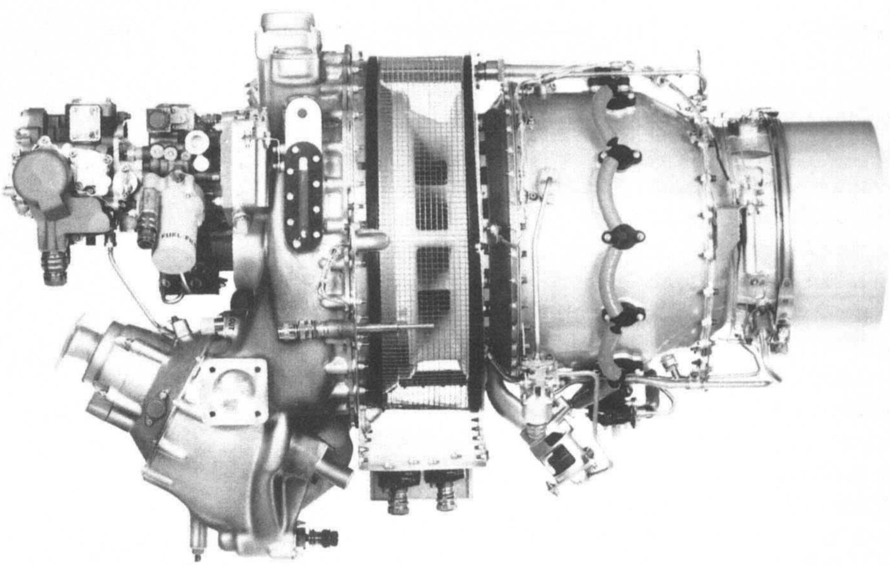
Engine of the Shorts 360, the PT6A-65A of 1,409 ehp is one of the longer and more powerful PT6 variants.



The P&W Canada JT15D-5 is the latest and biggest version of this popular turbofan, and it can be seen to have at last got rid of part-span shrouds (snubbers).



The front half (left in picture) of the PW100 is occupied by the gearbox; the air inlet is underneath amidships, and right of centre can be seen the ring of diagonal curved pipes taking air to the combustion chamber.

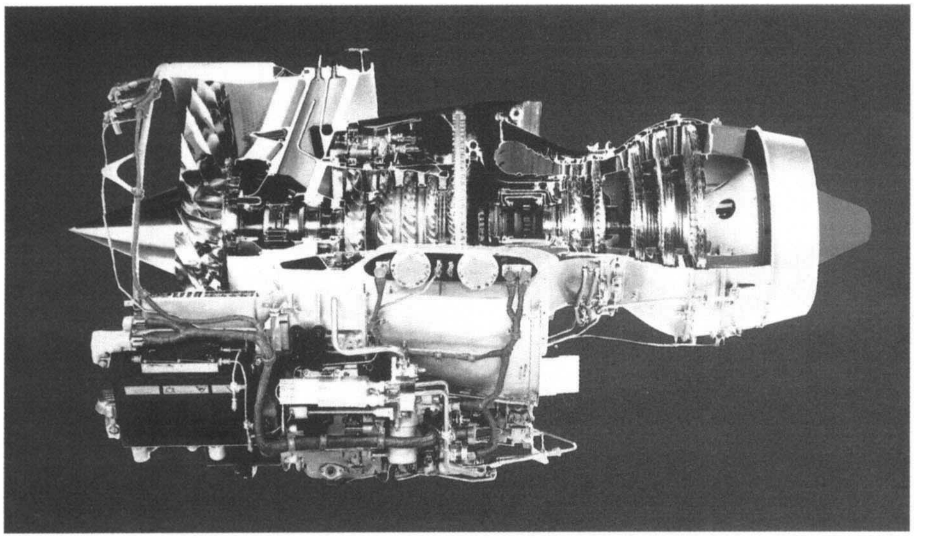


One of the PW206 family is the PW206B, with a diagonal drive shaft to suit the Eurocopter EC135.

Longeuil, cut their teeth by creating a new accessory gearbox for the RR Tyne-powered CL-44, and at last, in winter 1958/59, work began on a shaft engine in the 500-hp class. Studies showed it should have a gas generator with three axial stages preceding a centrifugal and a reverse-flow overall layout, with a free power-turbine shaft running away from, rather than through, the gas generator. Designated PT6, the gas generator ran in November 1959 and the complete engine in February 1960. It was way off the mark in performance and weight, but a 'Mark II' engine in July 1960 showed promise.

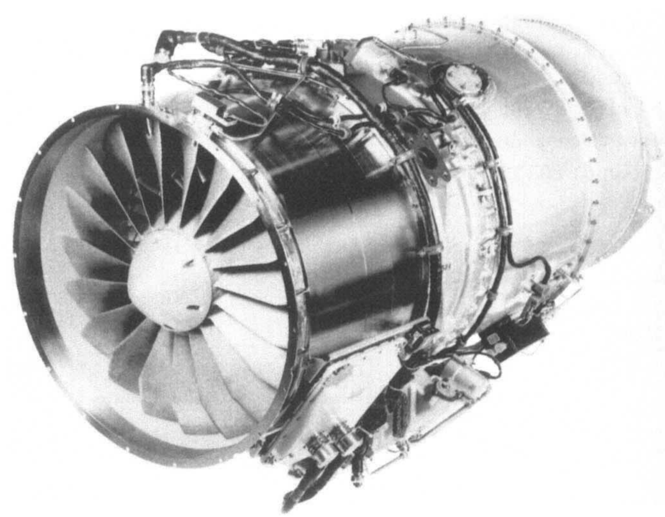
Features of the PT6 include: a compressor with three (-65 series, 4) axial stages plus one centrifugal, an annular reverse-flow combustor, an HP compressor-turbine, and an LP turbine (one-stage in early models, two-stage in high-power versions) driving the propeller gearbox. Airflow varies from 5.9 to 9.5 lb/s, with pr from 6.5 to 10, and there are many other variables to match no fewer than 29 distinct current production models to a host of applications, with powers from 475 to 1,327 shp. Not including the T74/PT6 helicopter turboshaft and the various T400/PT6T Twin-Pac twinned helicopter engines, which have sold as well as the fixed-wing versions, some 34,000 PT6 turboprops have been sold to over 5,500 customers. Further engines are being made under licence by Klimov (*qv*).

In 1966 design began on the JT15D turbofan, which contrives to combine simplicity with advanced technology. The original JT15D-1 has a fan aerodynamically scaled to 75 lb/s from the far larger JT9D fan, followed by a titanium centrifugal



This cutaway PW300 shows the large fan on the left driven by the three-stage turbine at the other end. The HP spool drives the accessories underneath.

Another of P&W Canada's great range of production engines is the PW545 turbofan.



compressor, annular reverse-flow combustor and 1 + 2 turbine stages, rating being 2,200 lb and weight 514 lb. The D-4 version adds an axial boost compressor stage and gives 2,375 lb, while the D-5 is a growth version with a rating of 3,045 lb.

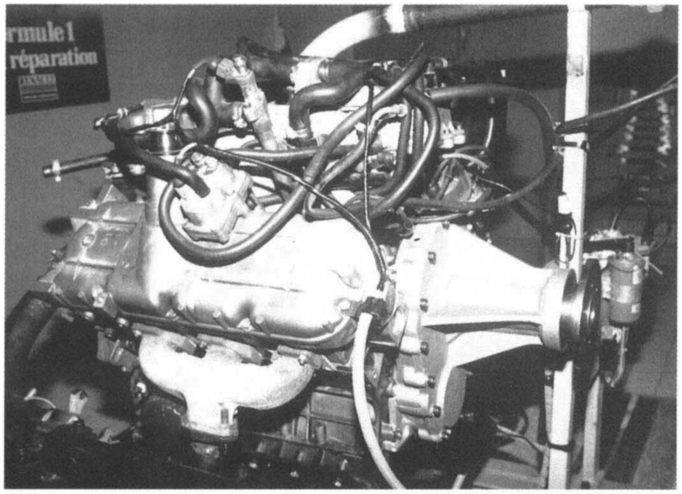
In the late 1970s work began on a totally new turboprop, the PW100 series, and this is now well on the way to rivalling the PT6 in number of versions and applications. Features include tandem centrifugal compressors (like the RR Dart, which it replaces), with the air delivered to the combustor via a ring of diagonal curved pipes. Early versions were rated at 1,800 shp, but today many versions are in service at up to 2,880 ehp (2,750 shp). The remarkable PW150A growth version, first run in June 1996, replaces the first centrifugal compressor by an advanced two-stage axial, the whole spool being driven by a two-stage HP turbine. This engine delivers 6,500 to 7,500 shp. The Montreal plant is also in production with a family of helicopter turboshaft engines designated PW206. These have a single high-speed centrifugal compressor and are rated at up to 690 shp.

P&W Canada has also developed two new families of turbofan. First, certificated in August 1990 for the Hawker 1000, is the PW305. This has a four-stage axial compressor followed by a centrifugal, driven by a two-stage HP turbine, and a 30.65-in fan driven by a three-stage LP turbine. This engine weighs 993 lb and is rated at 5,225 lb. The PW306 has a 31.65-in fan and is rated at 6,050 lb, applications being the Fairchild Dornier 328JET and IAI Galaxy, while the PW308 for the Hawker Horizon and 528JET is rated at 6,500 lb. First run in October 1993, the smaller PW500 has a single-stage HP turbine driving a compressor with two axial and one centrifugal stages. The PW530A for the Citation Bravo is rated at 3,000 lb, and the PW545A for the Citation Excel gives 4,450 lb; both are in mass production against large orders.

By 2006 many new versions had emerged for P&WC engines, and these had been joined by a new baby, the PW600. This was launched at a rating of 900 lb thrust to replace the Williams EJ22 as engine of the thousand-selling Eclipse 500. It was soon selected for many more entry-level jets, some being single-engined. The turboprop-derived PW150T powered the first Mi-38, and P&WC also bid the twinned PW150T to power the A400M, and claim their engine was cheaper than the winning Europrop submission. In 2006 neighbour Bombardier decided, at least temporarily, not to proceed with the C-Series twin-jet transport, which P&WC had hoped to power.

PRV (FRANCE) This excellent 90° V-6 water-cooled piston engine has been developed by FAM (France Aéro Moteurs, 50 per cent owned by Avions Pierre Robin) from a mass-produced car engine. The initials are from Peugeot, Renault and Volvo. Capacity is 2,850 cc (173.9 cu in) and typical take-off power 180 hp, the propeller being geared down from 5,500 to 2,430 rpm. It has dual computer control.

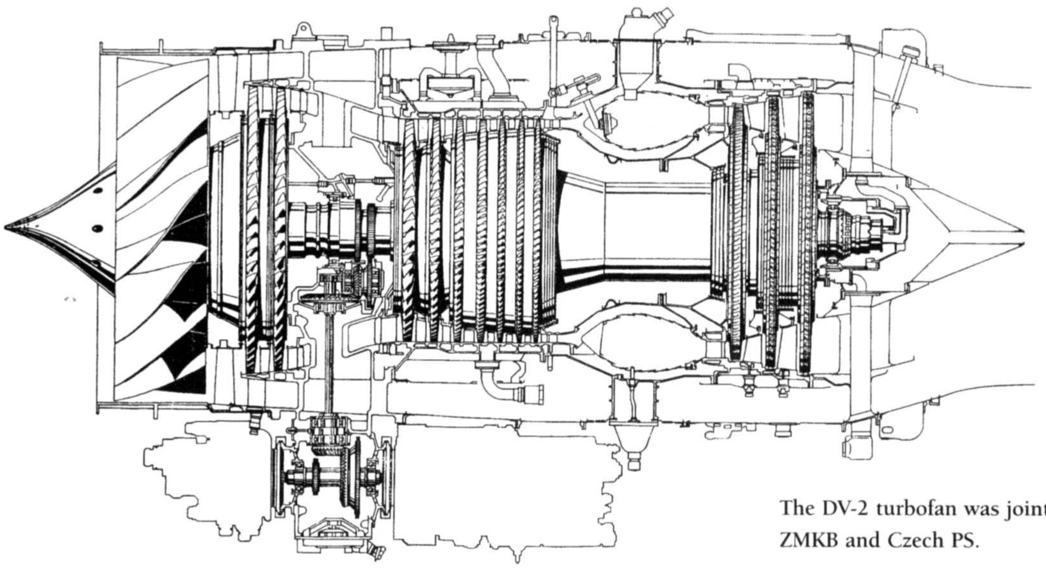
PS (SLOVAK REPUBLIC) The Považské Strojárne company at Bystrica was the principal developer of the DV-2 turbofan, rated at 4,852 lb. This has a single-stage fan of 25.4 in diameter, two-stage core booster and seven-stage compressor. Early development was in partnership with ZMKB of Ukraine, but in 1993 Klimov of Russia (*qv*) bought the ZMKB share in order to produce engines for the Yak-130. Meanwhile, PS has delivered engines for the Czech L-39MS and L-59. Numerous developed versions, including turbofans, turboprops and turboshaft engines, are on the drawing board.



One of the rapidly growing number of aero engines derived from mass-produced automotive engines is the PRV, rated at 160 hp.

PZL (POLAND) PZL is the association of Polish aero and engine producers, but before the war it had different divisions, one of which licensed such engines as the Pegasus and Walter Minor. In 1952 responsibility for manufacture and support of Soviet piston engines was transferred to what is now PZL Kalisz, which still supports the Ivchyenko AI-14 and Shvetsov ASh-62 (as the ASz-62IR). PZL-Rzeszów makes the Glushenkov engines as the PZL-10 series and Isotov GTD-350. The PZL-3 is a Polish seven-cylinder radial derived via the LIT-3 from the Ivchyenko AI-26; without change in capacity or rpm it has been uprated to 600 hp and is available in direct or geared forms. In the 1950s Wiktor Narkiewicz designed the WN-3 radial with seven smaller cylinders (135 × 134 mm, 13.4 litres), rated at 340 hp at 2,500 rpm and made in small series; the WN-4 was a helicopter version. Today PZL also licenses former Franklin opposed air-cooled engines (*qv*), in two-, four- and six-cylinder versions.

Among this mass of former Soviet and American engines, Poland still has an important indigenous design capability in the IL, Instytut Lotnictwa. This has produced several turbojets, such as SO-1 and SO-3 versions, for Polish trainers, and has now followed with the K-15, which is in production by PZL-Rzeszów to power the Iryda. It has a rating of 3,307 lb. Not yet certificated, the D-18A is a small turbofan with a rating of 3,968 lb.



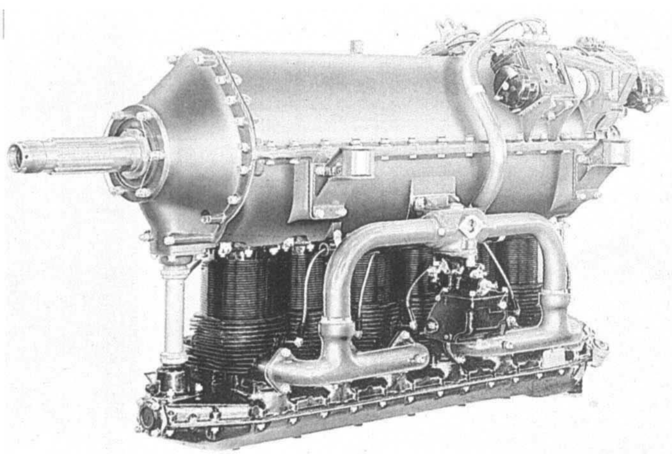
The DV-2 turbofan was jointly developed by ZMKB and Czech PS.

R

R

Ranger (USA) When the Fairchild Airplane Manufacturing Corporation was incorporated in 1925 Sherman M. Fairchild had already launched the design of an in-line air-cooled engine. This was designed in 1926, built in 1927 and marketed in 1928 as the 6-370, this giving the number of cylinders and capacity. This engine had steel barrels, shrunk/screwed aluminium cast heads with Al-bronze seats for the two valves, an underhead camshaft driven from the front (with a magnesium cover serving as the sump) and a built-up aluminium crankcase with seven main bearings. A distinctive feature was the mixture supply manifold which had a T-junction leading to 12 further T-junctions each serving a single cylinder on one side and two on the other. This basic configuration lasted through all the successor engines, all of which had slightly bigger cylinders. The sixes went through 390 and 410 to a final 441 cu in (4.125 × 5.5 in), the 6-440 being rated at 175 to 200 hp at 2,450 rpm, depending on sub-type and fuel grade, for a weight of about 376 lb.

The name Ranger was introduced in 1930, Ranger Engines Division becoming a subsidiary of Fairchild Engine and Airplane Corporation on the latter's formation in 1936. By this time a market was appearing for the V-770, an inverted V-12 with 773 cu in from cylinders 4 × 5.125 in and with fork/blade conrods. Fair numbers were produced in 1941–5 at 520 hp at 3,150 rpm, geared and supercharged, weight being 730 lb. Postwar business dwindled, ending with two-cylinder airborne generating sets for large aircraft. The J44 is dealt with under Fairchild (*qv*).



A typical Ranger, the 6-390-D was rated at 150 hp. Virtually all Rangers had accessories high at the back and the camshaft drive at the front.

Rateau (FRANCE) Auguste Rateau had a factory at La Courneuve, on the road from Paris to Le Bourget. Famed for his steam turbines, and from 1917 for his turbocharger, he also studied gas turbines and during the Second World War he designed the SRA.1 axial bypass jet, run in 1947. It had a four-stage LP and 12-stage HP compressor, the latter being bypassed by much of the flow, all on one shaft. Thrust was claimed to be 1,200 kg. After 1950 the all-steel SRA.101 Savoie followed, with 10-stage compressor and again with 12 pipes bypassing much of the flow round the 12 combustors. Planned for 4,000 kg, it was again unsuccessful. This may have been due to fundamental errors in aerodynamic design which surfaced when, in 1960–4, the company tried to sustain a gigantic lawsuit against other turbojet companies and operators (it lost).

Reaction Motors (USA) Reaction Motors Incorporated was formed in 1941 by four members of the American Rocket

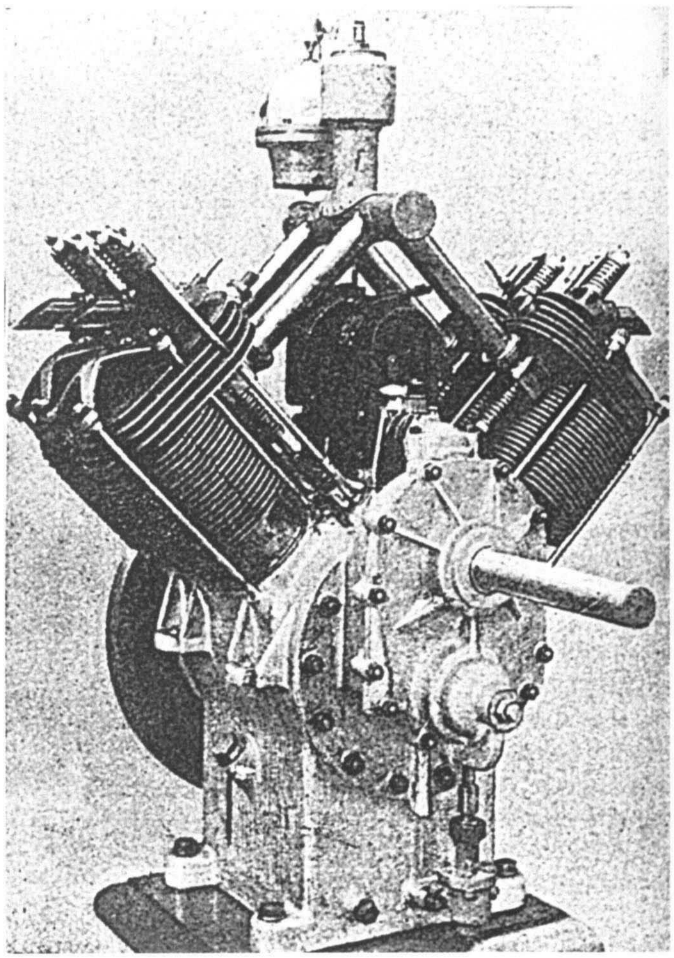
One of the main wartime Rangers was the 6-440C-5 (military designation L440-7), rated at 200 hp on 87-grade fuel. In 1947 the author helped sledgehammer 115 new ones, along with the Cornells in which they were installed; only the packing cases were spared under Lend-Lease rules. Location: Southern Rhodesia.

Society, and soon found itself involved in major development programmes for engines for test vehicles, missiles and aircraft. Of the latter the first was the 6000C4 (6,000 lb thrust, four chambers). Developed from 1943 for the XS-1 (later X-1), it used gas pressure to feed ethyl alcohol and lox to four stainless-steel thrust chambers each with its own electric ignition. Chambers could be fired separately or in any combination. As the XLR11 it was built in small numbers for X-1 variants and the D-558-II, later engines having turbopump feed. In 1955 RMI was awarded the propulsion contract for the X-15 hypersonic research aircraft. While the LR99 engine was being developed, the first two X-15As were flown with twin LR11-RM-5s each rated at 8,000 lb at SL. The first LR99 Pioneer engine was delivered in May 1960, and on 8 June exploded during a ground run in the No. 3 aircraft. As a result the first flight with the LR99 was made by No. 2 aircraft on 15 November 1960. No larger than the LR11, the LR99 had a diameter of 40 in, length of 72 in, weight of 910 lb, and burned anhydrous ammonia and lox at 10,000 lb/min to give 50,000 lb thrust at SL and 57,000 lb at high altitude. It was fully throttleable and could be repeatedly shut down and restarted in space. RMI also developed small helicopter tip-drive rockets. In 1958 the company was taken over by Thiokol Chemical (now Morton Thiokol).

Regnier (FRANCE) Starting as licensees of the Gipsy Major and Six, this small company quickly introduced successive modifications until the engines were fresh designs. The only one of importance was the 4L, with cylinders 120 × 140 mm (6.3 litres), first run in 1936 at 90 hp and developed post-war at 147 hp at 2,340 rpm, or with 7.2 compression as the 4L.02, giving 170 hp at 2,500 rpm. Unusual features included steel cylinders with baked varnish protection, Y-alloy heads held by long bolts into the crankcase, and special metal/plastics sealing rings for the two cylinder joints. Many sub-types existed, differing mainly in the arrangement of accessories. Regnier was absorbed by Snecma in 1947.

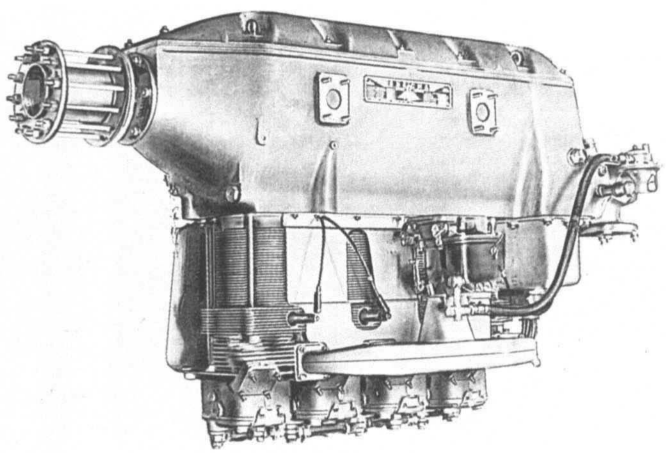
Renault (FRANCE) This great car company was started by the brothers Fernand, Louis (the designer) and Marcel Renault, and they completed their first aero engine in January 1908.

They chose a 90° V-8 with air-cooled cylinders 70 × 120 mm, producing 35 hp at 1,400 rpm. By January 1909 they had increased bore to 90 mm, giving 6.1 litres, the new rating being 55 hp at 1,600 rpm. Also run in 1909 were a 25-hp V-4 and a 45-hp water-cooled upright four-in-line. The latter had twin overhead valves, flywheel and (unlike the other engines) direct drive from the crankshaft, and proved a dead end. All the other engines had cast-iron cylinders of F-configuration, with a lateral projection on the inner side providing for an overhead exhaust valve worked by pushrod and rocker and an inlet valve on the underside, driven by a direct pushrod. Petrol feed was from a carburettor mounted low down on one side of the engine. The camshaft was

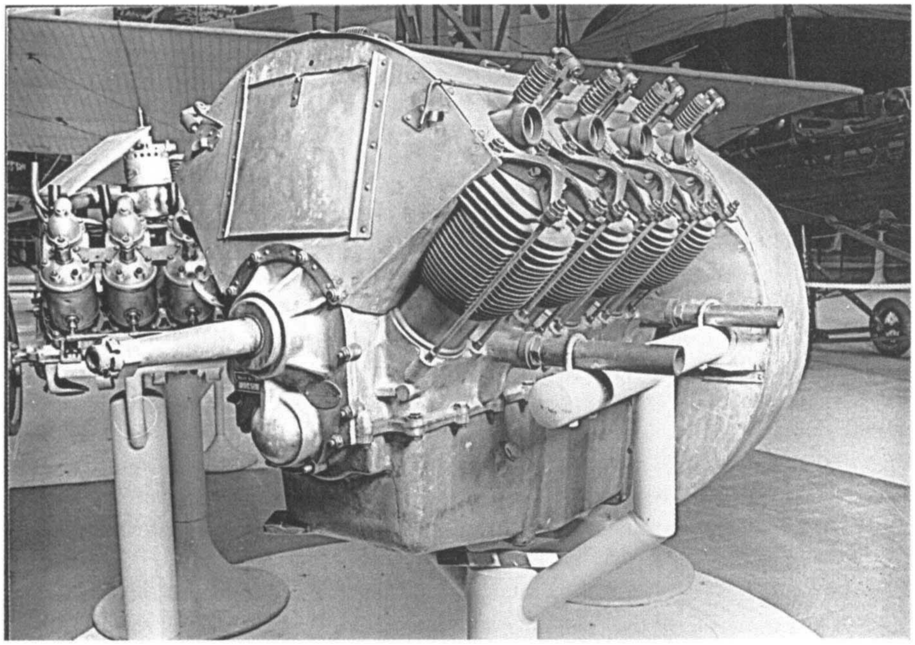


This V-4 of 25 hp of 1909 was a typical early Renault aero engine. The propeller was driven off the half-speed camshaft. This engine has a high carburettor.

R



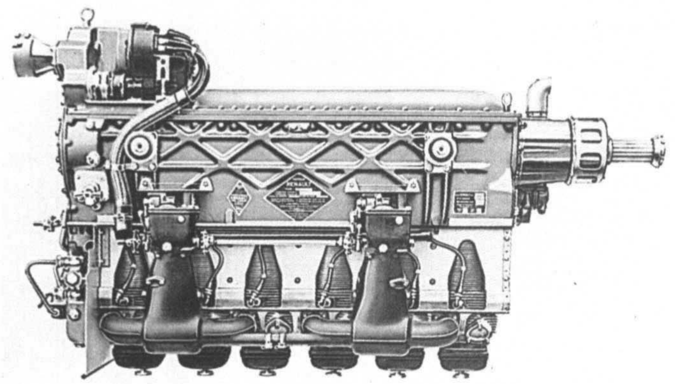
The Regnier 4L was made in large numbers by SNECMA, though at over 331 lb (150 kg) it was heavy for its power.

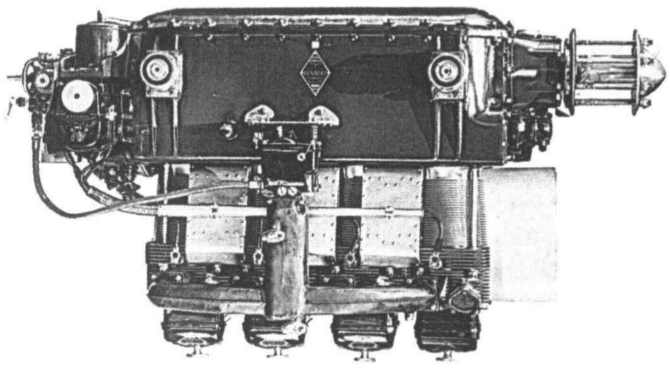


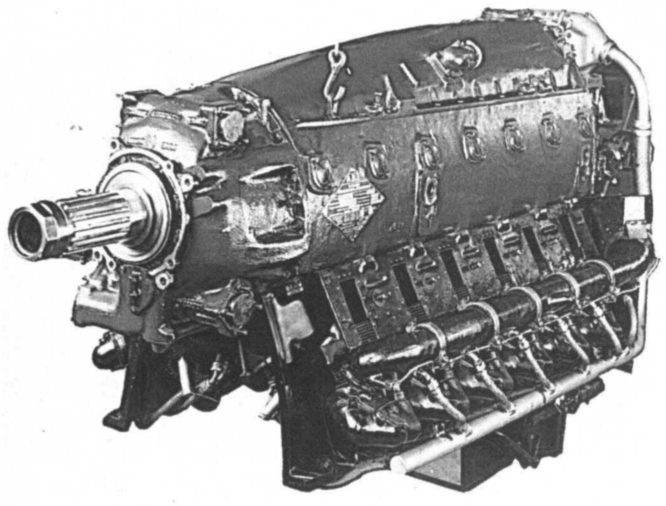
Left: A typical 1914 Renault air-cooled V-8, complete with upper cooling baffle. Most such engines were rated at 70–100 hp.

Below left: During the Second World War Renault made many hundreds of 6Q (Bengali 6) engines of 220 or 240 hp, but an RAF raid on Billancourt in 1943 brought output almost to a halt. Note the twin carbs, and magnetos above the crankcase.

Below right: Last of the Renault four-in-lines, the 4P was made in small numbers even after the company was absorbed into SNECMA in 1946. Like the 6Q it was known as the Bengali (with suffix 4 or 6 depending on number of cylinders), a typical rating being 140 hp.







Variously known as the Renault 12S and SNECMA 12 S, this 600-hp inverted V-12 was developed from the German Argus As 411, last and most powerful of the Argus range.

strengthened to drive the propeller, though it is doubtful if a big four-blade propeller at 650 cruising rpm was any better than a two-blader driven off a 1,300-rpm crankshaft. Tens of thousands of Renaults were delivered by 1918, many of them directly derived V-12s and with various cylinder sizes up to 125 × 150. Some were pushers, and these had a crankshaft-driven cooling fan and tight-fitting air casing. They were heavy, very conservatively rated, had to be decoked every 20 hours and fully overhauled every 50–70 hours, and, being partly fuel-cooled, were amazingly inefficient; but their reliability made up for all the rest.

The chief postwar engines were the 300-hp 12E and 12Fe and 420-hp 12K, all with 125 × 150 cylinders. The company persisted throughout the 1920s with big V-12s, both air- and water-cooled, but in 1928 wisely went for the low-power market with the 4P upright four-in-line. A crude but effective 90-hp unit, it was developed into the 4Pbi and Pci inverted engines; bore was then enlarged from 115 to 120 mm, stroke remaining 140, to give the 4Pdi Bengali of 6.3 litres (same as later Regniers), starting life at 145 hp at 2,350 rpm.

There followed a series of inverted four- and six-in-lines spurred by Coupe Deutsch racing, which by 1940 had also led to remarkable light fighters. Most of the latter had the 450-hp 12RoI inverted V-12, but the final Caudron prototype, the C.R.770, had the prototype of a new inverted V-16, the Renault 626 of 800 hp. Raymond Delmotte took off on the first flight as the German troops approached the test airfield at Guyancourt; the long crankshaft had insufficient bearings and broke after a few minutes, and Delmotte had to turn back. The 500-hp R468 inverted V-12 ran at 500 hp in April 1940, but its C.R.780 airframe was never completed.

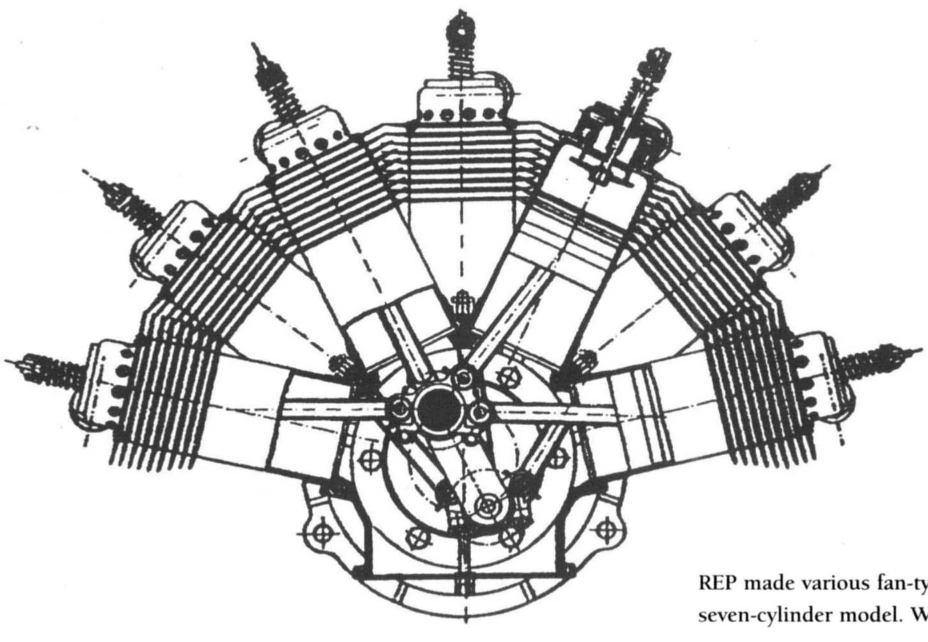
During the war Renault produced 4P and 6Q in-lines as well as the Argus As 411. In 1945 the latter was further developed, culminating in the Renault (Snecma) 12T of 625 hp at 3,300 rpm. Renault directors were taken by the Paris Communists in 1945 and never seen again, the company being nationalised into Snecma.

REP (FRANCE) Pioneer aviator Robert Esnault-Pelterie powered his 1907 and 1908 monoplanes by ingenious engines often described as seven-cylinder radials. In fact they were in effect two-row fan engines, the front row having four-cylinders and the rear row three, all mounted round the upper part of the crankcase. Cylinders were 85 × 90 mm (30 hp) or 85 × 95 (35 hp). Each cast-iron cylinder was bolted to the aluminium crankcase, pistons being very thin-walled steel with the gudgeon pin held by a cast pivot screwed into the piston head. The cylinders each had one valve, set alternately in one of three positions: inlet (pushed down), both ports closed, and exhaust (pulled up to open the surrounding collar). In 1909 REP even sold several 60-hp 14-cylinder four-row engines.

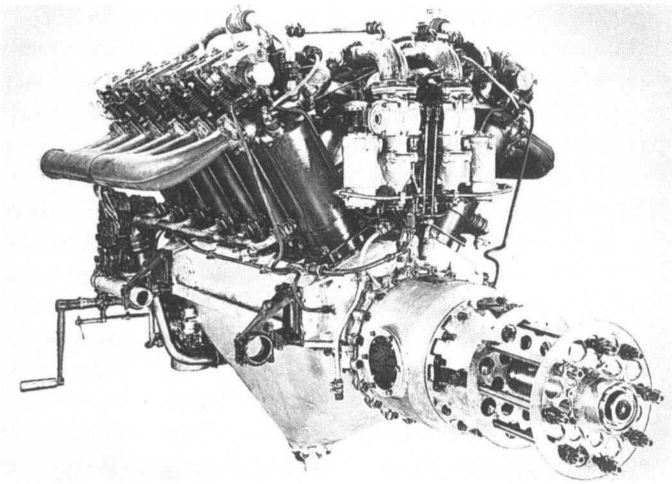
RKBM *see* Rybinsk.

Rolls-Royce (UNITED KINGDOM) One of the world's best-known companies was formed in 1906 by Henry Royce, who struggled from humble beginnings to become an engineer, and the Hon Charles S. Rolls, a wealthy sportsman who took an honours engineering degree at Cambridge. Their first product was the Silver Ghost car, in production in 1907, but the actual running of the firm was left to chairman Ernest Claremont and managing director (commercial) Claude Johnson. Royce had extraordinary foresight for the day in realising that there would soon be a market for aero engines, but his interest turned to antipathy when Rolls was killed in 1910 when his Wright suffered inflight structural failure. In 1911 Royce became seriously ill, and for the rest of his life convalesced, from 1913 in the south of France, then at St Margaret's Bay, Kent, and finally at West Wittering, Sussex. He nevertheless remained the focal point for every technical detail of the company's products to his death in 1933, and the extra effort and travelling this caused may be imagined.

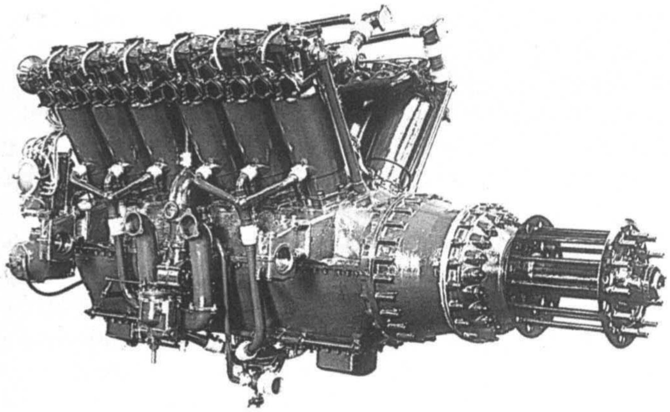
On the outbreak of the First World War Commodore Sueter of the Admiralty accepted the suggestion of Wilfred Briggs, head of the Air Engine Section, that the famous Derby firm should be asked to design a 200-hp aero engine, mainly as an insurance to back up Sunbeam. Briggs' assistant Lieutenant W.O. Bentley (later car designer) agreed that a good starting point would be the cylinder of the Mercedes racing car that had won the 1914 French Grand Prix, which happened to be on show in London. He did, however, later suggest the pistons should be aluminium. On the first Sunday of the war, 9 August 1914, Briggs and Bentley towed the racer to Derby. There its engine was immediately dissected by Ernest Hives, head of the experimental shop and chief test driver. Hives, Hs in company shorthand, was a man of towering character and capability. Even in 1914 with his small hand-picked team he exuded confidence to solve problems quickly.



REP made various fan-type engines, the most powerful being this seven-cylinder model. Weighing 462 lb, it was rated at 95 hp.



The start of Rolls-Royce in aviation was the Admiralty order for 'the 200-hp engine'. This Eagle VIII of 1917 gave double that output, establishing a tradition of ceaseless development.



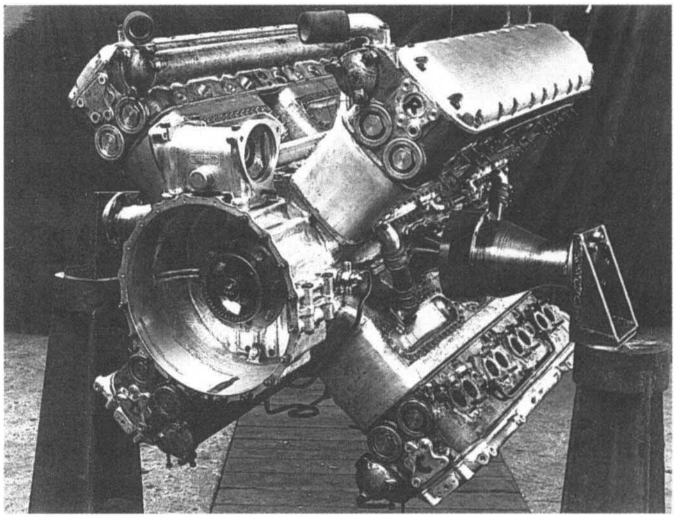
The original wartime Condor seen here was basically an enlarged Eagle with a horizontal sump and four-valve cylinders. In June 1921 Rowledge came from Napier and turned the Condor into a much more modern engine.

Hives alone would have put Rolls-Royce in a special position, and he was the perfect foil to Royce's humourless insistence on painstaking development to increase power and reliability by the methods which today are taken for granted but which were widely regarded with bemused disbelief in 1914. But there was an extra ingredient present from the start injected by Johnson. This was a belief in RR superiority and indeed infallibility. Like the Admiralty the War Office wanted the firm's resources applied to improving Britain's pathetic showing in aero engines, but did so by asking it to make Renault or RAF engines under licence. Johnson's reply was typically uncompromising: 'Such a plan would yield nothing but mountains of scrap . . . I would go to prison rather than agree to it.' It is rather surprising that he did agree to using features borrowed from Mercedes, and in fact both licensed Renault and RAF.1A engines were made.

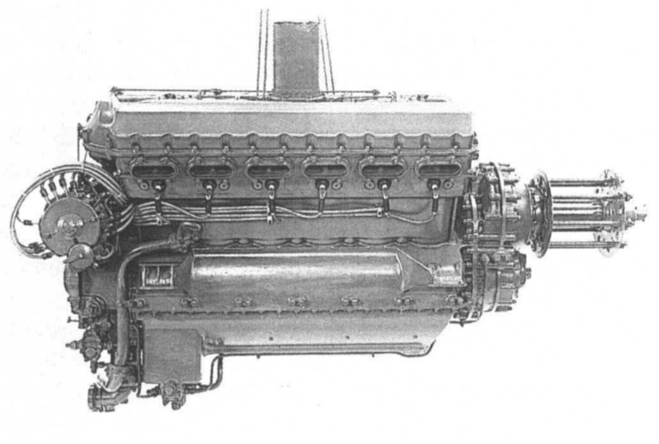
Down on the Kent coast Royce had fewer inhibitions. As a true engineer, his objective was the best product. He spent nearly a month evaluating alternative engine layouts, and took particular care not to infringe any Mercedes patents. On 8 September he finally settled on a water-cooled V-12 with cylinders 4.5 × 6.5 in, 1,238 cu in, to give the required 200 hp at 1,600 rpm, with 0.64 geared drive. Each cylinder was a steel forging, held by studs through the flanged base on the cast aluminium crankcase. Inlet and exhaust ports were forgings welded on opposite sides of the head, the two overhead valves being driven by single part-exposed camshafts. At the rear were bevel drives to the centrifugal water pump, main oil pump, two 12-cylinder magnetos serving two plugs per cylinder, a tachometer and hand-cranking dog clutch. Two Claudel Hobson updraught carburettors were used (the handbooks called these 'Rolls-Royce') each serving one cylinder bank. The V-angle was 60°, and each crankpin was driven by one master and one articulated rod. Water jackets were welded steel pressings, each needing its own piping. The only unusual feature was the reduction gear, of the epicyclic type.

Royce strove for refinement and reduced weight having wooden models of many parts sent from Derby and returned with detailed instructions for modifications. The prototype '200-hp engine' was started in March 1915 and Hives soon had it running at 1,800 rpm and giving 225 hp. Meanwhile, Royce approved two further engines, a six-in-line with 4 × 6 in cylinders, and a V-12 with cylinders 4 × 5.75 in (867 cu in). Prototypes appeared in winter 1915–16, the V-12 being designed at Derby by R.W. Harvey-Bailey. Johnson then named all three engines respectively the Eagle, the Hawk and the Falcon.

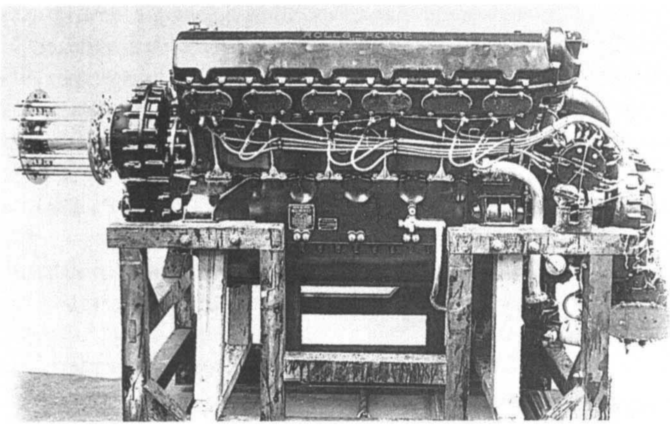
Almost all the effort went into the Eagle, which Royce, increasingly delegating work to assistant A.G. Elliott, kept



This photograph of the Eagle XVI was taken from the drive end, showing the casing of the epicyclic reduction gear. Cast aluminium throughout, it was a very clean engine.

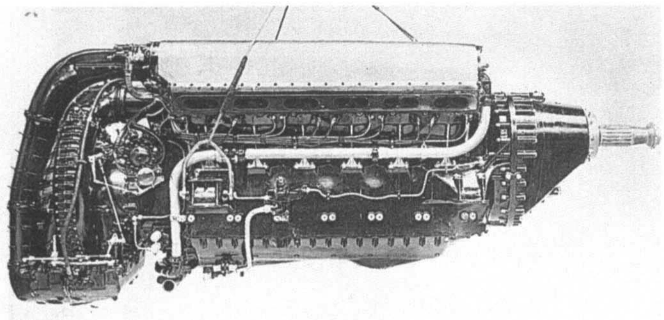


Rowledge also played a big part in designing the Kestrel, with cylinders in cast blocks. This is an early production example, geared but unsupercharged (and with Hucks starter dogs on the front of the propeller shaft).



The Buzzard was essentially an enlarged Kestrel; only 100 were built, but they powered a great variety of aircraft. Its chief importance was in providing the basis for an engine to contest the Schneider Trophy.

R



The R was by a wide margin the No. 1 racing engine of its era, and Campbell and Eyston later used it to set land and water speed records. Note the enormous ram inlet duct and supercharger, which by October 1931 was generating a manifold pressure of 72.3 in – yet an R could idle at 475 rpm.

improving. His stream of letters, memos and drawings to Derby, outlining design philosophy, test procedures and many other matters, were considered so important – and so far ahead of other companies – that in December 1915 the directors had them printed in a limited edition of 100 and bound, one copy being shown only to selected young engineers to ensure the tradition of excellence. A basic philosophy, though expressed in very different words, was 'flog it until it breaks, think about the failure and modify the part'. By this means the Eagle power rose from 225 hp to 266, 284, 322 and by March 1917 to 350 hp in the Eagle VIII, all continuous ratings at 1,800 rpm. Higher powers were available for 5 minutes at 2,000 rpm. Except for the Eagle I and IV all had four carburettors, the Mark VIII having two at each end, and later engines had four six-cylinder magnetos. A typical 350/375-hp Eagle VIII weighed 847 lb.

The Eagle, the 75/105-hp Hawk and 205/285-hp Falcon all had important wartime applications, and in the immediate postwar era the Eagle was the leading British engine in large military and civil aircraft, making the first direct crossing of the Atlantic and the first flights to Australia and South Africa. Later Eagles were cleared for an overhaul life of 100 to 180 hours, then exceptional figures. In the 1920s it faded against competition from the Jupiter and Lion, but firmly established RR's reputation in aero engines.

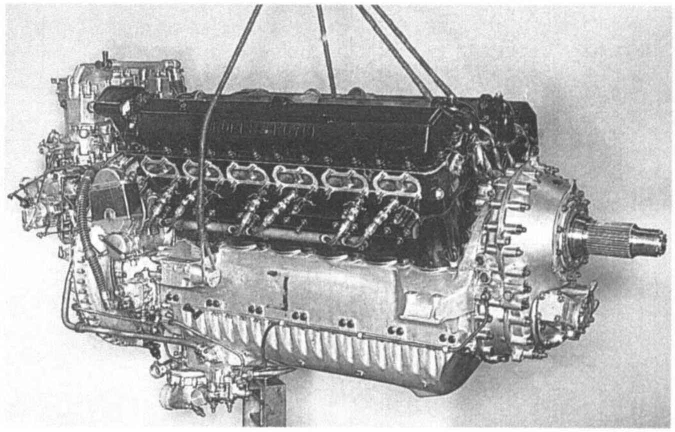
In 1917 design was started on an Eagle scaled up to 5.5 × 7.5 in cylinders (2,138 cu in) to power the V/1500 bomber. This was the Condor, and though it was not ready in time for its original application its power of 550/600 hp found plenty of other uses. The big cylinders each had four valves, though still with a single camshaft on each bank, and the twin carburettors were mounted low down on each side at the midpoint of the engine. Another new feature was an electric starter. In the early 1920s A.J. Rowledge, from Napier, was given the job of redesigning this obsolescent engine, and the resulting Condor III of 650 hp had fork-and-blade conrods, spur reduction gear, and improved valve gear and accessories. But Trenchard wished all RAF engines to be capable of dispersed manufacture by car firms; RR still insisted they alone could make their engines, and when he read this Trenchard scrawled across the page 'No more Condors'.

Royce had already thought about a new engine, so that when in 1925 Lieutenant-Colonel L.F.R. Fell of the Air Ministry asked British firms to beat the Fairey Felix, the groundwork had been done. It is recorded that Royce drew preliminary outlines with his stick on the sand at West Wittering, leaving Rowledge to do the design in detail. The new engine was called the Eagle XVI, though it had nothing in common with the Eagle but water cooling, for it was an X-16 with four banks of small two-valve cylinders supercharged by a double-sided gear-driven blower with four volute outlets, one to each bank. This was run at some 500 hp in mid-1926, and a bigger Eagle XX was planned, but both were then dropped in favour of a modernised V-12 to compete more directly with the Felix.

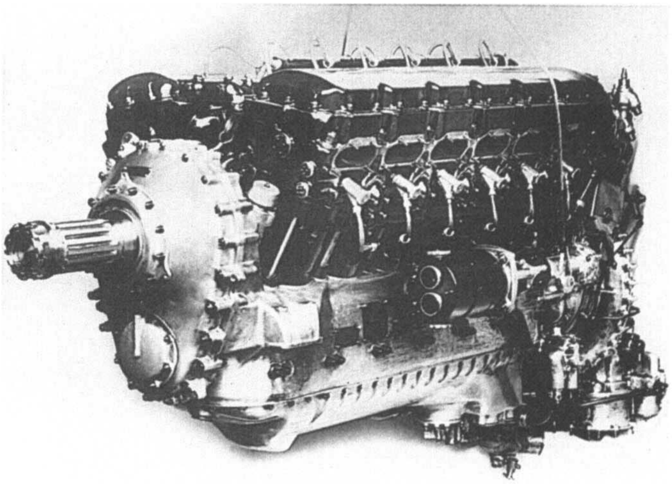
Elliott helped at Wittering, while at Derby Jimmy Ellor, top supercharger expert at Farnborough, joined the firm to help Rowledge design this new component. The big difference in the F, as the new engine was called, was that each bank of six cylinders was a monobloc aluminium casting, with thin steel open liners of 5 × 5.5 in size (1,296 cu in) resembling those of the Puma rather than the Hispano or D-12. The first type-test, at 490 hp at 2,350 rpm, was gained by the compact F.10 direct-drive engine in spring 1927. In 1928 various geared Fs appeared, and in 1930 it was named Kestrel. By this time the company had begun to develop its own aircraft installations at Tollerton, later moving to Hucknall airfield, north of Nottingham, and this growing establishment played a major role in almost all subsequent engines. One of its first tasks was to produce a ram air inlet, first used on the R (see below), which added some 10 mph to Kestrel aircraft. During the 1930s full supercharge, automatic boost control, 87-octane fuel and salt-cooled exhaust valves all resulted in improved Kestrels, the final marks being rated at 745 hp at 14,500 ft at 3,000 rpm. Kestrel deliveries were 4,750, just topping the wartime total of Eagles (4,674).

In the late 1920s some work was done on diesels, aided by Harry Ricardo and the RAE, and two compression-ignition Condors were type-tested in 1932 and flown. The future, however, lay with the monobloc petrol engine, and to power large flying boats an enlarged F was designed in June 1927 as the H, later named Buzzard. This geared and supercharged engine had cylinders 6 × 6.6 in (2,239 cu in), and initially weighed 1,460 lb, rating at sea level being 925 hp. Few were built, but in 1928 it formed an admirable base for the R engine to contest the 1929 Schneider Trophy. Basil Johnson, brother of the late Claude, was opposed to any form of racing (and in fact resisted increased expenditure on aviation by what he considered a car company). Air Ministry pressure secured from Royce an assurance that an engine would be forthcoming. Royce schemed a narrow V-16, but there was not enough time and the only way to meet the schedule was to use the Buzzard as starting point. Highly stressed parts were strengthened, the crankcase, valve gear and accessories redesigned to improve streamlining, and a giant double-sided supercharger fitted with a ram induction pipe between the blocks. The first endurance run was in May 1929, the promised 1,800 hp being held for 1 h at 2,900 rpm. F.R. Banks then advised on special fuel mixes, and the 1929 race was won using 78 per cent benzol and 22 per cent Romanian naphthenic petrol, plus 2.5 cc TEL per gallon. Power was 1,900 hp for a weight of 1,530 lb. On the night before the race there was a frantic cylinder-block change on Flying Officer Waghorn's S.6, the fitters being rounded up from Southampton's pubs. Waghorn was not told until he won the race; his son still has the failed piston.

After Lady Houston had donated £100,000 to enable the RAF to contest the 1931 race, the government having declined to do so, Rolls realised they were faced with the biggest challenge yet posed by a petrol engine. The go-ahead was delayed until January 1931, so all that could be done was to work around the clock on the R. Rpm were increased, supercharger gear ratio raised and the air inlet enlarged; fork/blade rods were replaced by articulated rods, main bearings gave prolonged trouble, and all main moving parts were again strengthened. Valve springs lasted minutes only, and at one time oil consumption was 112 gal/h, but in August 1931, using a further Banks (Associated Ethyl) special brew and pure castor oil lubricant, 2,350 hp was held at 3,200 rpm at 67.2 in manifold pressure, weight being 1,630 lb. Spare blocks were not needed, and the trophy was won for keeps on 13 September 1931. Soon afterwards Banks came up with 30 per cent benzol, 60 per cent methanol and 10 per cent acetone, plus 4.2 cc/gal TEL, and with this 2,783 hp was obtained at 72.3 in at 3,400 rpm. Nothing remotely like this



Big downdraught carburettors on an unpainted Kestrel-size engine show this to be a Peregrine, used in the F.9/37 and Whirlwind twin-engine fighters. It introduced progressive boost control, each increment of throttle-lever travel giving a corresponding variation in power.



The Merlin I had little in common with the wartime Merlins but the maker's name.

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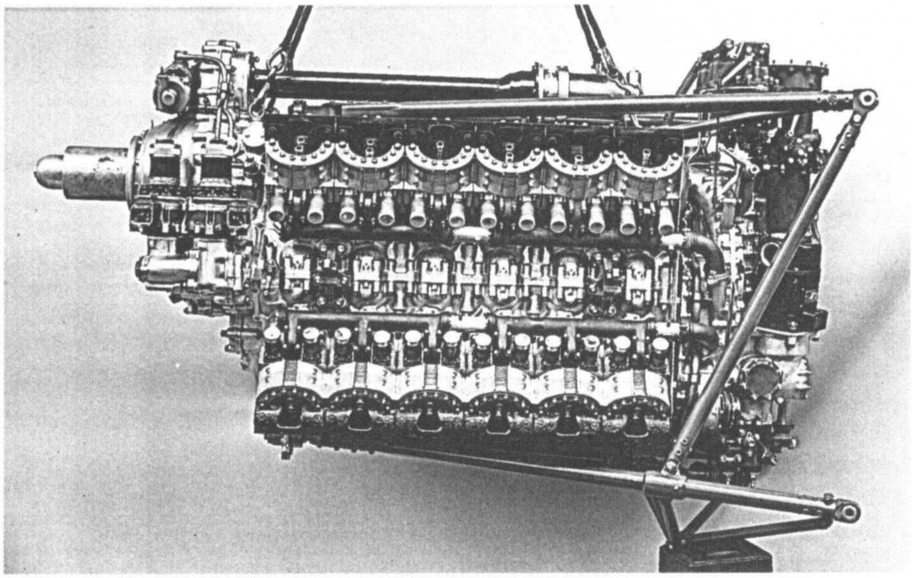
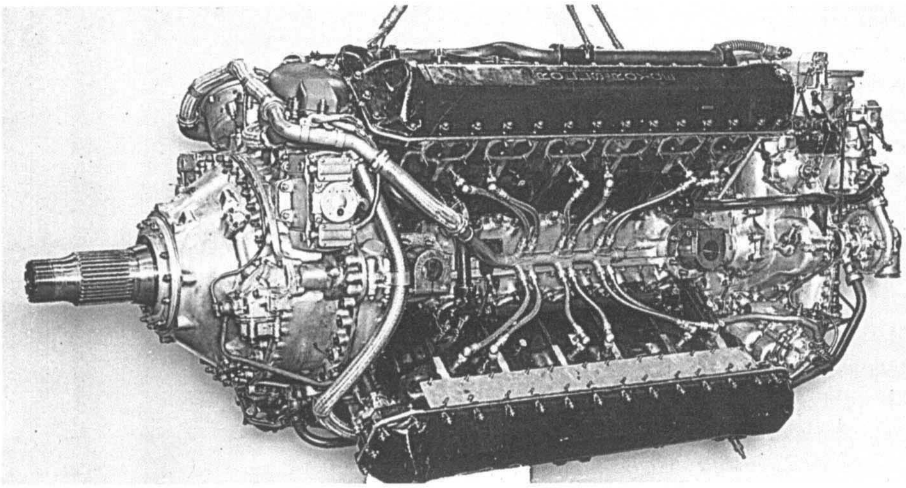


The air-cooled sleeve-valve Exe was Rowledge's last design, and it never gave a moment's trouble. The company Exe-Battle flew several hundred hours as a regular liaison aircraft after the engine itself had been cancelled.



In stark contrast Vultures gave so much trouble that 97 Squadron (Manchesters) were invariably grounded and known in Bomber Command as 'the 97th Foot' ('Foot' meant an infantry regiment).

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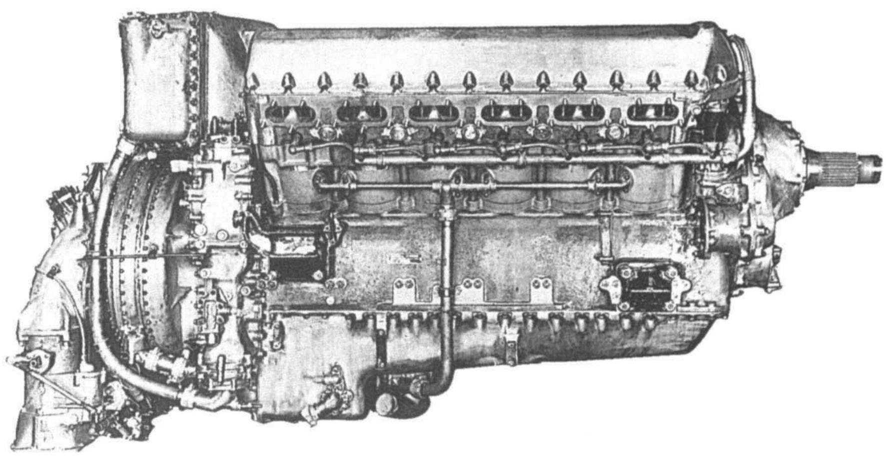
had been done before, and when the company said 1931 equalled 'five years of normal development' it was probably an understatement.

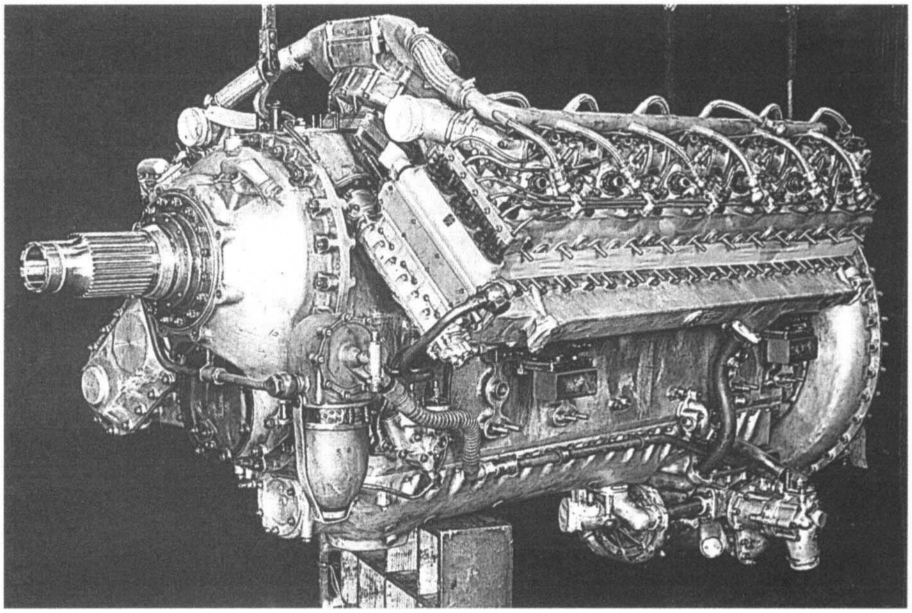
By 1927 the company was thus firmly in the aero engine business, and had begun to engage engineers such as Lovesey, Rubbra and Dorey. They studied competitive weaknesses, and the most obvious one seemed to be the massive weight and other drawbacks of the water-cooling system. In 1928 a special F was designed to use steam cooling. As the heat dissipator (radiator) in such a system is full mainly of steam instead of water it weighs much less, and condensing the steam gets rid of about 30 times as much heat as cooling the same flow of water by the typical 17°C. The steam-cooled engine, which became the Goshawk, ran very well at around 660 hp, but flight testing revealed various problems, such as the impossibility of pumping condensate at near boiling point back from a condenser lower than the header tank, as it inevitably had to be in low-wing monoplanes. So in 1935 Rolls-Royce followed the US lead and went for ethylene glycol cooling. A 97/3 per cent mix with water boils at sea level not at 100°C but at 164°, so heat can be dissipated through a very hot but smaller and lighter radiator.

Thus only 24 Goshawks were made, though they were flown in 12 different aircraft. Another smaller engine was the Peregrine, a 1939 modernised Kestrel with a downdraught carburettor and many new features. In the Whirlwind it was rated at 885 hp at 3,000 rpm at 15,000 ft, on 87-grade fuel. Almost the same cylinder blocks were used in the Vulture, described later.

Where next, then, after the 1931 Schneider win and world speed record? The Air Ministry declined to fund a new engine, and in December 1932 the RR board voted to pay for one. Three years later the Hawker board did the same in tooling up to make 1,000 Hurricanes, powered by the engine that RR were to develop, and in neither case could any of the people who took those courageous decisions have had any idea how important they would prove to be in 1940. In early 1933 Royce, then weak and frail, decided to go ahead with a



Though 36 per cent larger in capacity, many Griffons were actually shorter and lower than other typical two-stage Merlins. This Griffon 65 (Spitfire XIV, once flown by the author) developed almost 200 hp per cylinder.



Like the Exe, the Crecy liquid-cooled sleeve-valve two-stroke seemed to be less troubled than some mature production engines. The six-plunger injection pumps can be seen at the front of each block. The Crecy, like the four-stroke Pennine, never flew.

conventional V-12 with cylinders 5.4 × 6 in (1,649 cu in), to begin life at 750 hp and develop to 1,000. Called the P.V.12 (private venture), it almost went ahead with the inverted layout, which gave better pilot view, but there were lubrication problems and Royce disliked anything new that was not essential. He died on 22 April 1933, on the very day the last P.V.12 drawing was completed. Elliott had deserted Royce some time earlier in order that the design team could be concentrated in Derby where Rowledge and Colonel Barrington had been the leaders. The first P.V.12 ran on 15 October 1933.

Seldom has an engine proved so disappointing for so long. The double-helical reduction gears had to be replaced by plain spur gears, and the ambitious aluminium monobloc casting that included the upper crankcase and both cylinder blocks kept cracking through the water jackets. By 1941 such cracks were being repaired by the hundred, but in 1933 it meant paying for a new casting and losing weeks. Somehow a P.V.12 was got through a type-test in July 1934 at 790 hp at 2,500 rpm, weight being 1,177 lb, and another flew in a Hart on 12 April 1935. By this time Air Ministry support was forthcoming, and the engine was named Merlin. The Merlin B introduced ramp-type (semi-penthouse) detachable heads with the twin inlet valves at 45°, but continued cracking forced the use of separate cylinder blocks, in the Merlin C. This failed a type-test at 955 hp in May 1935, but did complete a 50-h civil test in December and the Merlin F was committed for production with minor changes as the Merlin I, for the Fairey Battle and Hawker Hurricane.

Within days it was realised the ramp-head potential was not being achieved, and it was at once replaced by the Merlin G with an improved flat head cast integral with the block, with all four valves parallel. About 180 Merlin Is had been delivered before the G came on the line in early 1937 as the Merlin II, type-tested at 1,030 hp at the full rpm of 3,000. It required complete redesign of the noses and engine controls of the Hurricane and Battle. Hives, by this time 'King' of the Derby works, sanctioned a racing Merlin in 1937 which ran 15 h at 1,800 hp and for short bursts at 2,160 hp at 3,200 rpm at

27 lb boost, on fuel of about 100 octane. This amazing achievement confirmed that the 27-litre Merlin would probably be adequate to beat the much bigger German engines. The Mk X with two-speed blower went into production for the Whitley and Halifax, and in 1938 'Doc' Hooker joined the firm and quickly discovered how to make a major improvement to the performance of the supercharger.

The Battle of Britain, however, was won by the original Mks II and III, but operating on the very limited quantities of 100-octane fuel first brought to Britain in bulk in June 1939. A boffin at the RAE, Miss Shilling, hit on the brilliantly simple idea of adding a metal diaphragm with a small calibrated hole inside the float chamber of the carburettor to keep the engine running under sudden negative-g in combat, and thus stay on the tail of a direct-injection 109 even if it went into a dive. Hooker's new supercharger resulted in the Mk XX (Hurricane), 45 (Spitfire) and many related engines for bombers. The conversion of the Manchester into the Lancaster was made possible because of the prior existence of a Merlin 'power egg' developed for the Beaufighter II, all ready to bolt on. Production was more than quadrupled by new factories at Glasgow and Crewe, and by Ford Motors at Manchester. A plan involving Ford at Dearborn fell through, to be replaced by Packard Motor Corporation, where the first V-1650, a totally redrawn Americanised Merlin, was run in August 1941. Half a dozen development V-1650s were made by Continental.

In mid-1940 a demand for a high-altitude Merlin for the Wellington VI was expected to be met by turbocharging. Instead Hooker developed a two-stage supercharging system, with an intercooler, the first blower being derived from that of the Vulture. The result was the Merlin 60-series, which doubled power at high altitudes, adding 10,000 ft to the Spitfire's ceiling and 70 mph to its speed. General engineering improvements were introduced continuously and piecemeal, so as not to disturb production, so that by the war's end the Merlin had been transformed. In 1945 special Merlins were giving up to 2,780 hp (over 100 hp per litre) at 36 lb boost, running on fuel with monomethyl aniline added. Merlin production figures were Derby, 32,377; Crewe, 26,065; Glasgow 23,647; Ford 30,428; Packard 55,523.

Ever alert to new technology, Rolls-Royce began research with sleeve-valve cylinders not later than 1933, and in 1934 built a complete sleeve-valve Kestrel. This ran satisfactorily, though it was used to provide design experience and never flew. With the knowledge gained, Rowledge spent 1935 designing the aptly named Exe. This totally new engine was a single crankshaft 90° X-24 with tiny cylinders 4.225 × 4 in (1,348 cu in) with sleeve valves and pressure air cooling. First run in September 1936, it was initially rated at 920 hp at 11,000 ft but was soon giving 1,200 hp with plenty more to come. One of the smoothest and most trouble-free engines imaginable, it was intended for Royal Navy aircraft, starting with the Barracuda, because of its air cooling. It was always a low-priority oddball and in the vast expansion of 1938 was cancelled, but it was so popular with the Hucknall test pilots they used the Exe-Battle as their 'hack' communications aircraft until at least 1943. Exe-type design never stopped, and the Pennine was planned as a much more powerful (2,500 hp) successor for postwar civil aviation, only to be overtaken by the gas turbine.

More sustained effort was applied to the Vulture. This was the direct route to higher power, in having four Peregrine blocks (2,592 cu in) arranged in the same X-24 form with 60°/120° spacing and one crankshaft. Design began in September 1935, testing started in May 1937 and the Vulture II was type-tested at 1,800 hp in August 1939. Production began in January 1940, but endemic conrod failures forced maximum rpm to be reduced from 3,200 to 3,000 and finally to 2,850. Despite this, the take-off rating was raised to 2,010 hp at 9 lb boost on 100-grade fuel in March 1941, but in-service accessibility was poor, inflight fires and other snags made the Vulture unpopular, and Hives decided his engineers could spend their time more profitably on better engines. At termination in April 1942 only 508 production Vultures had been delivered, all for Manchesters.

On 1 January 1939 Harry Cantrill, previously with Armstrong Siddeley, was given the job of developing the Griffon. This was to be a conventional V-12 scaled up from the Merlin to give over 1,500 hp at low altitudes in naval torpedo bombers (oddly, the obvious application, the Barracuda, was left with the small Merlin when the Exe was cancelled). Sensibly it was decided to make the new engine as compact as possible so that it might replace the Merlin in some applications. Cantrill moved the drives to the camshafts and magnetos to the front, not only saving length but almost eliminating torsional vibration in the drives. Another feature, previously tried only on RR experimental engines, was to feed oil end-to-end down the hollow crankshaft to the main and big-end bearings. The Griffon had cylinders of Buzzard/R size (6 × 6.6 in, 2,239 cu in), and started off with a lot of Merlin experience built in; yet for most of the war Lovesey managed to keep the Merlin ahead, especially at altitude. The Griffon never equalled the Merlin's specific output, but was nevertheless a fine engine, which transformed the Spitfire and Seafire (not least in rotating in the opposite direction, which reversed take-off procedures, though this attribute disappeared with contraprops, which were common on the Griffon). Later marks gave around 2,000 hp to at least 20,000 ft, maximum power being about 2,540 hp, though in such racers as the Red Baron Mustang Griffons have delivered 1,000 hp more than this.

Least known of the company's piston engines, because everyone was too busy to write it down at the time, the Crecy was the most advanced two-stroke aero engine ever built. Sir Harry Ricardo began the work in about 1937, testing single-sleeve cylinders with a clever system of charge stratification from an injector in the head. One feature was the high exhaust energy, making an exhaust turbine desirable. Ricardo's results justified Derby building a complete engine, and by 1941 the Crecy was on test. A liquid-cooled V-12, it had cylinders 5.1 × 6.5 in (1,593 cu in), a little smaller than the Merlin in

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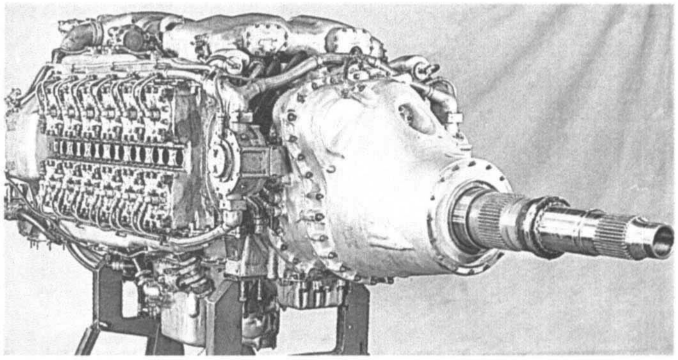
displacement, and with the blocks spaced at 90°. Project engineer Harry Wood recalled from a distance of 25 years that without a turbine the engine gave 2,000 hp at 2,600 rpm, and was expected to reach well over 3,000 hp with a gas turbine geared to the crankshaft. The Crecy team made extravagant claims for it, but it suffered from severe piston overheating and Hooker concluded it could never compete with the four-strokes in output per unit piston area.

In most ways it was a more advanced engine than the last Rolls piston engine, again named Eagle. Started in December 1942, this was a 'clean sheet of paper' engine, the premises being that for reasons of flame travel bore could not exceed 6 in and that it was undesirable to have more than 12 cylinders on one crankshaft, while experience with the Exe and Crecy confirmed at least a potential advantage of sleeve valves. The result was a flat-H with 24 cylinders 5.4 × 5.125 in (2,808 cu in), the crankcase being split into left/right halves each carrying a monobloc casting interchangeable left/right, with upper and lower rows of six cylinders held by 28 nickel-steel through-bolts. The engineering looked good, though the 3,500 hp rating established at 3,500 rpm for the first small production series demanded 28 lb boost.

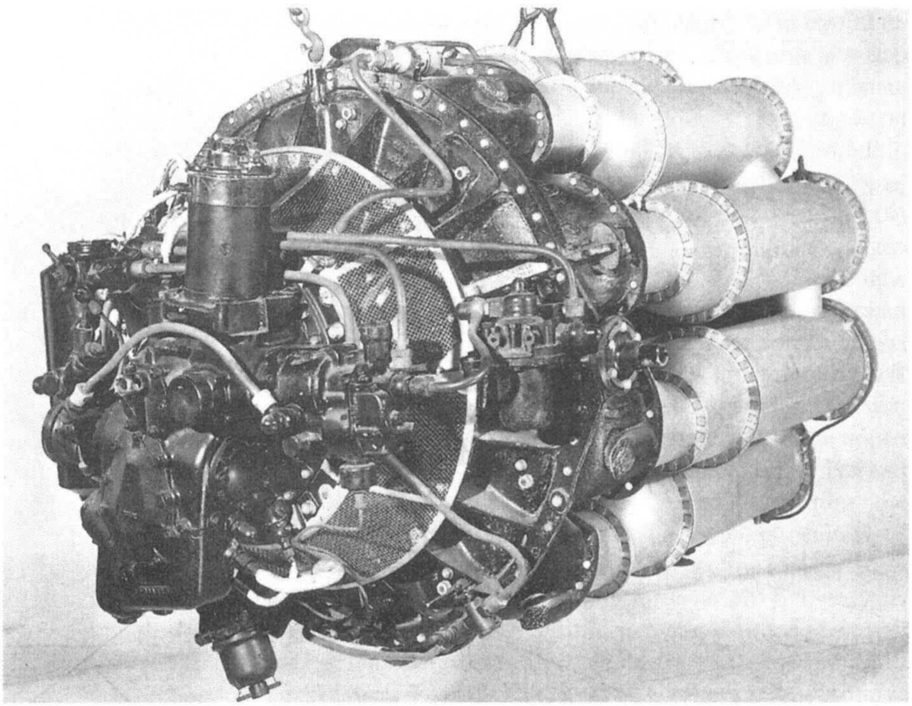


Last Derby piston engine, the mighty Eagle was very much like a scaled-up Sabre, but avoided the latter's problems. This is a contra-rotating Mk 22, rated at 3,500 hp and with 3,020 hp available at 15,250 ft.

Gas turbines

Prompted by Hooker, Hives visited Whittle at Lutterworth in August 1940 and immediately broke a bottleneck in Power Jets operations by making blades, casings and many other parts in the Derby experimental shops. This got Derby into turbine hardware, though the chief scientist, A.A. Griffith, who had joined from Farnborough in June 1939, had brought with him a scheme for a turbojet as complex as Whittle's was simple. Griffith had tremendous knowledge of gas turbines, and proposed turbofans and turboprops both using his 14-stage CR (contra-rotating) gas generator which also had contraflow of air and gas. The research unit, designated CR.1 never cured its air and gas leakages which prevented realisation of the efficiency predicted.

The need to get into gas turbines and jet propulsion remained, and by 1941 Hives was seeking a link with Power Jets. After many discussions he collected a small design staff at Derby to build the WR.1 turbojet (actually as a subcontract from Power Jets), using Whittle parts except for the conservatively designed 2.6 pr compressor. The basic reason was to explore the possibility of making a turbojet totally



A production Welland I from Barnoldswick in December 1943. As the W.2B/23, progress on this engine a year before had been virtually at a standstill, with Whittle and Rover totally at loggerheads.

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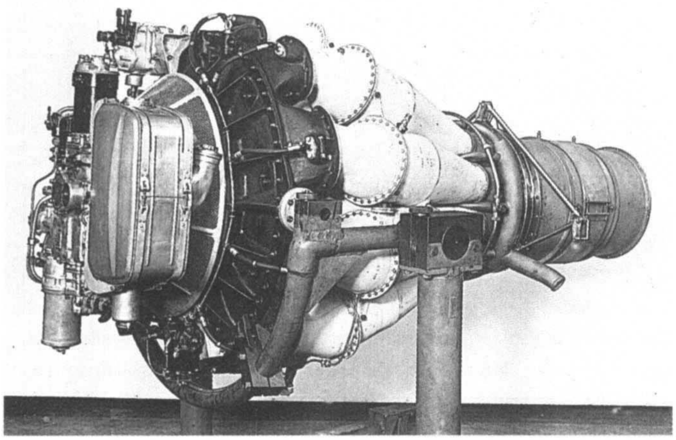
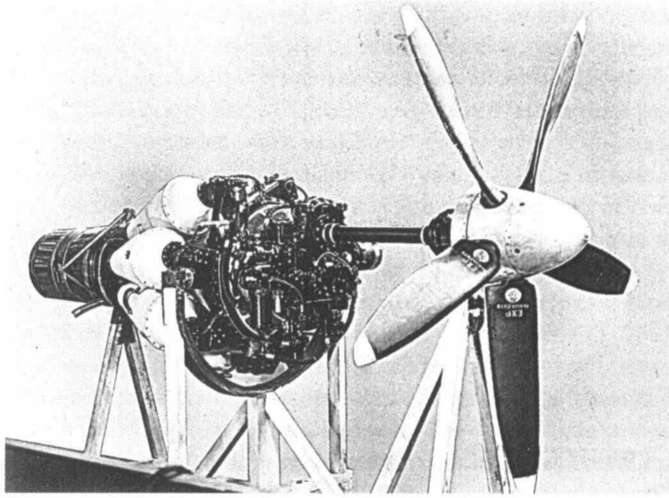


The B.37 Derwent I introduced 'straight through' chambers which transformed the appearance. This engine was made at Newcastle-under-Lyme for the Meteor III.



The first turboprop to fly was this lash-up marriage between a Derwent II (with only seven combustion chambers) and a gearbox to drive a small five-blade Rotol propeller. It was very useful in solving engine/propeller control problems. Today the same name, Trent, has been used for an outstanding family of airliner engines.

reliable, but by the time two WR.1s had been run in late 1942 they were overtaken by events.

The scandalous situation at Barnoldswick (see Power Jets) would probably have continued, and kept British jets out of the war, had not Hooker kept Hives informed. Unlike most of British industry, who regarded Whittle as an upstart and potential competitor, RR got on well with Whittle and understood the colossal importance of his invention. So one day in November 1942 Hives, Hooker and S.B. Wilkes, chairman of Rover, met for a cheap wartime dinner at the Swan and Royal in Clitheroe. After the meal, in a few short words, a deal was struck that was to change history. Hives asked 'Why are you playing around with this jet engine? It's not in your line of business'. Wilkes replied that he would like to be shot of the whole business, whereupon Hives said, 'You give us this jet job, and I'll give you our tank engine factory at Nottingham.' Thus from 1 January 1943 Hooker became chief engineer at a disused cotton mill at remote Barnoldswick, which had been planned for W.2B production but which was henceforth used merely for development. To say the British jet-engine scene changed almost overnight is to put it mildly: W.2B running time was 24 h in December 1942 and it was over 400 h in January 1943. A situation that disgraced the nation was suddenly rectified, and Whittle's engine was – for the very first time, incidentally – at last in full development, with proper resources.

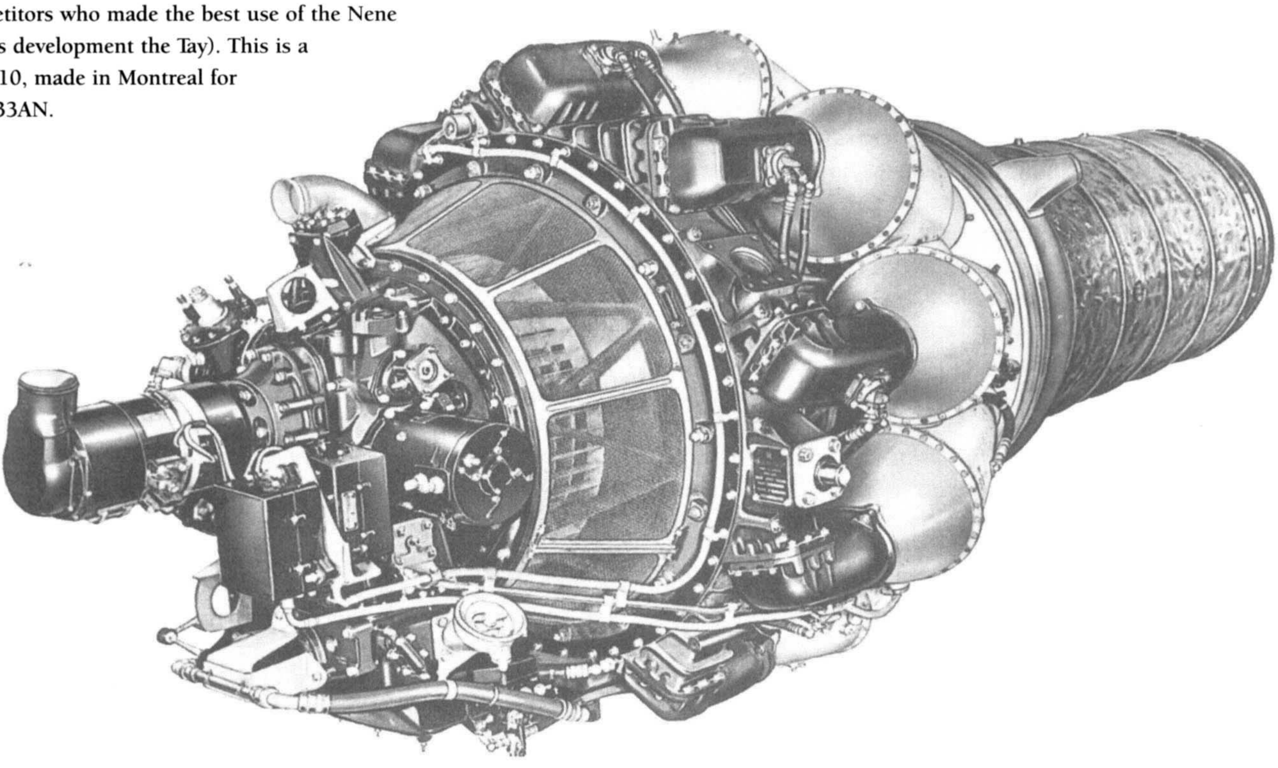
Among the Rover engineers taken over at Barnoldswick were Adrian Lombard and John Herriot, the latter chief test engineer and the key to making the W.2B/23 work, and 'Lom' destined later to be director of engineering until his sudden death in 1967. Rolls left off the 'W.2', without offending Whittle, and as the Rolls-Royce B.23 the engine flew in the F.9/40 Meteor at 1,400 lb on 12 June 1943. In October it was cleared to 1,600 lb and a batch of 100 delivered as the Welland I from Barnoldswick to power the Meteor I. The weight was 850 lb, and in August 1944 squadron aircraft were fitted with nozzle inserts which reduced area and increased thrust to 1,700 lb to catch flying bombs.

It had long been known that greater airflow could be handled by a redesigned Welland, and to produce the B.37 engine Geoffrey Wilde reprofiled the diffuser, the turbine being modified to accept the new airflow of 38.6 lb/s compared with 32.4. Straight-through (B.26) combustion chambers were used, the outstanding Lucas team under Dr E.A. Watson continuing to mastermind combustion problems. The fuel system was redesigned with a barometric control governing the stroke of a swash-plate multiplunger pump. Many new features were introduced, including expansion joints in hot parts and a recirculating oil system with oil cooler, which were to become standard gas-turbine practice. The new B.37 engine, named Derwent I, ran at 1,800 lb in August 1943 and was type-tested at 2,000 lb, the design figure, in November. By this time Herriot had gone to run a new factory at Newcastle-under-Lyme where 500 Derwent Is were turned out in the second half of 1944 for the Meteor III. They raised low-level speed from 415 to 470 mph, roughly 100 mph faster than any other Allied fighter at this height.

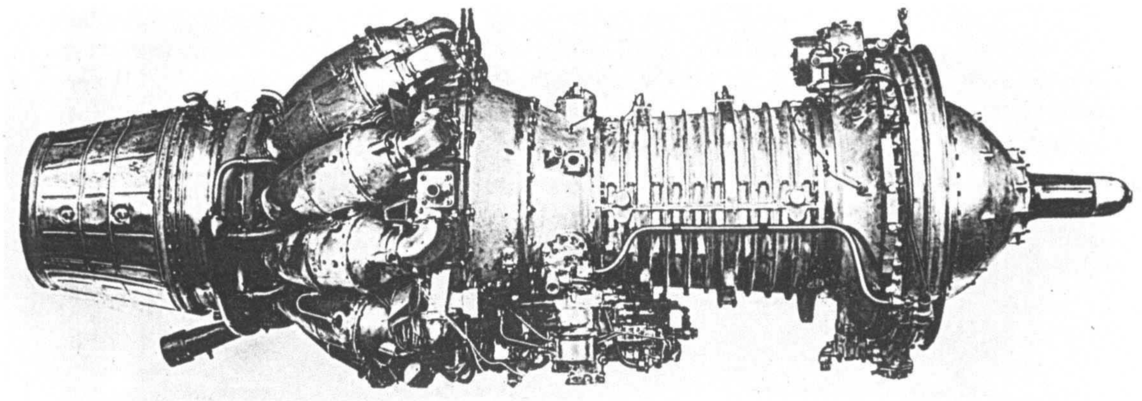
Because of its better aerodynamic design the Me 262A was slightly faster, but there was a startling contrast between the engines. The best TBO for any Jumo 004B was 30 h, whereas the Welland and Derwent both passed type-tests of 500 h and had a service TBO of 150 h. At last combustion ceased to be a wholly dark art, and with the Derwent the fuel system, burners and chambers had reached close to the form used on thousands of subsequent engines. Turbine blades also ceased to be a limiting factor, and though the Derwent I ran at 843°C compared with 754° for the Welland (because of removal of troublesome inlet guide vanes) the Nimonic blades took it in their stride. When improved vanes were restored, the gas temperature returned to the original figure, without altering the 2,000 lb rating and reducing sfc from 1.178 to 1.083. Meanwhile, Whittle's team produced the magnificent Type 16 compressor casing which kept the airflow under perfect control from the impeller tip to the entry to the combustor liner. It was applied to the Derwent II, raising thrust to 2,200 lb. The Mk III engine incorporated powerful suction pipes for boundary-layer control on the A.W.52. The Mk IV had an impeller enlarged from 20.68 to 21.7 in diameter, giving 2,450 lb, but suddenly a way was found to leapfrog all such development.

In early 1944 the Ministry requested RR to design an engine of 4,200 lb thrust, and Hooker and Lombard schemed the RB.40 (initials for Rolls-Royce Barnoldswick were used henceforth). In mid-1944 Hooker visited the USA and discovered that GE had two types of engine of 4,000 lb already running. He therefore decided to go for 5,000 lb, and under Lombard the B.40 was turned into the B.41 Nene. While actually reducing engine diameter slightly, to 49.5 in, the impeller was enlarged to 28.8 in, to handle 80 lb/s, and other features were incorporated from Derwent testing. The prototype was built in six weeks, and arranged so that inlet vanes could be added if desired. Harry Pearson failed in his efforts to get them put in for the first run, on 27 October 1944. Various snags delayed things until near midnight. Then, with virtually the entire day and night shifts watching, the engine was started. It failed to light; positioning the igniter was then a hit-or-miss affair. After several attempts Denis Drew unscrewed the igniter and, as the big Nene cranked up to speed, he lit it with an acetylene welding torch (thus was born the torch igniter). Gradually the throttle was opened, and the cheer as the needle pased 4,000 lb could be heard all over Barnoldswick. Hooker heard the Nene running as he arrived early next morning, and was told the inlet vanes had been installed in the small hours. He looked at the instruments: the Nene was now giving 5,000 lb at the same temperatures as the 4,000 lb on the previous night.

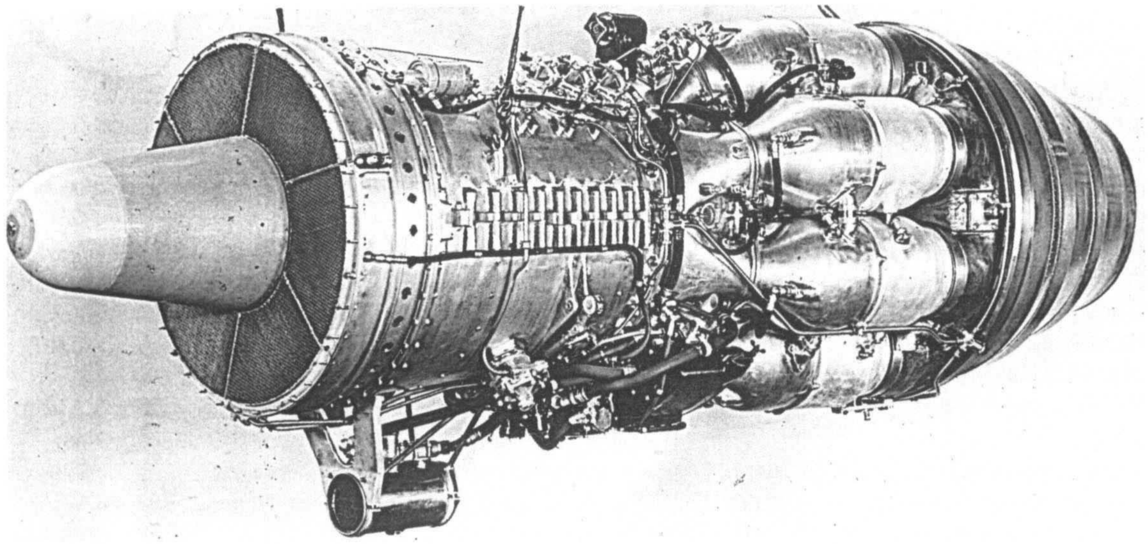
Thus in five months the Barnoldswick team, small by today's standards, had created the most powerful engine in the world. They had done it by using a superior compressor with efficiency at pr 4 raised from 74 to 79 per cent, housed in a Type 16 casing with nine efficient outlets to nine large Lucas chambers of the latest type. The compressor and turbine were now on separate shafts, linked by a quick-detach coupling and running in pressure-lubricated ball and roller bearings and with a small impeller added to cool the turbine bearing and disc. It was supplied by a pair of the previous standard fuel pumps, arranged so that it could run (at reduced thrust) on either, and the pilot's throttle was rigged so that, instead of getting all the power in the last half-inch of travel, equal movements of the lever gave equal increments of thrust. Materials were Nimonic



With the Nene, Hooker and Lombard multiplied available thrust by a factor of 2.5 within a few months, and for very modest increases in engine size and weight (yet it was Britain's foreign competitors who made the best use of the Nene and its development the Tay). This is a Nene 10, made in Montreal for the T-33AN.



Though it looked a bit like two engines joined together, the Clyde two-spool turboprop performed brilliantly and reliably. The author always regretted Hives' refusal of the production contract.



In ironic contrast to the Clyde, the AJ.65 Avon looked fine but performed abysmally. This early RA.1 at least has the actuator above the compressor driving the variable inlet vanes, and a row of three blow-off valves at the upstream end, but it retains the massive one-stage turbine.

75 for the cans, Nimonic 80 for the turbine blades, and Jessops G.18B for the disc. Weight was about 1,600 lb.

Roy Chadwick wanted to put four Nenes in a Lancaster, which would have been almost immune to interception or flak, but by this time the rot had set in at the political level and the Nene was left to the Soviet Union, Hispano-Suiza, Pratt & Whitney, RR Canada, Commonwealth Aircraft and, later, the Chinese. Whittle came to see its first tests, and at the Swan and Royal that evening everyone bewailed the lack of any application. Someone (thought to have been Whittle) suggested scaling it down to fit the nacelle of the Meteor. Herriot or Lombard did the calculation on the tablecloth and got the amazing answer of 3,650 lb thrust. As they were toiling to increase Derwent thrust from 2,200 to 2,450 lb this seemed too good to be true. Hooker did a very quick sum and said 'We've got a 600-mph Meteor'. Hives had just got the production line turning out Derwent Is, but he did not specifically forbid Hooker's suggestion, so on 1 January 1945 the drawings began for the Derwent V, a 0.855-scale of the Nene. On 7 June the first engine started a 100-h test at 2,600 lb, and it soon reached 3,500 lb, weight being 1,250 lb. Meteors set world speed records at 606 mph in November 1945 and 616 mph in September 1946, the latter with 4,200 lb engines with Nimonic 90 blades.

In late 1943 Hooker concurred with Griffith's arguments and decided to work on turboprops for aircraft speeds of some 400 mph. By early 1944 an interim scheme had been drawn. Called the RB.50 Trent, it was effectively a Derwent II with a flexible quill shaft (to isolate the flimsy engine from feared vibration) linking the gearbox and 95 in Rotol five-blade propeller. These parts were designed by A.A. Rubbra, then chief designer at Derby, and Lionel Haworth, who was already working on the RCA.3 three-spool axial jet of 80 lb/s airflow (never built). The Trent ran in June 1944, and Eric Greenwood made the world's first turboprop flight at Church Broughton with the Trent-Meteor (converted Mk I EE227) on 20 September 1945. On landing, Greenwood throttled back, the propellers going into the special flat zero-pitch used to facilitate starting; the Meteor dropped like a stone, and only quick full power saved a crash. This aircraft flew 47 h, and prompted development of a real turboprop.

This matured as the RB.39 Clyde. Hooker calculated that a pr of at least 6 was desirable, and after studying two-stage centrifugal compressors picked a new arrangement: an axial followed by a centrifugal. Thanks to Metrovick, Dr Smith's existing F.2 spool was offered, and the second stage was a single-sided impeller scaled up from the Merlin 46 supercharger. The axial was derated to nine stages (pr 2.65) running at 6,000 rpm, while the 2.35-pr centrifugal ran at 10,800 rpm, so for the first time the answer was a two-spool engine, with separate one-stage turbines driving the HP compressor and (via gearing) the LP axial spool and propeller. The HP spool drove all accessories and was all that had to be cranked for starting. Combustion was in 11 skewed chambers. The Clyde first ran as a complete engine on 1 August 1945. After a hiccup due to an error in matching the centrifugal and axial, almost every achieved figure was a little better than predicted. The first run was at 2,000 shp, and altogether nine Clydes ran, No. 9 demonstrating 4,200 shp (4,543 ehp). Had the overloaded LP turbine been replaced by a two-stage turbine considerably higher power and efficiency would have been achieved. The Clyde proved to be an outstanding and reliable engine and, following severe tests to clear it for 500 mph at full throttle at sea level, an order was placed for 100 engines for the Wyvern. Hives refused this; he claimed the Avon turbojet would be 'the Merlin of the future' and that turboprops would soon be superseded. In view of the subsequent history of the Python and Proteus this was a great pity.

Herriot managed the Clyde development almost alone at Barnoldswick. Hives had by this time decided to close what he scathingly called 'Hooker's bloody garage' at the remote northern site, and bring all gas-turbine work to company HQ at Derby. With piston engines apparently being phased out, he was afraid of the jet tail at Barnoldswick wagging the giant dog. Even the final development of the centrifugal jet was done at Derby. This was the RB.44 Tay, a Nene redesigned to 115 lb/s and with many detail improvements. Initially rated at 6,250 lb, it found no application except in licensed forms by Pratt & Whitney and Hispano-Suiza, another failure by Britain to use a world-beating engine.

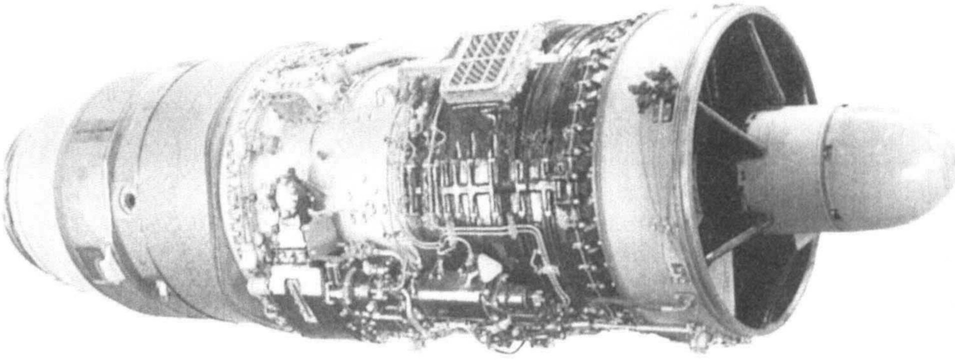
Part of the trouble lay in the belief, fostered during Whittle's early struggle by such experts as Griffith and Constant, that not only were axials better than centrifugals, but that the latter were a crude idea put forward by Whittle that would soon be rendered obsolete. Nothing could have been further from the truth, but in 1944 the centrifugal was limited by the strength of the available aluminium alloys to straight radial vanes and tip speeds around 1,500 ft/s. This meant about 80 per cent efficiency at a pr of 4. Today titanium impellers with curved vanes and tip speeds exceeding 1,800 ft/s achieve 84 per cent at a pr of 9.4 or more, which is far beyond what any axial could do in 1944. But RR decided to abandon the classic Whittle formula, and in early 1945 Hives ordered Griffith to start on the AJ.65 (axial jet, 6,500 lb), a simple engine by contrast to the CR complexities. After doing preliminary designs in June 1945 it was handed to Hooker, then still at Barnoldswick. From the start there was trouble, beginning when Lombard calculated that Griffith's optimistic weight would be exceeded by 50 per cent. When the prototype was started in spring 1946 it refused to accelerate, broke its first-stage blades and could hardly reach 5,000 lb thrust. Sadly, this triggered deep disharmony between Hives and Hooker which led to the latter's departure at the end of 1948.

Though RA.1 prototypes had only eight or 10 stages, the AJ.65 was designed with a 12-stage compressor achieving 20°C per stage and pr of 6.5 overall at 85 per cent efficiency, handling 120 lb/s. Eight Lucas chambers then led to a large one-stage turbine. Gradually the compressor was made to behave, though it needed variable inlet guide vanes and blow-off valves linked with an automatic starting and acceleration control. Early RA.2 engines weighed 2,550 lb and gave 5,800 lb, but in 1949 a new two-stage turbine increased power and saved 300 lb in weight in the Avon RA.3. The first 100-series production engines were delivered in 1950 at the RA.3 rating of 6,500 lb and a weight of 2,240 lb. Almost all had a cartridge starter and direct compressor bleed for cabin pressurisation. The later 100-series at RA.7 rating of 7,500 lb (later 8,050) had full anti-icing and other improvements, and were made by Derby, Bristol, Napier, Standard Motors and CAC (Australia). Hiccups still occurred, such as the discovery that when an Avon-Hunter fired its guns the engine stalled, but the Avon gradually did fulfil Hives' hopes that it would be the 'Merlin of the jet age'.

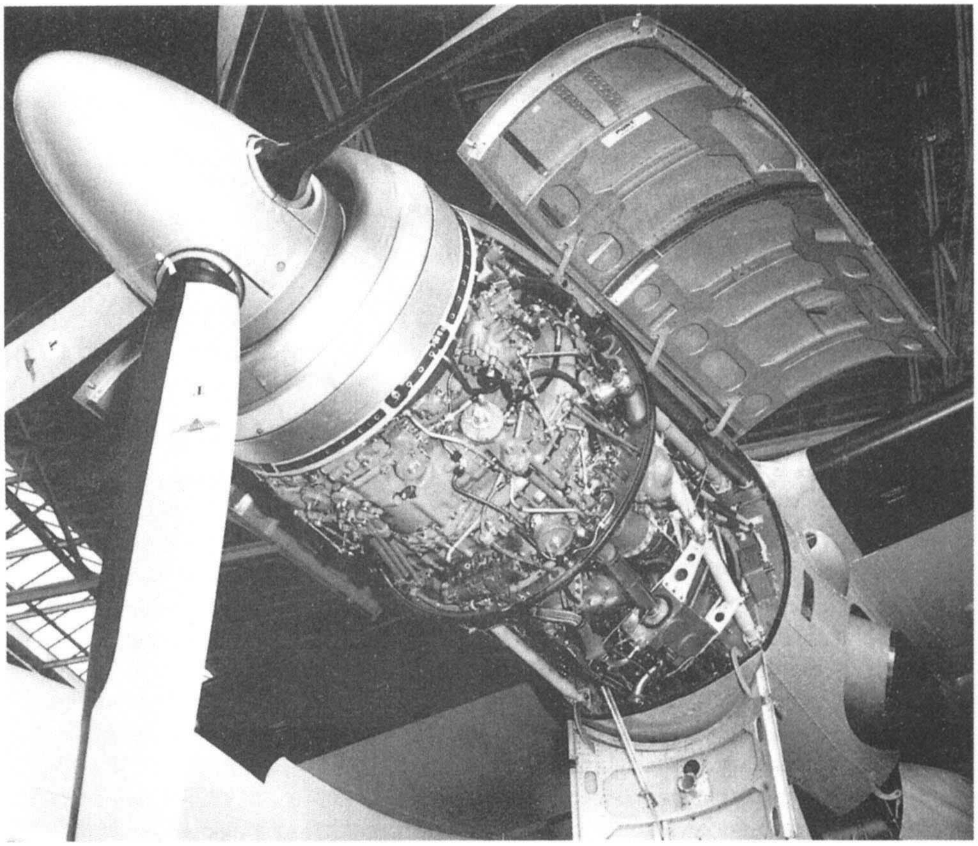
It really became competitive when in December 1952 it was redesigned as the 200-series with a much better compressor whose first four stages followed the aerodynamic design of the Sapphire, and a cannular combustor. The first 200-series engines had a 15-stage compressor of 150 lb/s, with pr 7.45, and were type-tested in April 1953 at the RA.14 rating of 9,500 lb with sfc reduced from 0.92 to 0.84. This thrust was the same as for the 100-series RA.7R with afterburner and primitive twin-eyelid nozzle. In July 1956 the RA.24 of 11,250 lb was type-tested, with the first production air-cooled blades. For the Comet and Caravelle the civil RA.29 was produced, with a zero-stage giving 10,250 lb at sfc of 0.786, and the RA.29/6 added a '00-stage' and three-stage turbine giving 12,600 lb at the same sfc. Fighter Avons culminated in the RB.146 300-series for Lightnings and produced by Svenska Flygmotor as the RM6 for Drakens, with a zero-stage (airflow 170 lb/s, pr 8.43) and an efficient afterburner and multi-flap nozzle giving 17,110 lb thrust. In 1959 an aft-fan Avon was tested outdoors at Hucknall, recording world-record low sfc.

In 1946 Lionel Haworth designed the RB.53 Dart, another Derby engine with tandem centrifugal impellers in close series. Though Griffon and Eagle supercharger aerodynamics helped, getting the air from the first stage into the eye of the second in a compact engine was not simple. The seven skewed chambers led to a two-stage turbine, driving both compressors and the compound helical propeller gearbox in the centre of the annular inlet. The Dart flew at 890 shp in the nose of a Lancaster in October 1947, and went into production for the Viscount in 1952 at RDa.3 rating of 1,400 shp. The RDa.6 raised this to 1,600 shp, and the RDa.7 with three-stage turbine to 1,800 shp, airflow being 21.5 lb/s and pr 5.4. Later

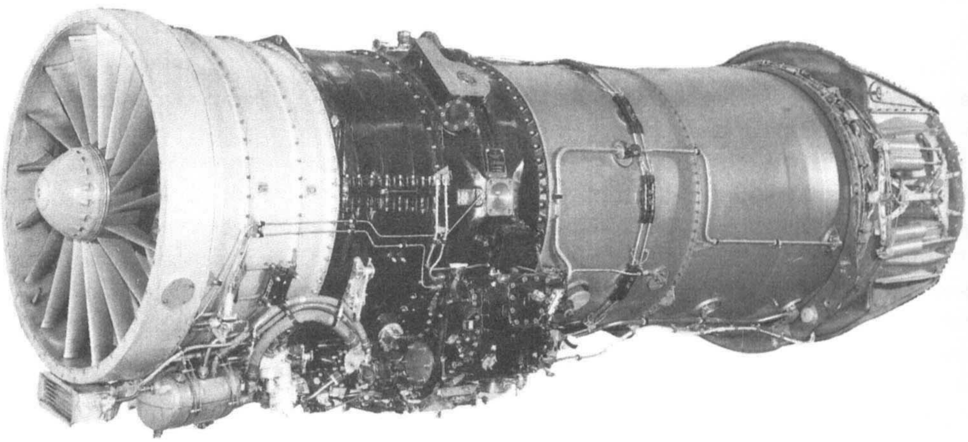
The same size as the RA.1, but a bit heavier, this Avon 300-series with much greater airflow and air-cooled blades gave 12,690 lb dry, or 17,110 lb with afterburner. It could have saved Westinghouse.



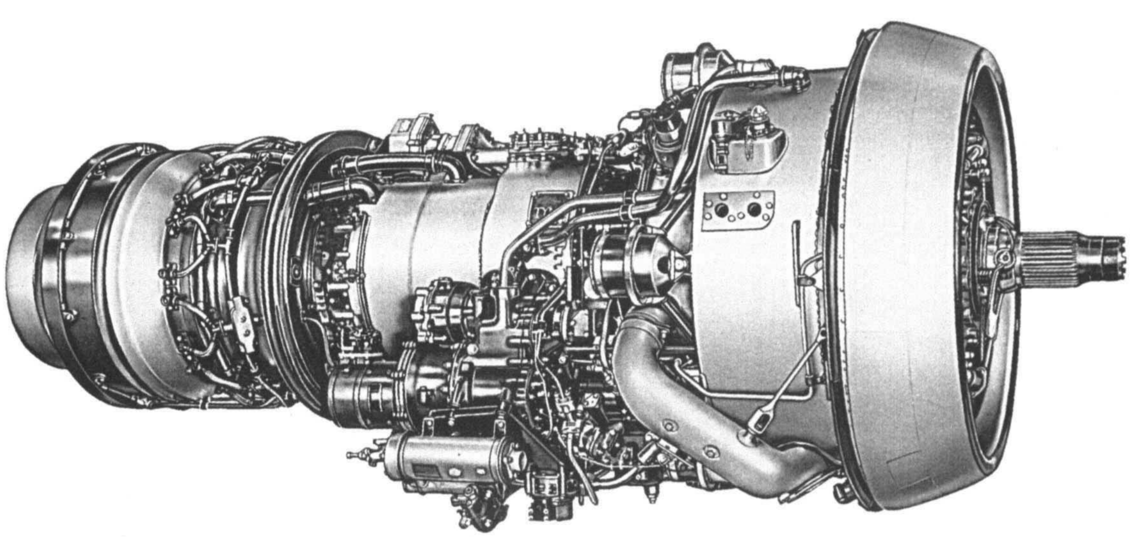
Forty years from the prototype, this Dart 551 was in 1985 installed in an F27. Rolls-Royce now regret having underestimated the importance of the 'Dart replacement' market.



Last of the Conways, a Mk 550 (RCo. 43) of 21,825 lb rating, flies RAF VC10s with high reliability, outer engines having the reverser seen here. The only criticism of the Conway was timidity over choice of bypass ratio.



The first 'two-spool' turboprop, the RB.109 Tyne, was outstanding. Unfortunately it hit the market just as turboprops seemed to be being replaced by jets, and it never found the mass fixed-wing and helicopter market it deserved.



Darts were rated at up to 3,245 ehp, and remained in production until 1987,with over 7,100 engines having flown some 170 million hours. Rolls-Royce bitterly regret handing this enormous market to foreign competitors.

In 1953 effort began to be applied to jet VTOL, resulting in the TMR 'Flying Bedstead' powered by two Nenes, and also in the RB.93 Soar, first of a series of light and simple turbojets. The Soar was intended mainly for RPV propulsion, with thrust and weight of 1,810 and 267 lb, but it led to the RB.108 lift jet, with corresponding figures of 2,340 lb (with 5.9 per cent control bleed) and 270 lb. This led to the RB.145 used in supersonic V/STOLs for both lift and thrust, rated at 2,750 lb dry or 3,650 lb with afterburner. The prospect by 1961 of thousands of military and civil V/STOLs, each with up to 36 lift engines, was enough to launch massive sales efforts, but the market evaporated. The final production lightweight jet was the RB.162, first run in January 1962. This marked a total breakaway from established practice, with engine length being reduced near to the diameter, and virtual replacement of exotic metals by glass-fibre and aluminium. Lift versions typically had 86 lb/s airflow and gave 4,200 lb for a weight of 280 lb, while for the Trident 3 the RB.162-86 was developed as a long-life take-off booster. Schemes were drawn for attractive lift turbofans of very high bypass ratio, and with diameter much greater than the length.

Following prolonged Griffith studies, government funding was obtained in 1952 for the first bypass jet, the RB.80 Conway. Had the turbofan concept been coined this engine might have had a useful bypass ratio of at least unity, but it was viewed as a two-spool turbojet with a slightly oversized LP spool, and accordingly the bypass ratio was established at only 0.3, insufficient to make much difference to sfc or noise. The engine ran in 1953 and flew in a pod under an Ashton at RCo.2 rating of 9,250 lb in 1954. Subsequent ratings were 11,500 and 13,000 lb for the V.1000, followed by 17,250 lb for the Victor B.2, 17,500 lb for the 707 and DC-8, 20,600 lb for the Victor and 21,800 lb for the Super VC10. The final Mk 550 engine had a zero-stage on the seven-stage LP compressor, handling 375 lb/s, nine-stage HP, 10-tube cannular chamber, one-stage air-cooled HP and two-stage LP turbines, weight being 5,101 lb.

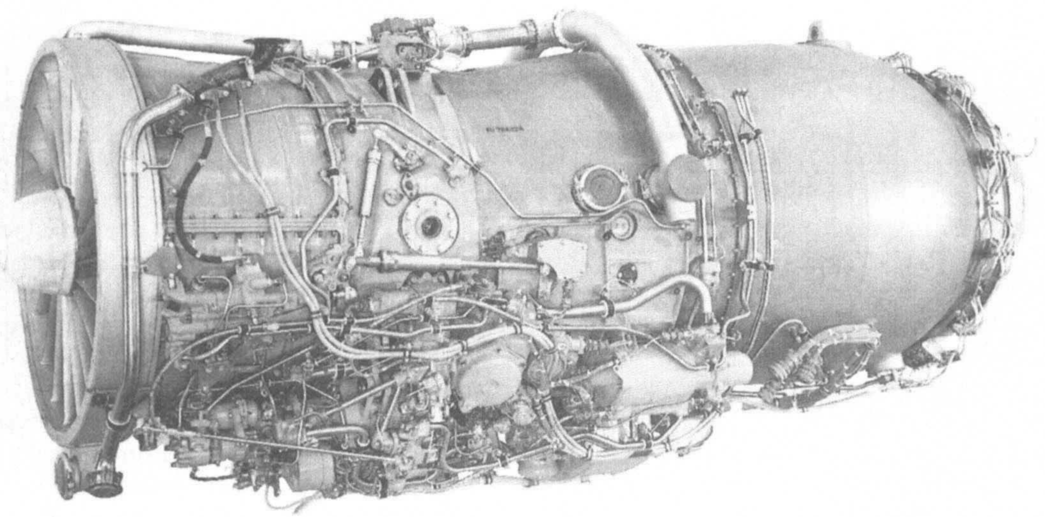
Haworth spent 1954 designing the RB.109, a second-generation turboprop to take over at 2,500 hp where the Dart left off. Run in April 1955 and named Tyne, it far exceeded expectations and was quickly type-tested at 4,220 shp (4,690 ehp) at 15,250 rpm with airflow of 41 lb/s and pressure ratio of 13.5. It had a six-stage LP compressor driven by a three-stage turbine with the shaft extended forwards to the compound epicyclic reduction gearbox centred in the annular inlet, a nine-stage HP spool driven by a one-stage air-cooled turbine, and 10-tube cannular combustor. Today airflow is 46.5 lb/s and pr 14. Tynes are rated at 6,100 ehp, weight remaining just over 2,000 lb, and the last few were made in the 1990s by an RR/Snecma/MTU/FN consortium.

In 1957 design began on the RB.140, a totally new bypass jet of 8,000 lb thrust. This became the 14,000 lb RB.141/142 Medway, for the DH.121 and, with a switch-in deflector to vector the thrust, the HS.681. Seven development engines ran well. Foolishly BEA demanded that the former aircraft be made smaller; the Medway, which would also have powered the Saab Viggen, was therefore scaled down to 200 lb/s to become the RB.163 of 9,850 lb. Designed by Freddie Morley, this was a neat two-spool engine with four-stage (later five) LP, 12-stage HP, 10-tube cannular combustor and two-stage HP and LP turbines, with the first HP stage air-cooled. Named Spey, it gained an important civil and military market, with ratings around 12,550 lb (wet) or 20,500 lb with afterburner. Previously named Spey Junior, the RB.183 powers the F28; it has a four-stage LP, reducing pr from around 21 to 15 but raising bypass ratio from 0.64 to 1. Almost 20 years were spent studying Spey derivatives before deciding in 1983 to retain the HP spool but add a new LP with single-stage fan (with advanced wide-chord blades rotating with a three-stage compressor), driven by a new three-stage LP turbine. Named Tay, this engine has a bypass ratio of just over 3. First certificated in June 1986, the Tay has sold in large numbers at ratings from 13,850 to 15,400 lb to power the Fokker 70 and 100 and Gulfstream IV and to re-engine the Boeing 727 and BAe One-Eleven.

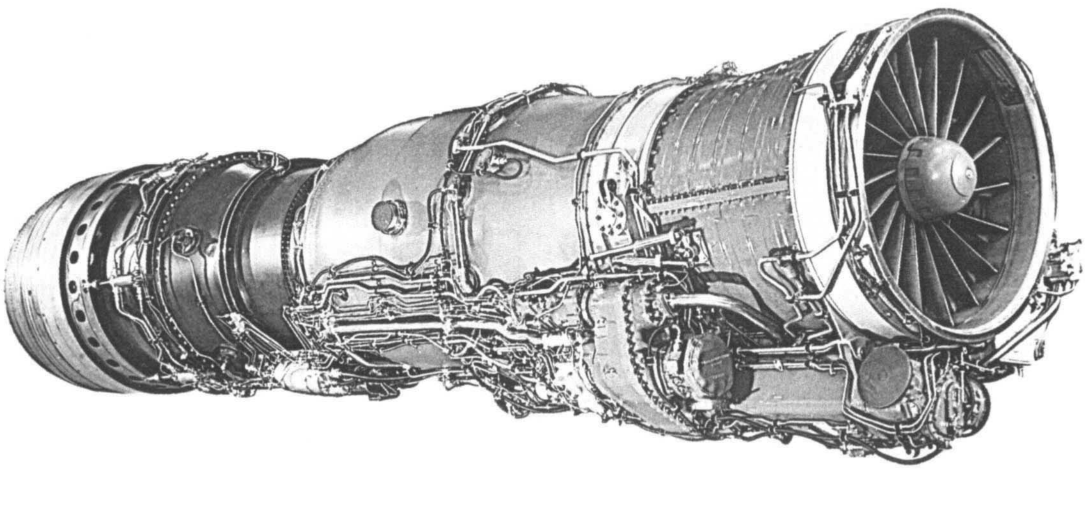
One major puzzle is why the Spey bypass ratio was pitched so low; a contributory factor was overestimation of nacelle drag at higher ratios. A greater puzzle is why, having discovered the engine needed to be refanned in 1966, the Tay did not appear for almost two decades.

A Spey derivative was produced by Allison as the TF41 (*qv*). More distant relatives were developed from 1960 in collaboration with MAN Turbo (later MTU) of West Germany for V/STOL fighters. The RB.153 was scaled down from the Spey figure of just over 200 lb/s to 121, giving a very compact engine rated at 6,850 lb or 11,645 lb with afterburner. The latter incorporated skewed rotating joints so that the variable nozzle could be rotated down through 90°. In contrast the RB.193 had Pegasus-type pairs of hot and cold nozzles. Though it had the same airflow as the Spey it was a new design with three-stage fan and two-stage IP compressor driven by a three-stage LP turbine, and counter-rotating six-stage HP spool driven by a one-stage air-cooled turbine; weight was 1,742 lb bare and thrust 10,163 lb.

In 1961 competition from high-ratio turbofans spurred long-term studies which embraced large three-shaft engines, which appeared to offer advantages in flexible operation, reduced numbers of parts, rigidity, elimination of variable stators and very low performance deterioration in service. In 1967 the two-spool RB.178 was tested as a research tool, and

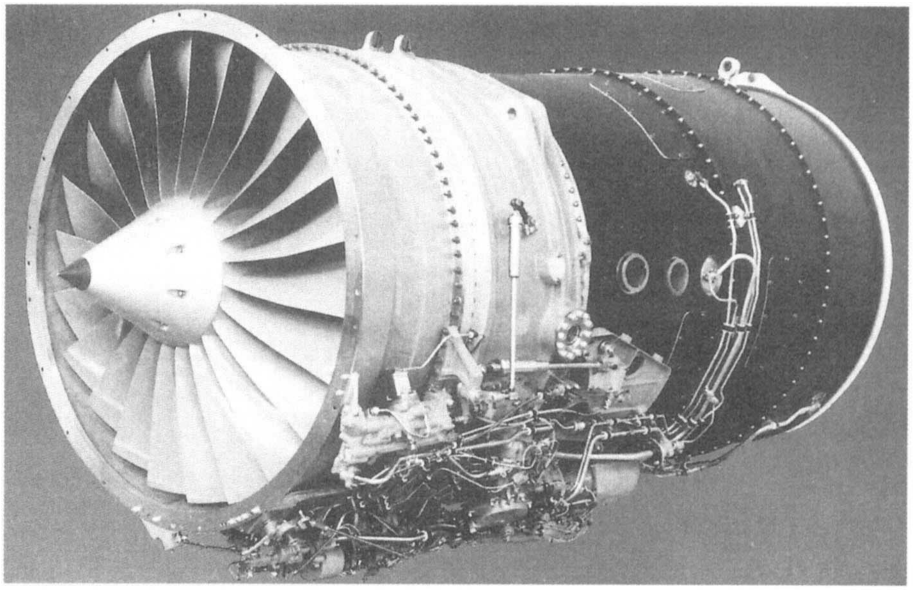


Previously called Spey Junior, the RB.183 Mk 555 is a simplified engine which powers the F28. Rated at 9,850 lb, it weighs 2,250 lb.

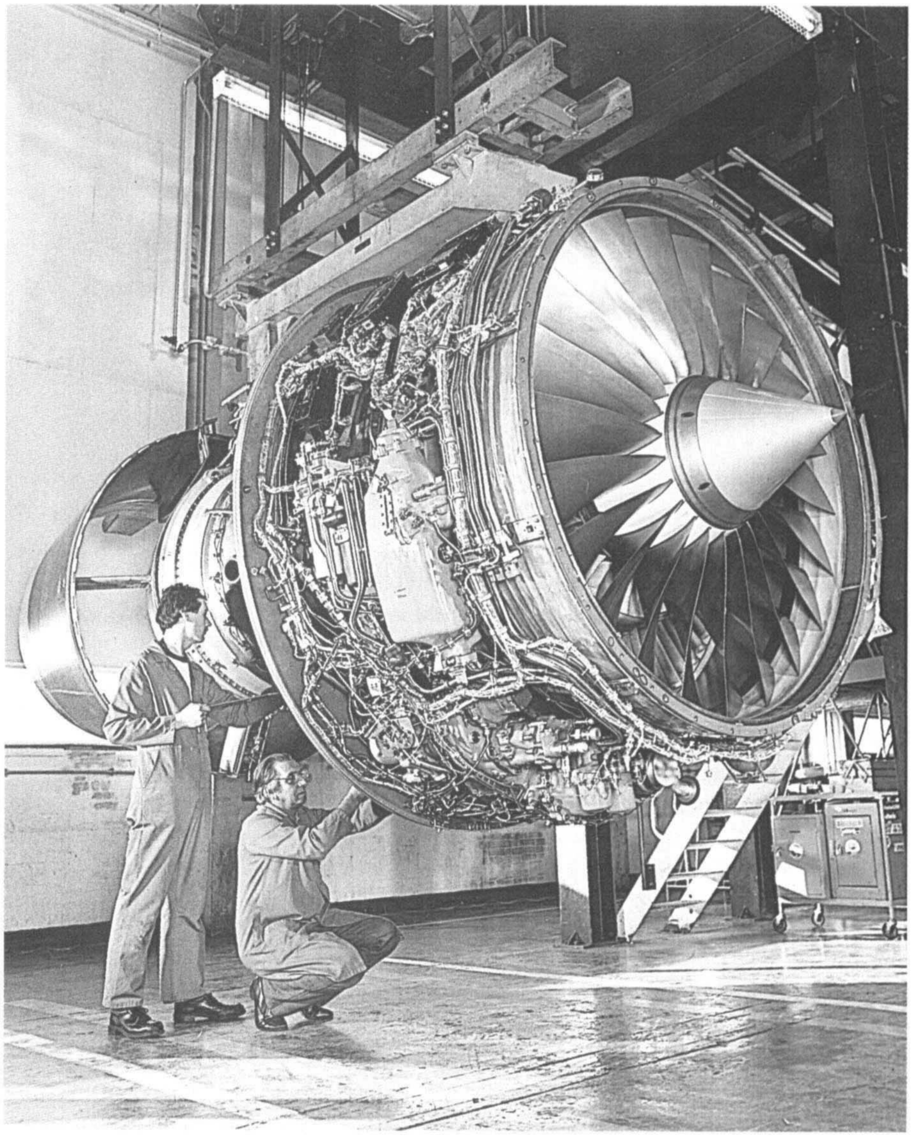


Rated at 20,515 lb with afterburner, the Spey version for Mach-2 fighters was produced as the Mk 202 for RAF Phantoms and the Mk 203 (with fast afterburner light-up for carrier overshoots) for the Royal Navy. The People's Republic of China took a licence, built a mighty factory, delivered an engine that sailed through its tests and then took 10 years building an aircraft to use it, which has recently gone into production.

First run in August 1984, the Tay could have carried on where the Spey left off, with potential for development into the 20,000-lb class. Instead Rolls-Royce handed the next generation to the German firm BMW Rolls-Royce (*qv*).



Former astronaut Frank Borman, President of Eastern Airlines, called the Rolls-Royce 535C 'The finest airline engine in the world'. The Derby engineers replied, 'You ain't seen nothin' yet, here's our new 535E4.' The E4 entered service with Eastern in 1984 and fulfilled its early promise.



Biggest of the Trents is the 800 family, much lighter than the competition yet with ratings up to 102,000 lb. In the background is a Trent 700, with a fan roughly a foot smaller in diameter.

in September of that year the definitive three-shaft RB.207 was selected at 50,000–60,000 lb to power the A300. In March 1968 strenuous sales efforts succeeded in getting the smaller RB.211 of 40,600 lb chosen as launch engine for the L-1011 TriStar. With initial launch orders for 144 aircraft this seemed far more important than the nebulous Airbus, and the latter's reduction in size to A300B standard was used as an excuse for the British government to withdraw from the consortium.

Sir Denning Pearson at Derby was perfectly happy to ignore the A300B, and ordered all Derby resources harnessed to the RB.211. By far the company's biggest project, in all senses, its five modules included a single-stage 89-in fan with 25 blades of Hyfil (carbon-fibre composite), which seemed an ideal application for this revolutionary material which made possible supersonic lenticular-profile blades of wide chord and extremely low weight, the weight-saving being multiplied many times in enabling other parts of the engine and airframe to be made lighter. This fan was driven by a htree-stage LP turbine. The seven-stage IP spool included glass-fibre in its construction, and was driven by a one-stage turbine. The six-stage HP spool was driven by a one-stage air-cooled turbine. All turbine blades were of the traditional wrought type. By this time RR had ceased to subcontract combustion systems to Lucas, and Derby designed the fully annular chamber with 18 atomising burners. Weight was to be 6,353 lb, a figure that proved as optimistic as the price.

For the first time, and bereft of Lombard who died suddenly in 1967, the Derby team had bitten off more than it could chew. The Hyfil blades proved unable to meet the requirements for birdstrike and erosion, and had to be replaced by 33 narrower titanium blades, with part-span snubbers, at a stroke losing what had been sold (some say 'oversold') as one of the chief technical advantages. The turbines proved to have pathetic performance, and the forged air-cooled blades for 1,250°C proved incredibly difficult and costly to make. Bristol, bought in 1966, might have made them far more easily using investment casting but was not asked, nor was it asked to contribute vaporising burners. There were also multiple mechanical problems, notably affecting bearings and seals, which for an engine of 27 pr are crucial to the attainment of acceptable efficiency. It added up to an engine that was nowhere near guaranteed performance, uncertifiable, and thus unsaleable. With insufficient money coming in, and millions a week going out, RR declared itself bankrupt on 4 February 1971. When the government formed Rolls-Royce (1971) Ltd 19 days later it excluded the RB.211, but after prolonged negotiation a conditional fresh contract with Lockheed was signed on 11 May.

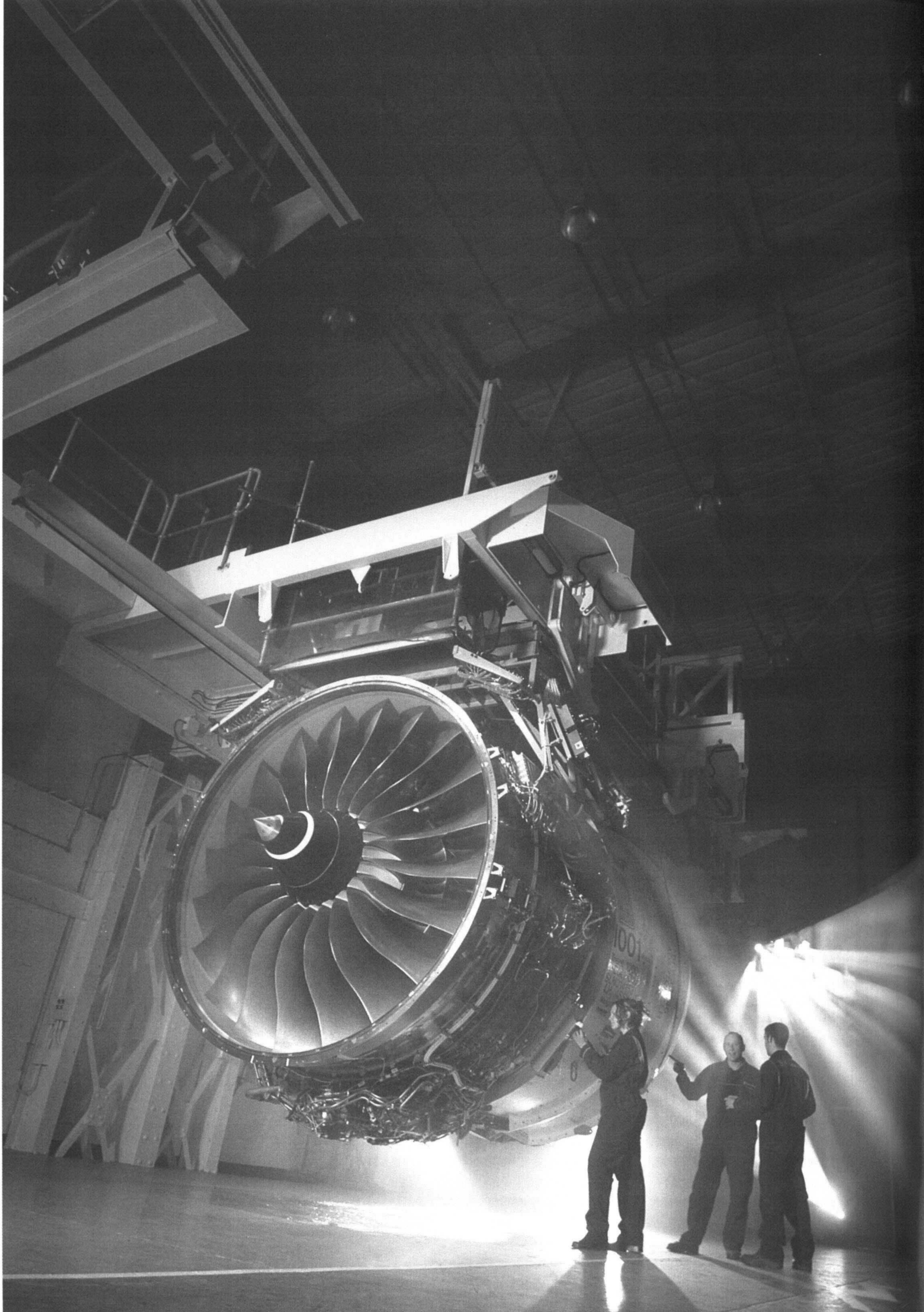
Previously, in 1970, Dr S.G. Hooker had been recalled from retirement to study the RB.211, and as a result a redesigned RB.211-22 went on test the day before the bankruptcy. It improved thrust on Standard Day bench test from 34,000 lb at 1,167°C to 39,340 at 1,227°, followed by 41,500 lb with modified nozzle guide vanes and 43,500 lb with cast blades. In February 1973 the -22B was certificated at 42,000 lb to 28.9°C, the weight being 9,195 lb. Airflow is 1,380 lb/s and bypass ratio 5. Alec Harvey-Bailey is convinced that 'had it not been for the 3-shaft modular concept, which enabled sick engines to be dealt with rapidly, we should not have survived the introductory years'. Hooker had meanwhile completely redesigned the engine in order to compete in the 50,000 lb market, and the resulting -524 ran on 1 October 1973 after two years' waiting for permission to build it. It has a new fan of unchanged diameter but handling 1,550 lb/s, with bypass ratio 4.4, improved compressors, a new HP turbine, and a larger and simpler jetpipe. Today a series of improved -524 engines extend to the 524G of 58,000 lb rating, and the 524H of 60,600 lb launched by British Airways' order for the 767. Today's
524G-H/T incorporates the core of the Trent 700.

In 1974 RR(71) studied the market for engines in the 20,000–30,000-lb class and offered a scaled-down RB.211-524 known as the RB.235. This was replaced in 1979 by the RB.211-535, later redesignated Rolls-Royce 535C to de-emphasise kinship with the RB.211. It has an HP module based on the -22B, a six-stage IP compressor without variable stators, and an advanced -524 fan scaled down to 18 per cent less airflow. Weighing 7,294 lb, the 535C is conservatively rated at 37,400 lb, and has proved the most reliable engine of all time. From it has been derived the 535E4, with a new fan with 22 wide but light snubberless blades formed from titanium skins on a bonded honeycomb core, and revised compressor and turbine blading to improve efficiency. Certificated at 45,000 lb, it has outstanding fuel efficiency and promises to beat even the 535C for reliability. The new fan, the result of 10 years' development, was probably RR's greatest single lead over the competition.

In 1987 work began on the RB.211-524L, to meet the needs of the future A330 and 777. Eventually this became so different that it was named Trent, and it has since been developed in four main versions, with seven foreign risk-sharing partners (Rolls-Royce's share of 71 per cent is higher than GE's 59.09 on the GE90 and Pratt's 63 on the PW4084). The first version to go on test, in August 1990, was the Trent 700. This has a 97.4-in fan with a single stage of advanced wide-chord blades of hollow titanium, an eight-stage intermediate compressor (core booster), six-stage HP spool, single-stage HP and IP turbines and four-stage LP turbine. Rated at 67,500 to 75,150 lb, the Trent 700 powers the A330. Next to be developed was the most powerful version, the Trent 800. First run in September 1993, this has a fan increased in diameter to 110 in, driven by a five-stage turbine. The 800 is in production for the 777 at ratings from 77,900 lb to 98,000 lb; it has been tested at 115,000 lb, and in April 1997 an agreement was signed with Boeing for the Trent 8102 (102,000 lb), more powerful than any previous engine. However, Boeing then entered into a unique exclusivity agreement which made the GE90-115B the only engine available on the heavier 777 versions, cutting Rolls-Royce out, even though the Trent had been the most successful engine on earlier 777s. In October 1996 Airbus signed for the Trent 900 as the launch engine of what became the A380, the natural successor to the 747. Rated at 70,000 or 76,500 lb, this introduced an advanced curvy-blade fan with a bypass ratio (BPR) of 8.7, and overall pressure ratio (OPR) of 41.1. This engine powered the first seven A380s, and entered service with Singapore Airlines. Next came the Trent 1000, selected together with the GEnx to power the Boeing 787. Rated at from 53,000 to 69,800 lb, this even more advanced engine has a BPR of 11 and OPR of 47.7, so the air is 'red hot' as it enters the combustion chamber. Latest of all the Trents is the 1700, a customer option against the GEnx on the Airbus A350. This impressive family underscores what Rolls-Royce claim to be the unrivalled versatility of the three-shaft design.

In 1973 various small turbofans were studied, and an RB.401-06 was run in 1975, but no go-ahead for an engine in this class has been forthcoming. At Leavesden, formerly DH Engines, the Small Engine Division once built an Anglicised T58 as the Gnome, and developed the BS.360 into the Gem. A three-spool turboshaft, the Gem has seven modules, one comprising the four-stage LP compressor and one-stage shrouded turbine, another the centrifugal HP compressor and one-stage air-cooled HP turbine, another the annular reverse-flow combustor, and another the two-stage power turbine and jetpipe. The power turbine can give direct drive at 27,000 rpm or a 6,000 rpm output from the double-helical gearbox centred in the air inlet. Pr is typically 12, airflow 7 lb/s, weight 320 lb, and output 900 to 1,200 hp.

In 1986, testing began of the XG40, an advanced augmented turbofan for fighters with thrust of over 20,000 lb and weight under 2,000 lb. It assisted development of the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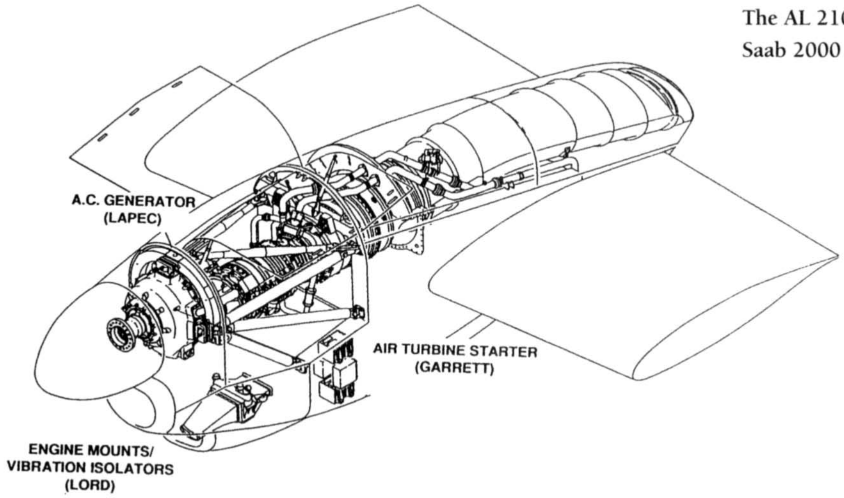
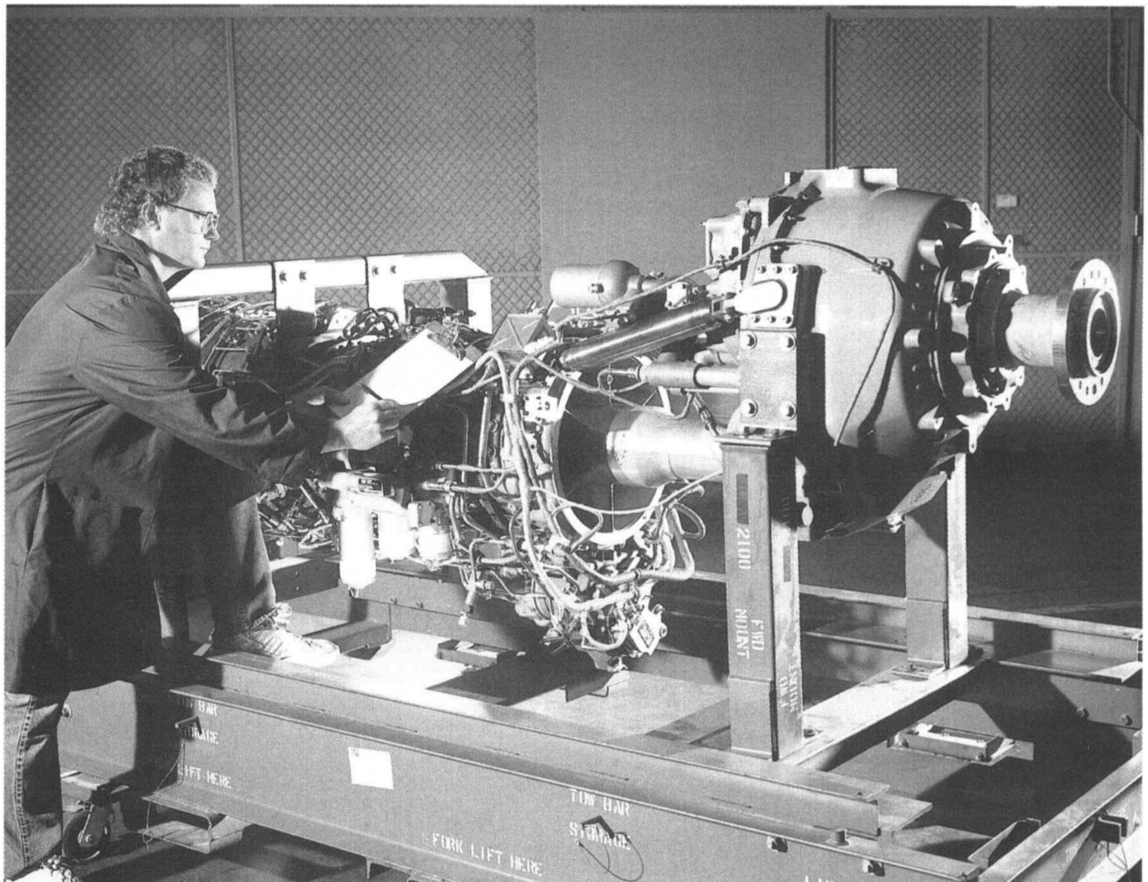
EJ200, described under Eurojet. The Olympus and Pegasus are described under Bristol Siddeley, the Adour and RTM 322 under RRTI, the RB.199 under Turbo-Union, the V2500 under IAE and the MTR 390 under MTR.

Rolls-Royce Corporation (USA) To the benefit of both, the former Allison Engine Company was acquired by Rolls-Royce in March 1995. The principal programmes have continued: the Model 250 turboshaft has almost reached the 30,000 mark, the AE1107C Liberty turboshaft is in production at 6,150 shp to power the unique Bell/Boeing V-22 Osprey; the AE 2100 turboprop is in production for the C-130J, C-27J, IPTN 250 and US-1A Kai (but Saab stopped making the 2000), and the AE 1107 turbofan is in mass-production for a wide range of

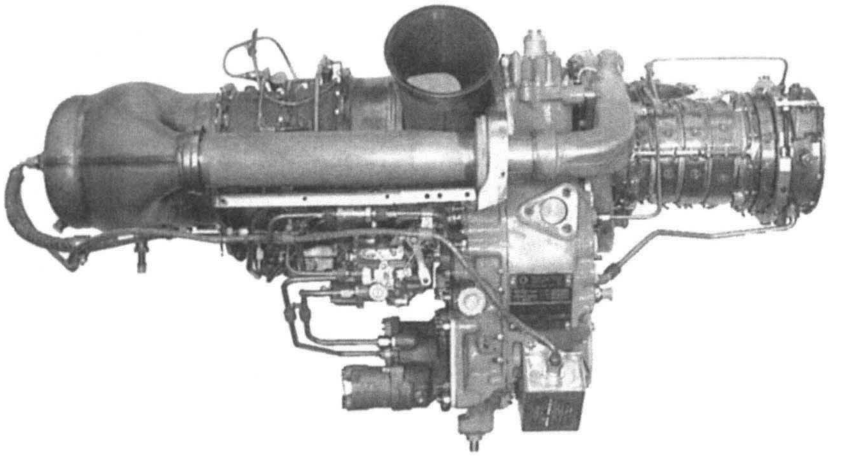


The AL 2100, selected for the Saab 2000 and C-130J.

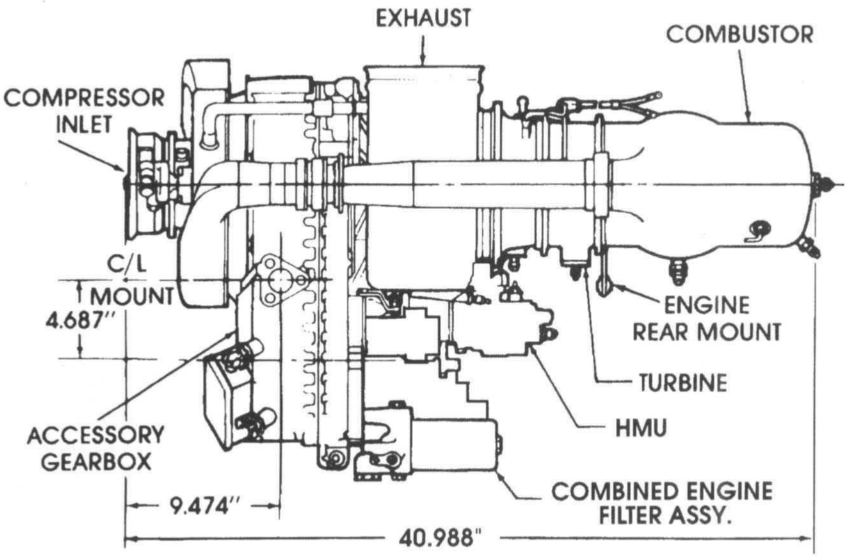


Readying for shipment, an AE 2100D 3 turboprop engine of the C-130J.

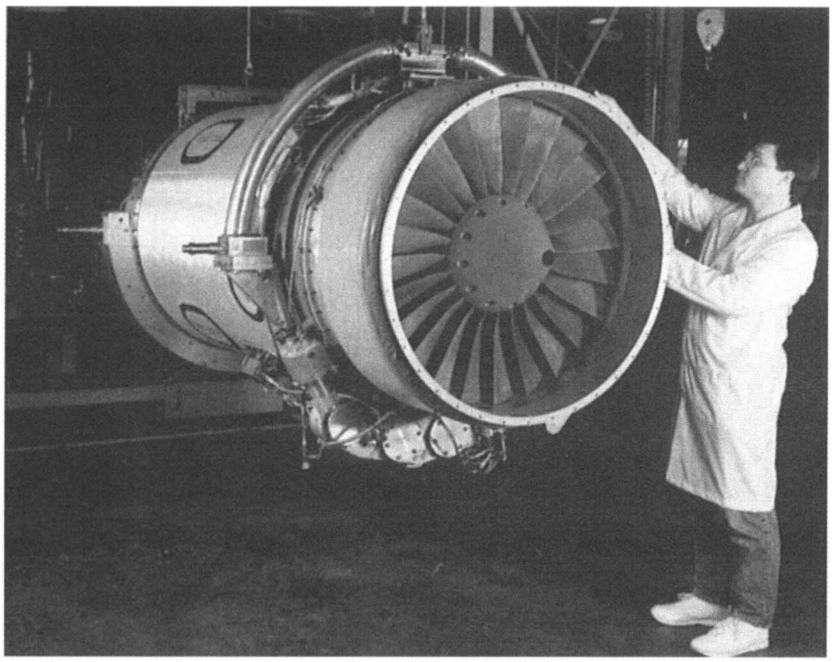
***Opposite*: The Rolls-Royce Trent 1000 has been chosen by Boeing as the lead engine for its 787 Dreamliner. (Rolls-Royce Plc)**



The C20R is the 1965 version of the original series of Allison 250 turboshaft engines, with axial stages upstream of the centrifugal. It has a 5-minute rating of 450 shp.

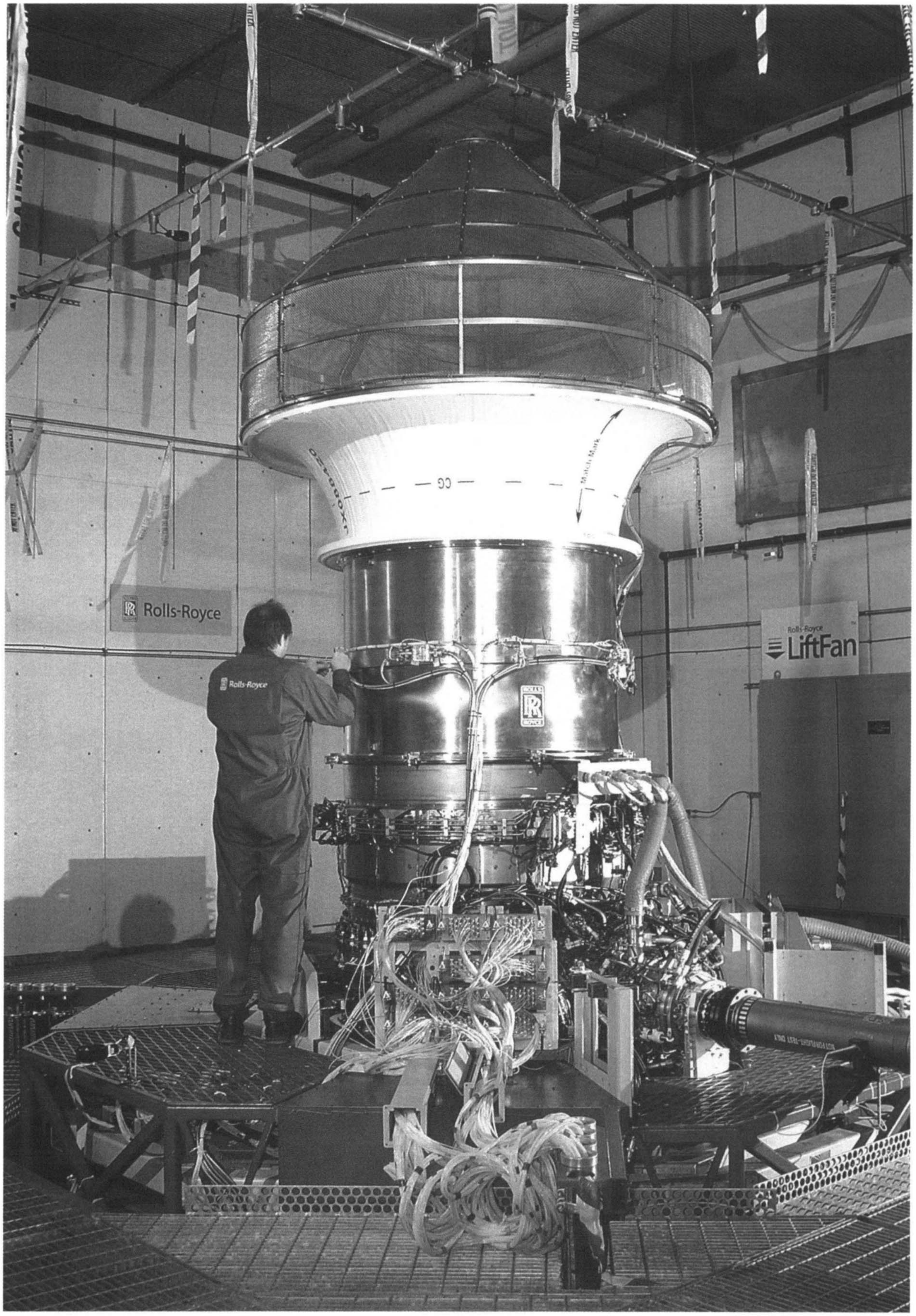


This shows the layout of the most powerful Model 250, the C47B with a 30-second rating of 820 shp. The weight is 274 lb, and the centrifugal compressor rotates 850 times per second.



One of the first Rolls-Royce AE 3007 turbofans.

Opposite: Both Pratt & Whitney and Rolls-Royce are developing the propulsion system for the F-35 Joint Strike Fighter. The lift fan (seen here on a test rig) provides up to 18,500 lb of thrust. *(Rolls-Royce Plc)*



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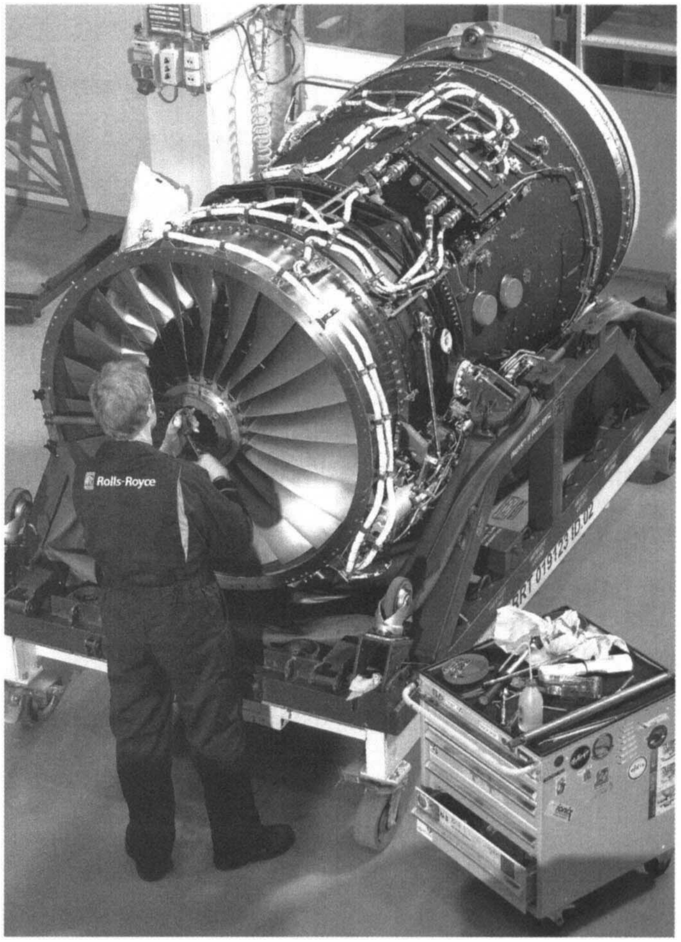
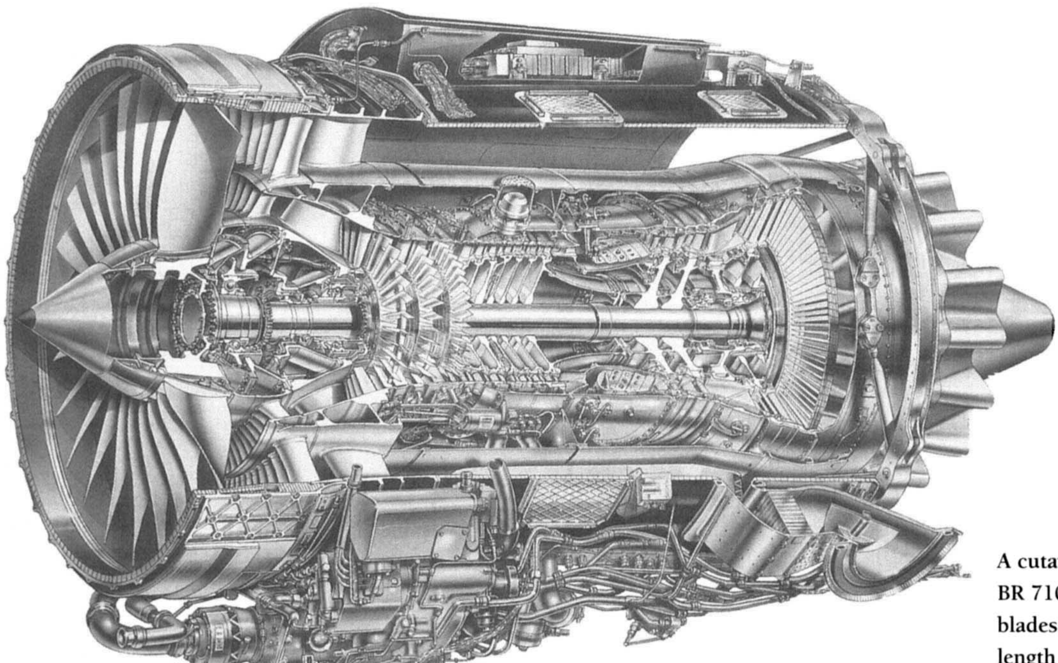
Embraer and Cessna transports and the Global Hawk UAV. In an enormous programme Rolls-Royce Corporation is prime contractor for the LiftFan of the F-35B Joint Strike Fighter. In late 2006 funding was still permitting development of the superb F136 'alternate engine' for the F-35, in partnership with GE, despite political uncertainty.

Rolls-Royce Deutschland (GERMANY) Instead of developing the Tay 670, Rolls-Royce formed a joint venture with BMW in July 1990 to develop engines in the same class. It is a German company, of which BMW had 50.5 per cent. The baseline engine of the BR 700 family is the BR 710, with a large single-stage 48-in fan, three LP stages and 10-stage HP spool, driven by two-stage HP and LP turbines. The 710 quickly gained two applications, the Gulfstream GV, in which it is rated at 14,750 lb, and the Canadair Global Express (14,690 lb); large orders have been placed for both aircraft. In 1996 a further 84 engines rated at 14,900 lb were ordered for the Nimrod MRA.4, and BR 710 engines are on offer for four projected types of civil transport.

In October 1995 a Valujet (now AirTran) order for the MD-95-30 (later the Boeing 717-200) launched the BR 715, in which thrust is increased to 21,000 lb, for that aircraft, with options to 23,000 lb. Compared with the BR 700 the LP turbine has a third stage, to provide power to drive a 58-in fan and a two-stage core booster; there are also upgrades to the HP system. Engine dry weight is increased from the BR 710's 3,600 lb to 4,660 lb. The BR 715 first ran in April 1997, and achieved 25,745 lb thrust on the following day. In 2006 Boeing terminated production of the 717 at fewer than



Checking out a Rolls-Royce BR710.



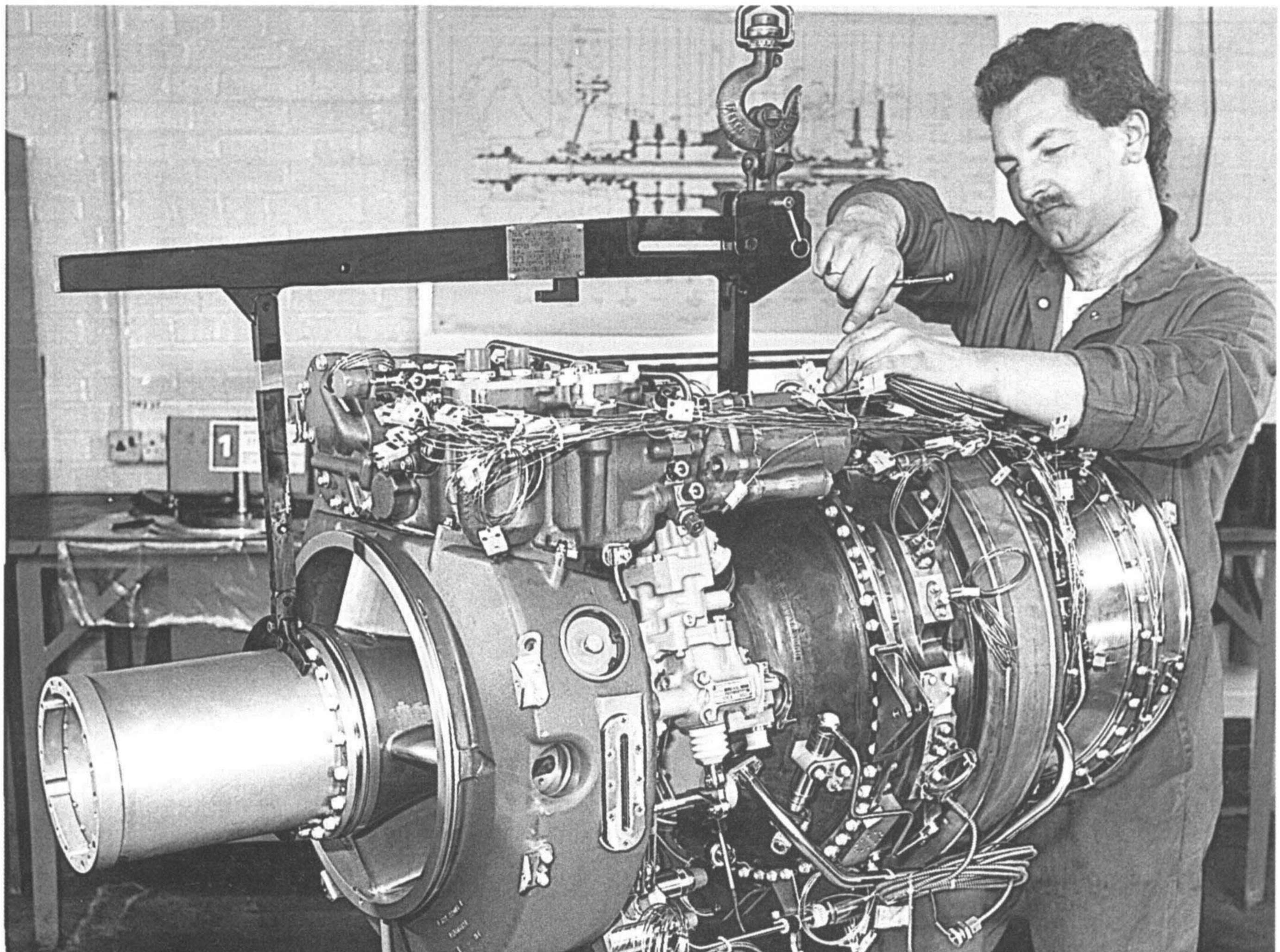
A cutaway drawing of the Rolls-Royce BR 710. The fan has 22 solid titanium blades and sends air down the full-length bypass duct to the multi-lobe mixer nozzle at right.

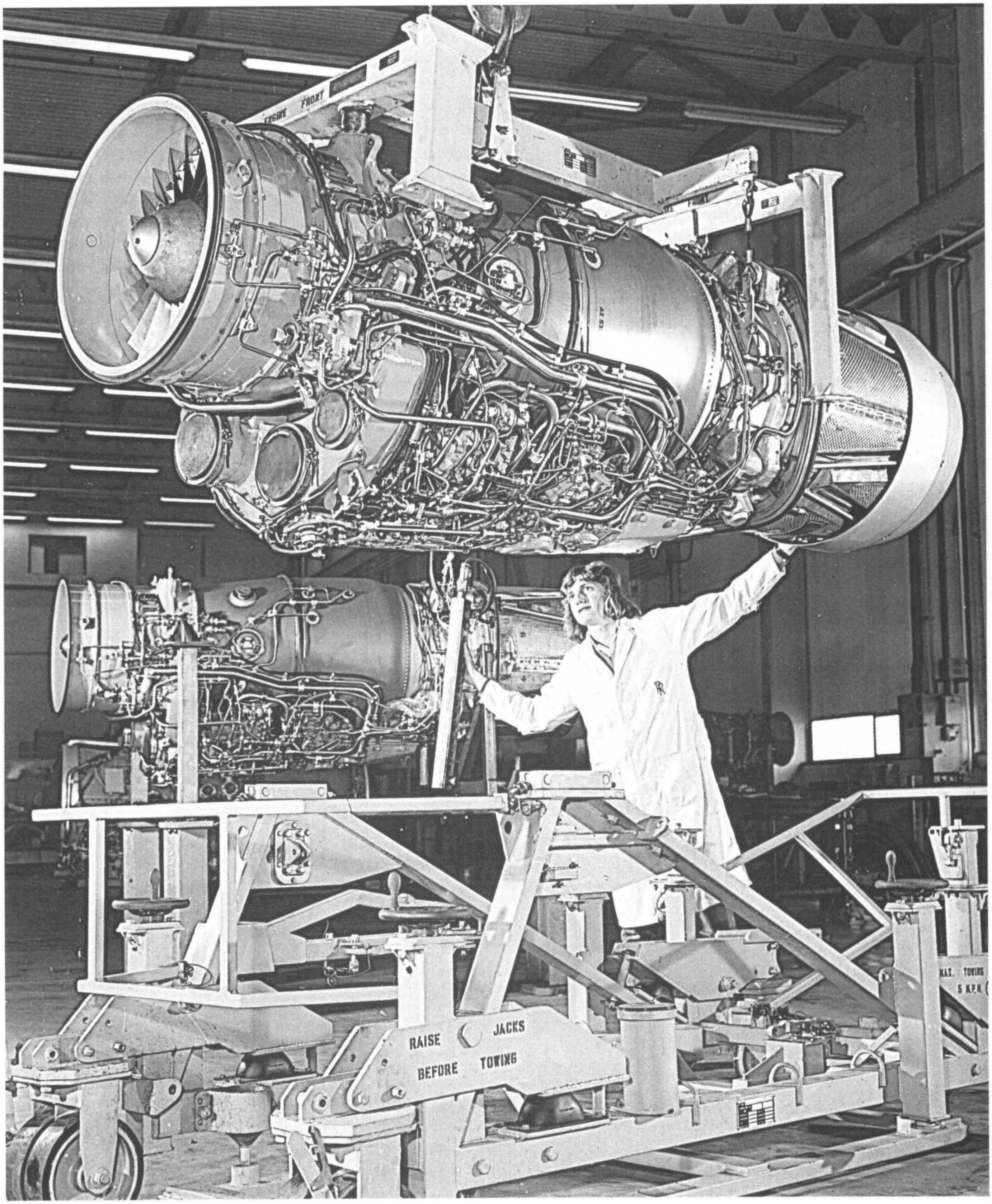
200 aircraft, and at that time none of the other BR715 applications had materialised. In their place the impressive new buildings of RR Germany are busy part-making, and assembling and testing the TP400-D6 turboprop for the A400M airlifter.

Rolls-Royce Turbomeca (FRANCE/UK) Rolls-Royce Turbomeca Ltd was formed by the two companies in June 1966 to manage the programme for the Adour turbofan, initially for the Anglo-French Jaguar. The Adour was conservatively designed with a two-stage fan driven by a one-stage turbine, five-stage compressor (95 lb/s, overall pr 11) driven by a one-stage air-cooled turbine, annular combustor and, in most applications, an afterburner. France handles the compressor, casings, external piping and (assigned to Snecma) afterburner; RR handles the rest. Ratings with afterburner vary from 7,305 to 8,400 lb. Over 2,150 have been delivered, excluding 500 licensed to Finland, India and Japan. Assembly of the F405 version, for T-45A Goshawk, was temporarily transferred to Allison. For several years much more powerful versions have been available, especially for the Jaguar, but have not been demanded.

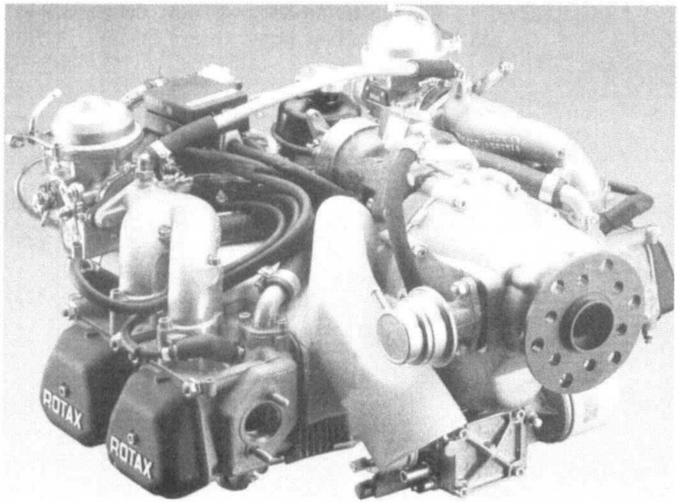
Since 1978 the two partners have studied engines for helicopters, and on 4 February 1985 the first RTM.322 began bench testing. Rated initially at up to 2,308 shp, the 322 has a three-stage axial plus one-centrifugal compressor, annular reverse-flow combustor and two-stage turbine with air-cooled first stage and uncooled single-crystal second stage. The separate two-stage power turbine drives to front or rear. Today the RTM 322 is in production at ratings from 2,011 to 2,429 shp for the EH101/Merlin/Griffon, WAH-64D Apache and NH-90.

The Rolls-Royce Turbomeca RTM 322 first ran in February 1985. Since then it has been adopted for particular versions of the EH101, AH-64 and NH 90, in each case competing against the GE CT7.

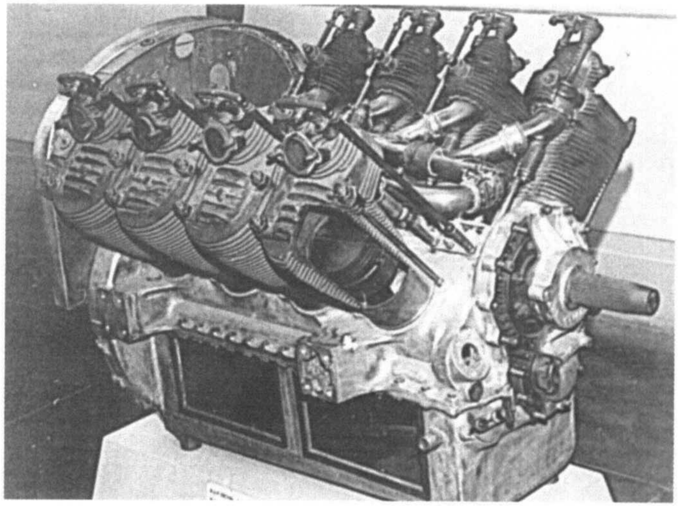




Despite the complexity of the dressing (the external pipework and accessories) the Rolls-Royce Turbomeca Adour is one of the simplest engines, and these afterburning examples are only 117 in long.



The Rotax 912 is one of the world's best-selling range of aero engines. This success stems partly from having distributors and service centres everywhere in the world where there might be customers.



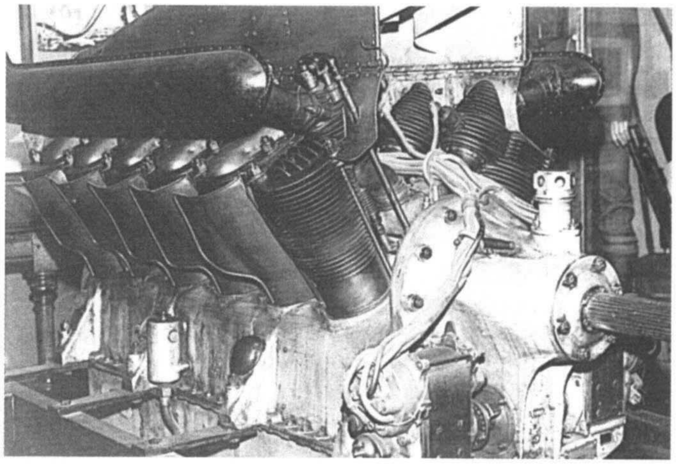
The RAF.1A air-cooled V-8 was made in very large numbers, mainly for BEs. It was rated at 90 hp.

Rotax (AUSTRIA) Part of the Canadian Bombardier group, this company made engines for snowmobiles and gradually found in the 1970s that the odd engine was being bought for a light aircraft. Gradually this became a trickle and then a flood, and today with roughly 60,000 engines flying, Rotax outsell all other makes combined. A few, such as the Model 582, are two-strokes. The 582 has two water-cooled cylinders in line, and gives 63 hp for a weight of 74.5 lb. A long-stroke 582 is designated 618UL, rated at 74 hp. Probably the most important current model is the 912, with four cylinders with air-cooled barrels and liquid-cooled heads; capacity is 1,211 cc (73.9 cu in), weight 143 lb, and rating 80 hp. The same-size 914, certificated in 1995 on a wide range of fuels, weighs 145 lb and has a rating of 115 hp. In 2005 the company was renamed BRP-Rotax.

Royal Aircraft Factory (UNITED KINGDOM) In 1912 HM Balloon Factory became the RAF (Royal Aircraft Factory), and by November of that year had produced a conventional water-cooled six-in-line, Colonel Mervyn O'Gorman's chief engineer being Major F.M. Green. Other engineers who became famous included G.S. Wilkinson, Jimmy Ellor, Sam D. Heron, Professor A.H. Gibson and A.A. Griffith. In early 1913 the RAF.1A was completed, based on the V8 Renault but with larger cylinders (100 × 140 mm, 8.8 litres), aluminium pistons, and various other changes including a scoop air inlet with no cooling fan except in pusher installations. The heads were not detachable from the cast-iron cylinders but had an overhead exhaust valve and an inlet valve in a detachable pocket. Oil was carried up from the sump by a light flywheel, to be scraped off at the top and allowed to feed by gravity to bearings and gears. As in the Renault, a very rich mixture was used, to help avoid over-heating. Rating was 92 hp at 1,600 rpm.

In late 1915 the RAF.1B introduced 105 mm bore cylinders (9.7 litres), with differences to the cooling baffles and oil system, running at 1,800 rpm to give 115 hp; it was mass-produced by car firms. The RAF.2 was a 120-hp nine-cylinder radial designed in October 1913. Various water-cooled engines were built, including the 200-hp RAF.3 of September 1914, but the other mass-produced engine was the RAF.4, a V-12 first run in December 1914. The cylinder banks were not at 90° but at 60°. With RAF.1A-size cylinders the power was initially 90 hp, a poor figure for 13.19 litres even with compression ratio of 4.5 and over-rich mixture. There were two carburettors and two six-cylinder BTH magnetos, lubrication again being by flywheel pickup, weight being 605 lb.

In 1916 the improved RAF.4A, weighing 637 lb, was rated at 140 hp but at 1,800 rpm actually developed 160, and made up the bulk of the 7,000 Factory engines made by car firms in 1915–17. By 1916 Gibson and Heron had carried out the first



Close up of the later RAF.4A, a V-12 also made in great quantities. It has its air-cooling scoop and baffles fitted.

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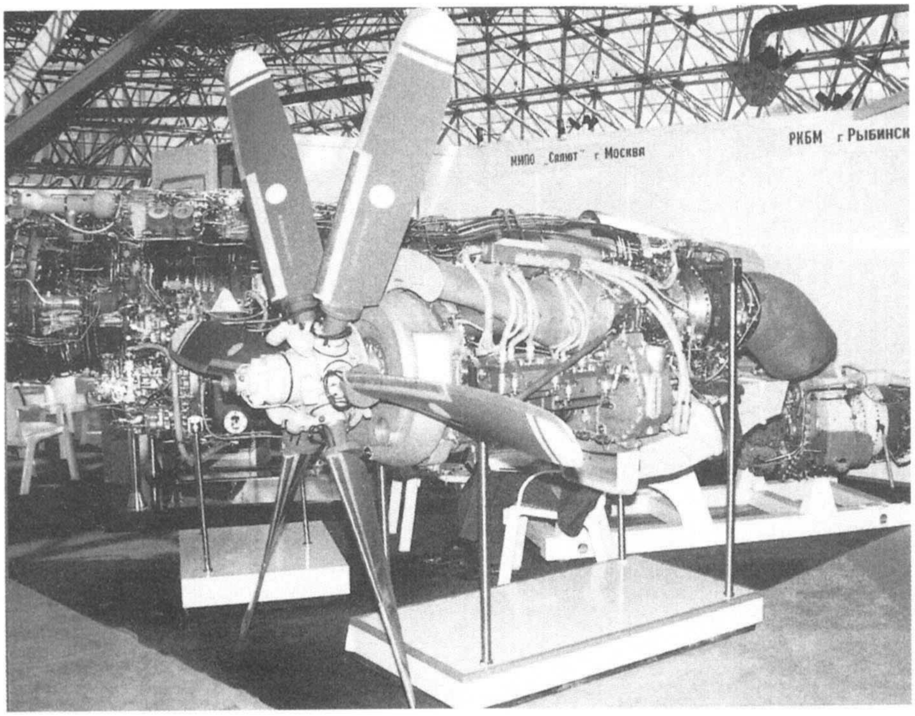
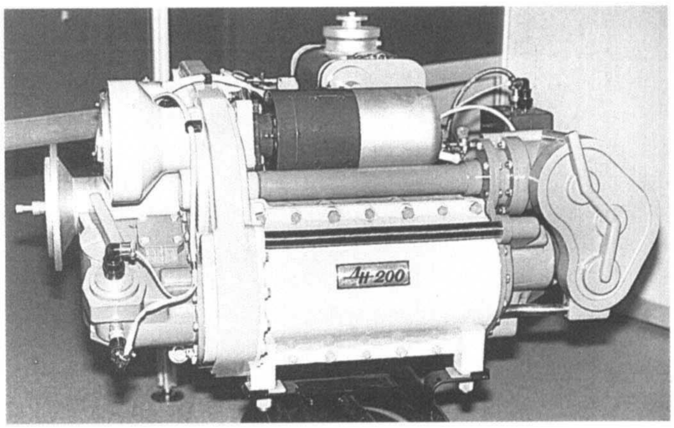


A complete An-38 power unit, the engine being the TVD-1500.

systematic research into air-cooled cylinders performed anywhere, developed gear-driven superchargers, and begun work on aluminium cylinders. In early 1917 the RAF.4D (100 mm bore) and RAF.4E (105 mm bore) introduced vastly superior cast aluminium cylinders with integral oversize spherical heads incorporating brackets for the overhead valve gear. Open-ended steel liners were pressed into the hot cylinder. With compression raised to 4.7 these much better engines gave 200 and 240 hp respectively at 2,200 rpm, for a weight of 670 lb. Service rating was 196 hp at 1,800 rpm, but they never went into production. The RAF.5 was a fan-cooled pusher version. The RAF.8 of September 1916 was a totally new 14-cylinder radial using cylinders designed with help from the RAF.4D/E. It became the Armstrong Siddeley Jaguar. In 1917–24 the Factory, renamed the Royal Aircraft Establishment, pioneered turbochargers, but developed no more engines. Griffith's axial-compressor research is discussed under Armstrong Siddeley and Metrovick.

Rybinsk Motors (RUSSIA) Also known as RKBM. Based at Rybinsk, this large design office was founded by Dobrynin (*qv*), who was succeeded by P.A. Kolesov and V.I. Galigusov, and it is now led by Aleksandr S. Novikov. It has produced a series of lift turbojets, notably the RD-36-35 of 6,725 lb thrust for the Yak-38, the RD-38 of 7,165 lb thrust for the Yak-38M and the RD-41 of 9,040 lb thrust for the Yak-141. Kolesov developed his predecessor's designs into the RD-36-51A turbojet, whose 14-stage compressor had ten stages of variable stators, for the Tu-144D supersonic transport; basic rating was 44,090 lb.



A full-scale display model of the RKBM DN-200, with propeller shaft on the left, described under Rybinsk.

One of the most important of today's engines is the TVD-1500. This is initially being certificated as a turboprop, driving a six-blade Stupino propeller to power the An-38. The compressor has three axial stages followed by a centrifugal, fed by an inlet which curves down from above the reduction gearbox. This engine weighs 529 lb and has a rating of 1,300 shp. There are other turboprop and propfan versions, and the TVD-1500V turboshaft, with a contingency rating of 1,550 shp, powers the Kamov V-62 and future Ka-52 helicopters.

A totally different engine is the DN-200, DN meaning Diesel Novikov. The objective was to make the most fuel-efficient engine possible for light aircraft. It has three double-ended two-stroke cylinders driving crankshafts on each side. Capacity is 1,759 cc (107 cu in), weight 364 lb, and power 200 hp. Sfc is a mere 0.27.

S

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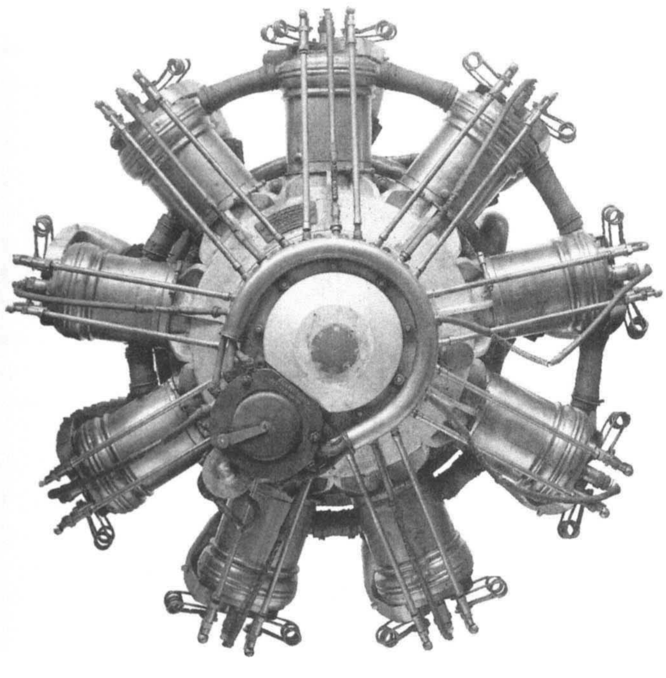
Salmson (FRANCE) Emile Salmson's modest company decided to make aero engines in late 1911. Early in 1912 the Billancourt (Paris) works produced the first of a long series of unceasingly improved static radials of novel design. At first they were water-cooled and used the patented (Swiss Canton-Unné) system in which all conrods drove a cage revolving on the crankpin on epicyclic gears. They had a separate cam ring for each pair (one inlet, one exhaust) of valves for each cylinder, with short stems and hairpin springs to reduce diameter. Some engines were mounted with the crankshaft vertical, driving through a bevel gear. In some applications two engines faced outwards from the fuselage to drive left/right propellers by transverse shafts and outboard bevel gears. The initial families had 120 × 140 mm cylinders, the seven-cylinder giving 90 hp and the nine-cylinder 100 to 140 hp. By 1917 the conventional master rod was being introduced on the important Z9 series, usually just called the Salmson 260 hp, which had cylinders 125 × 170 mm.

Despite the profusion of types and minuscule design staff the Salmsons were reliable; Handley Page picked a 200-hp model for his single-engined Transatlantic L/200 of 1913. In the 1920s there was an attempt at rationalisation, though the range included the nine-cylinder AD9 with bore/stroke only 70 × 86 mm, a size now returning for microlights. From 1920 all Salmson engines were air-cooled, with few unusual features. In 1946–7 the firm tried to market the Argus As 10C as the (240-hp) 8AS, as well as the pre-war (45-hp) 9ADB, (90-hp) 5AQ, (175-hp) 9ND and (230-hp) 9ABC, all radials. Liquidation followed in 1951.

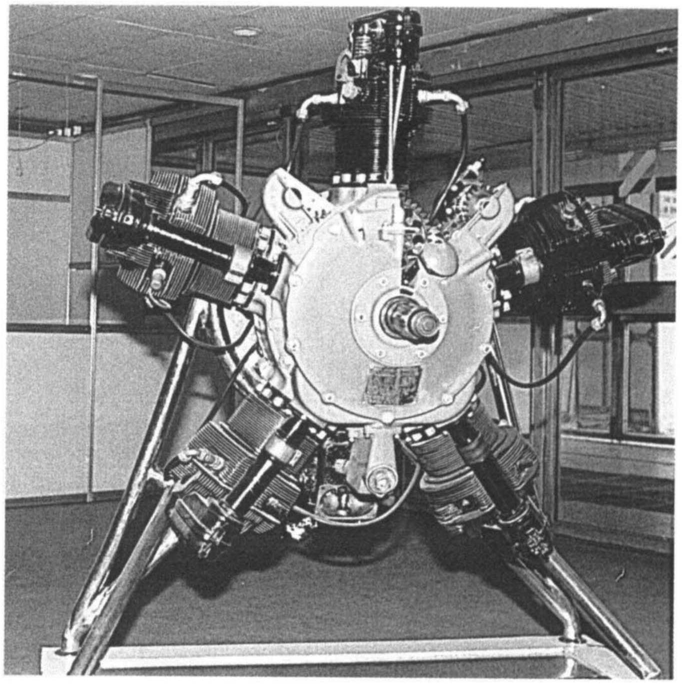
Samara (RUSSIA) Samara, or Kuibyshev, is one of the great Russian aero-engine centres. Also known as *Trud* (labour), and as SMPO (Samara machine-building production organisation), this partner to the adjacent bureau named for Kuznetsov carries out production of NK engines.

Saturn (RUSSIA) For Lyul'ka Saturn engines, *see* Lyul'ka.

Shvetsov (SOVIET UNION) Arkadiya Dmitriyevich Shvetsov was the first aero-engine designer to establish himself in the Soviet Union; in 1930 he was a founder of TsIAM, the central institute for aero engines. His firstborn was the unimpressive M-8 radial of 1925 (previous numbers were assigned to foreign engines). From this he developed the M-11 radial, one of the world's classic engines with 100,000–130,000 built in 1927–59. It had five cylinders 125 × 140 mm, 8.6 litres, and was qualified in 1928 at 100 hp at 1,590 rpm using any available motor spirit (later handbooks specified 59 octane). Subsequent versions gave 115, 145, 160, 165 and 200 hp at up to 1,980 rpm using better fuel. The M-12 was a 1930



The Salmson Canton-Unné engines were water-cooled radials, with hairpin-type valve springs. What appear to be third (central) valve rods are actually high-tension cables from the magneto on the front.



During 1927–59 over 100,000 M-11 engines were produced. This is a cutaway M-11FR, a refined 160 hp version.

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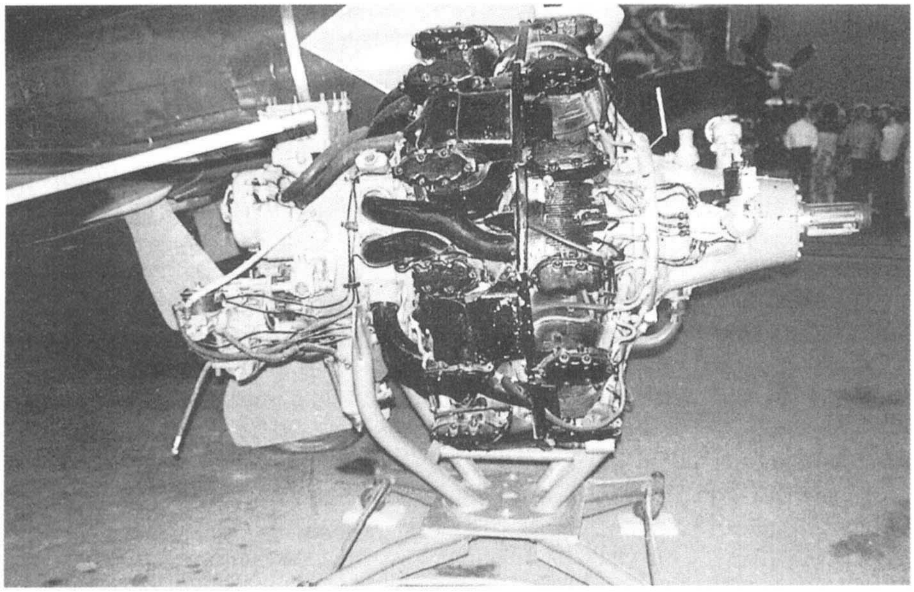
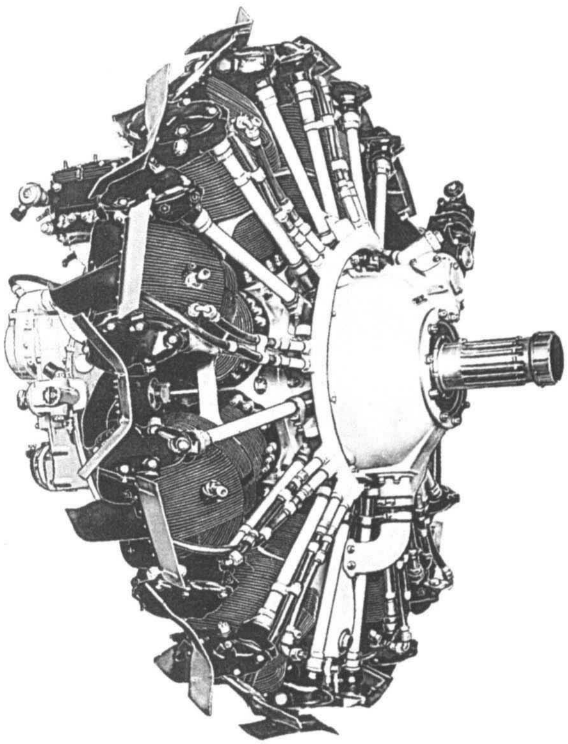


Another of Shvetsov's great successes was the ASh-82, of which about 70,000 were delivered. This 1,630-hp ASh-82FN is displayed at Monino alongside an La-5FN fighter. Another powers the FW 190 replica.

development of 190 hp. The M-15 of 1929, a nine-cylinder engine of 450 hp, did not go into production.

The M-21 was a 200-hp seven-cylinder from which Kossov derived the MG-21. Shvetsov's bureau managed the development of the licensed Jupiter into M-22 variants, and used M-15 cylinders in the M-26 of 300 hp based on the Bristol Titan. Shvetsov also played a managerial role in developing the Cyclone (M-25) into the M-62 by fitting a two-speed supercharger, improved induction system and other changes. In 1941 this was redesignated ASh-62 in accord with the new General Constructor scheme. Including the M-63 of 1939 rated at 1,100 hp, total production by 1985 exceeded 67,000, Polish designation being ASz-62 and Chinese, HS-5. The ASh-71 to -73 were 18-cylinder engines using M-63 cylinders, rated at 1,700 hp in 1941 and up to 2,650 hp in the 73FN of 1944.

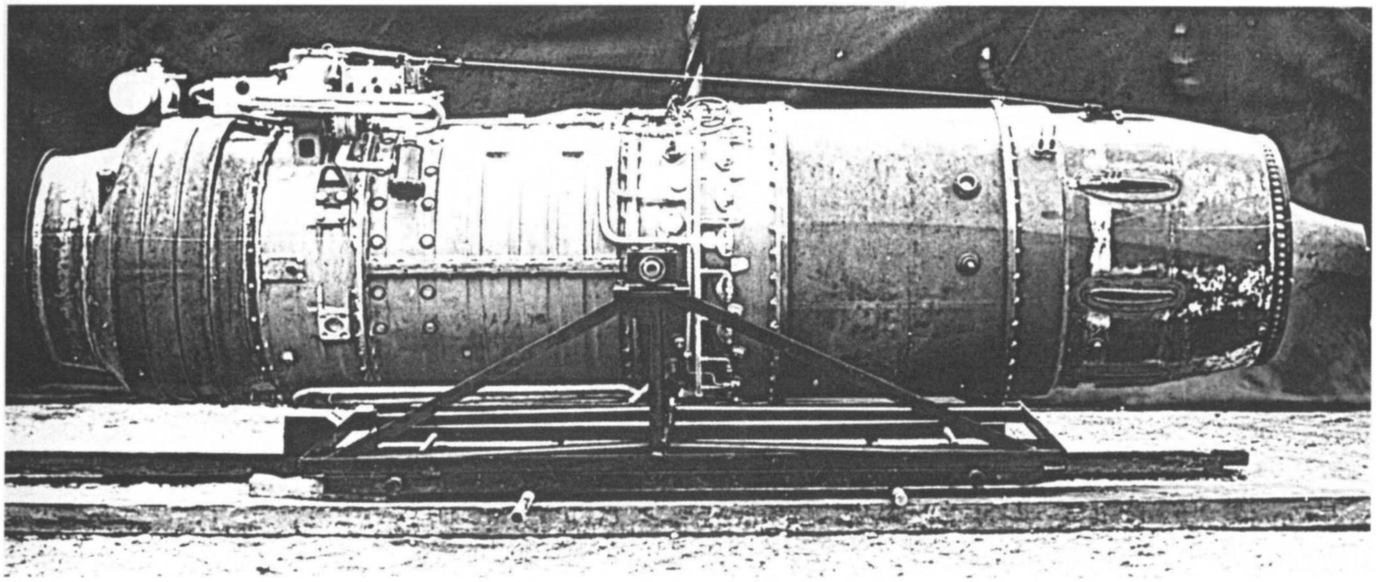
Most important of all Soviet radials was the ASh-82, a 14-cylinder two-row engine with M-62 cylinders with stroke reduced to 155 mm (bore remaining 155.5), giving 41.2 litres in a compact 1,259 mm diameter, which was the basis of the world's first good air-cooled fighter installations apart from the Fw 190. Qualified in 1940 at 1,250 hp on 87-grade fuel, the ASh-82 was developed in 22 versions up to 2,000 hp. About 70,000 were produced, some still being in use in Il-14s and Mi-4 helicopters, the latter having a 25° inclined installation with direct drive and cooling fan. Few ASh-83 1,900-hp engines, or 1,500 hp 18-cylinder ASh-90s (1941) were made, and the ASh-2 of 1950 (two ASh-82s in tandem giving a 3,300-hp unit) did not go into production. Substantial numbers were made of the seven-cylinder ASh-21, in effect half an ASh-82, qualified in 1947 at 700 hp and developed to 760 hp for aeroplanes and helicopters. In 1949 the ASh-2K, in effect two ASh-82s back to back, became the most powerful piston engine ever to fly, rated at 4,500hp. In 1953, Shvetsov was succeeded by Soloviev (*qv*).



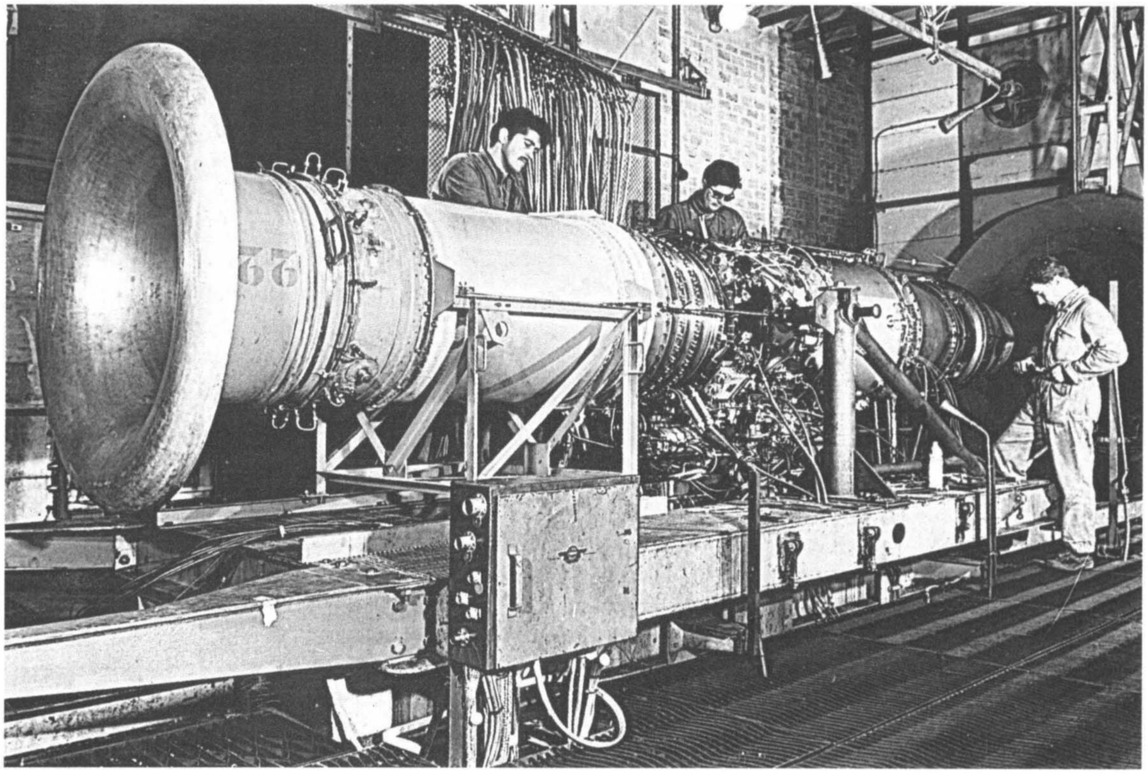
Qualified in 1937 at 840 hp as the M-62, Shvetsov's ASh-62 has been made in useful numbers, the An-2 biplane alone taking well over 20,000. Production was transferred to Poland in 1952, this being a PZL-built ASz-62IR, of 1,000 hp.

Siemens (GERMANY) *See* Bramo.

Snecma (FRANCE) On 29 August 1945 the Gnome-et-Rhône company was given the title Société Nationale d'Etudes et de Construction de Moteurs d'Aviation, on its enforced nationalisation. In 1946 SNECMA (then written all in capitals) took over the previously sequestrated Renault company, as well as SECM (Lorraine) and the GEHL oil-engine works. In 1968 SNECMA also took over Hispano-Suiza's engine business and licences.



The very first Atar, the 101 V1, at Decize in 1948.



British and French engineers ready the first SNECMA/Bristol Siddeley M45 for its first run at Melun-Villaroche in June 1966, 16 months after starting the programme. The M45 was the first engine ever designed from scratch by companies in more than one country. Unfortunately its many planned applications all collapsed, for political reasons.

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At the start the production engines were the GR14N, R and U, Regnier 4L and Renault (Argus-derived) 12S. Under Henri Desbruères work went ahead in 1947 on simple pulsejets which had been worked on from 1943 by Ingenieur en Chef de l'Air Raymond Marchal (by 1946 SNECMA technical director). These were purely resonant ducts without valves or other moving parts. The *Escopette* (carbine) weighed 4.8 kg and gave 10 kg thrust; the *Ecrevisse* (crayfish), bent back on itself in a U, with inlet facing aft, came in various sizes with thrusts from 10 to 150 kg. SNECMA's first gas turbine was the TB.1000 turboprop. Design began in February 1946 and settled as a simple single-shaft engine with nine-stage compressor, six combustion chambers and two-stage turbine with straight 0.109 spur gear to the propeller. The 1948 prototype gave 1,300 shp, being followed in 1951 by the TB.1000A of 1,760 shp (2,000 ehp), weight being 450 kg. It never flew.

Far more important was the Germanic turbojet designed in a small office at Rickenbach, Switzerland, by Dr H. Oestrich, former BMW 003 chief engineer, and several key colleagues, who escaped there in May 1945. They had made contact with the French, and adopted a French stance by naming themselves the Atelier Technique Aéronautique Rickenbach, their engine becoming the Atar in consequence. Design was complete in October 1945, and two months later the Ministère de l'Air awarded a development contract on the understanding that all manufacture would be done in France. A month later the ATAR was closed and the team relocated at Decize (Nièvre) with the delightful name 'Aéroplanes G. Voisin, Groupe O'. In June 1946 the drawings for the Atar 101V prototype were sent to SNECMA. It was made at the latter's Usines Kellermann and Gennevilliers, and assembled in March 1948 at the Melun Villaroche centre, then almost a virgin site. It was first run a month later on a lash-up bench of steel girders on four wheels. The 101V had a seven-stage compressor (pr 4.2 at 8,050 rpm), annular combustor with 20 burners, one-stage turbine with 53 wrapped-sheet air-cooled blades, and nozzle with a large central bullet translated in/out by a hydraulic ram on the centreline. The entire engine was made of ordinary commercial steels, nothing else being available. By 1949 improved 101A engines were flying in a Marauder and on a pylon above a Languedoc. By this time SNECMA was not only chaotic but near collapse, with vast overheads and payroll (16,950 in 1947) but practically no sales apart from licensed Hercules piston engines. Workforce was slashed to 6,600, and in June 1950 Oestrich's team was formally taken over, the Atar becoming a SNECMA property.

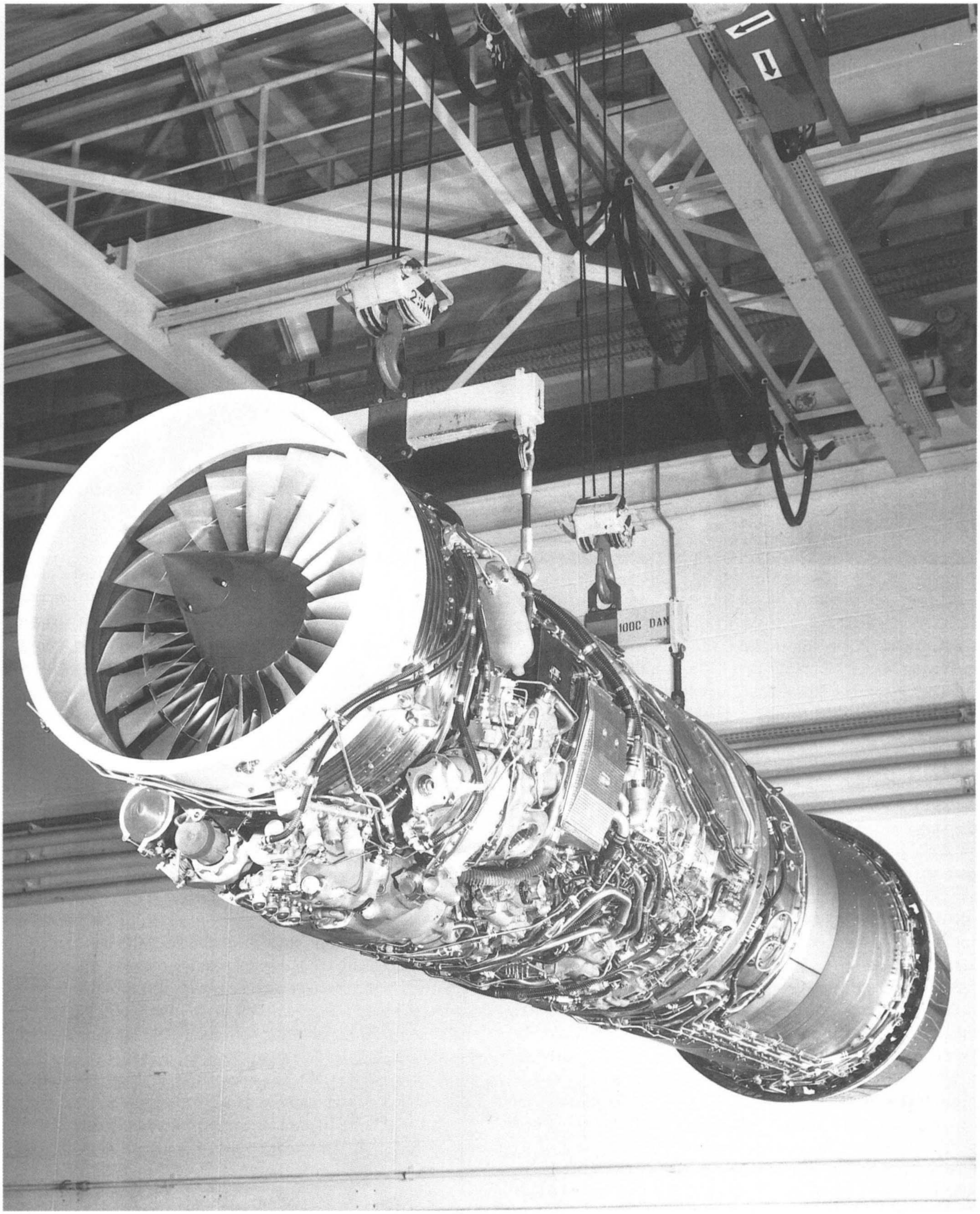
The 101B introduced solid Nimonic turbine blades with correct twist, as well as improved combustor airflow, and a thrust of 2,350 kg was established in Meteor RA491 (previously Avon-engined) in late 1949. The B2 had extra stator blades, raising pr to 4.4. The C achieved production for the Mystère IIC at 2,745 kg, with speed raised to 8,500 rpm, Air Equipement (Rotax) starter in the nose bullet, revised combustor, and nozzle bullet separated from the tailcone. The D reverted to 8,300 rpm, but had a larger turbine and new nozzle with the bullet replaced by upper/lower eyelid flaps. The E introduced a zero-stage handling 60 kg/s at 8,400 rpm with pr 4.8; the enlarged turbine diameter was carried forward through the combustor, and in the E4 (3,700 kg rating, 880 kg weight) the nozzle eyelids were improved. The F was a D with afterburner, tested in 1952 with much larger nozzle eyelids and qualified in 1954 at 3,800 kg. The G was an afterburning E, the G2 and G3 giving 4,310 kg and the G4 up to 4,700 kg.

In 1954 design went ahead on the new-generation Atar 8. Amazingly this modest improvement has led to the Atar, despite its now totally obsolete design, still being in wide service – Snecma having concentrated solely on the supersonic fighter market. The nine-stage compressor handles 68 kg/s at pr of 5.5 at 8,400 rpm, driven by a two-stage turbine of reduced diameter. Construction was improved throughout, rating of the 08B3 being 4,310 kg. The Atar 9 (originally 09) was the 8 with afterburner, but introduced a new compressor with a cylindrical drum formed from centreless discs and a casing of ZRE-1 magnesium alloy. The afterburner is enlarged and improved, 9B3 rating being 4,170 kg dry and 5,880 maximum. The 9C introduced a further enlarged afterburner with 18 nozzle flaps, as well as a Microturbo gas-turbine starter which established a new aero-engine company. Maximum thrust increased to 6,200 kg, and at over Mach 1.4 an overspeed to 8,700 rpm was permitted. In the 09D the compressor was largely titanium, for sustained Mach-2 flight, and this led to the 9K with improved combustor, turbine cooling and afterburner, ratings being 4,610/6,570 kg in the K-6 and K-10 (Mirage IVA). By 1967 this led to the 9K-50, with improved compressor blading (pr. 6.5), a new turbine with cast and coated blades, and many other changes. Weighing 1,587 kg, ratings are 5,015/7,200 kg at 8,700 rpm. Without afterburner the corresponding 8K-50 delivers 5,000 kg. Total Atar production was completed in 1995 at 5,250.

In June 1951 design began on the R.104 Vulcain, basically an early Atar enlarged to an airflow of 82 kg/s. First tests on 21 May 1952 reached 4,500 kg, and a little flying was done in a pod under an Armagnac in 1954, but the Vulcain was abandoned at 6,000 kg in January 1955. The R.105 Vesta, of December 1953 design, was a Vulcain scaled down to 24 kg/s at 12,900 rpm and intended to have an afterburner in twin-engined light fighters. It ran in December 1954 at 1,200 kg but was dropped before afterburning trials began. To fill the gap and replace the seemingly outdated Atar the Super Atar was designed in 1956–8 as an advanced single-shaft variable-stator engine for 9,000 kg thrust with afterburner. But after discussion with Dassault and the government it was decided to import foreign technology; Pratt & Whitney was chosen and licences obtained for all that company's piston and turbine engines in exchange for 10 per cent of Snecma's stock and membership of the board of directors (unusual for a nationalised concern). The June 1959 deal brought Snecma immediate military and airline overhaul business.

It was also intended to lead to production of a French augmented turbofan derived from the JTF10A. In November 1961 the go-ahead came on the TF-106, derived from the JTF10A-20 (TF30 variant) with an advanced Snecma afterburner. To gain experience SNECMA made TF-104 engines based on the JTF10A-2. In October 1963 a TF-104 stalled on its first take-off in the Mirage IIIT (an aircraft much bigger than other Mirage IIIs) but aborted safely. It finally flew on 4 June 1964, the first flight by an augmented turbofan. (P&W were later to suffer severe stall problems in the F-111.) Five TF-104Bs were followed by 13 TF-106 engines, of advanced supersonic design, first run in October 1963, flown under the Armagnac in early 1964 and in the Mirage IIIT on 25 January 1965, reaching Mach 2.05 on 26 November 1965 (before any other augmented turbofan had reached Mach 1). The last 106A3 was rated at 7,900 kg.

In early 1964 the deep problems with the TF30 caused Snecma to consider switching to the Spey, but the US firm's hold over Snecma prevented this. Instead in March 1964 Snecma agreed to develop a less-troubled engine, the TF-306, starting not with the 1959 JTF10A but with the 1964



The Mirage 2000 is powered by the M53-P2, with an afterburning thrust of 9,700 kg (21,384 lb).

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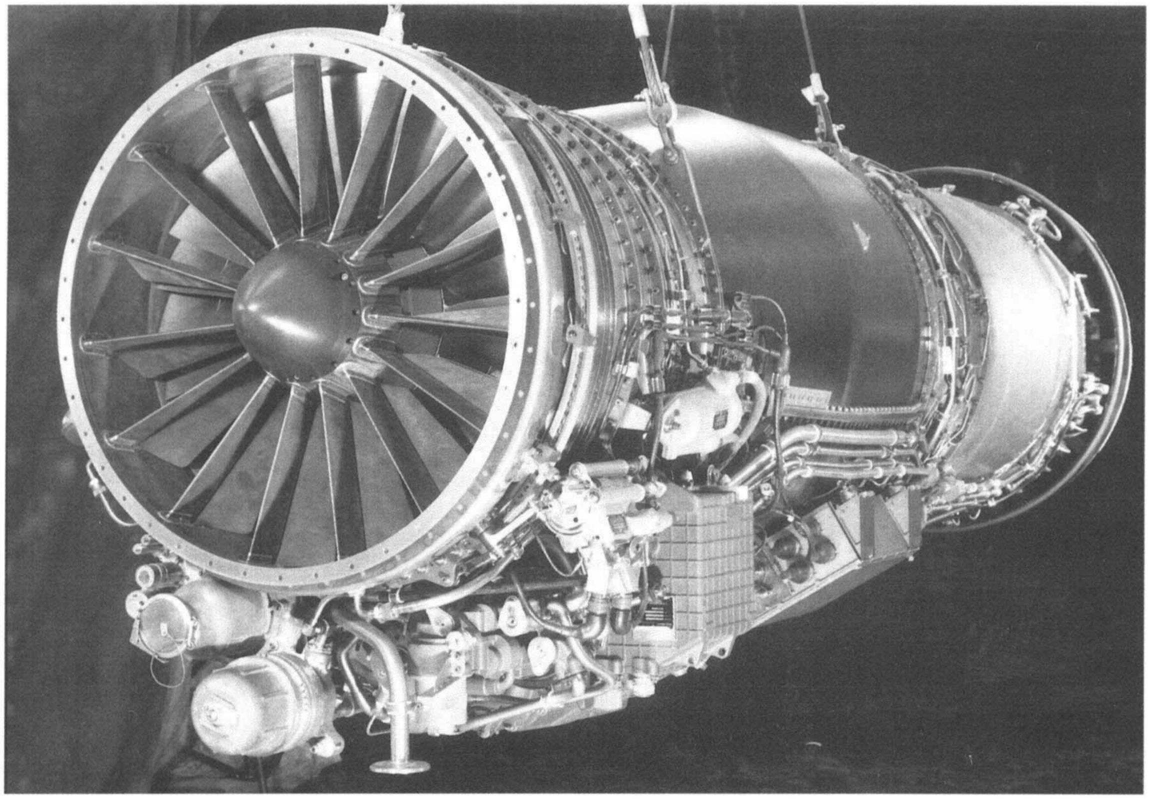

The SNECMA M88-2 is now in production as the power-plant of the twin-engined Rafale.

TF30-P-1. Eight TF30s were supplied by P&W, one flew under the Armagnac in December 1965, and another powered the high-wing Mirage F2 on 12 June 1966. Studies were made for the TF-306 inside a Nord ramjet fighter at Mach 4. The TF-306E powered the Mirage G, but in 1968 it began to appear that 'the P&W connection' had been a costly waste of ten years. The Mirage G was redesigned with two Atar 9K-50s and the Super Atar was looked at again.

In the mid-1960s Snecma had two further diversions. By far the larger was the M45 Mars, announced at the 1964 Hanover air show as a totally new range of turbofans for anything from trainers to supersonic fighters and transports. Bristol Siddeley, already a partner on the Concorde Olympus 593, joined as equal partner on 1 January 1965 to handle the HP spool and combustor, to form a common core for all M45s. The name Mars was dropped, and the thrust bracket widened to 1,500–6,000 kg. The HP spool was that of the BS.116, itself a scaled Olympus 320 (TSR.2). There is little point in describing the eight subsequent major variants, which included the 45G for the AFVG swing-wing fighter and 45H for the German VFW 614 airliner. Not one found a major application, though the M45H did power the 614 in service at 7,600 lb thrust and was taken over by Rolls-Royce (Parkside works, Coventry) at SNECMA's request in 1976. RR modified one into the 45SD-02 with a large Dowty Rotol variable-pitch fan, tested at Aston Down. The other diversion was the Larzac turbofan for the Alpha Jet trainer. Despite having SNECMA number M49 this was from the start a 50/50 project with Turbomeca. A conservatively designed engine, it has a two-stage fan, four-stage HP spool (overall pr 10.6), annular vaporising combustor and two single-stage turbines. Over 1,200 04-C6 engines were delivered at a rating of 1,345 kg, production being shared with KHD and MTU of West Germany. Teledyne CAE marketed it without success from 1973 as the CAE 490. It was later adopted for the Russian MiG-AT trainer and light attack aircraft.

When the Super Atar was dusted off in 1968 it was given the new designation M53. Later the name was dropped. A continuous-bleed turbojet, it finally ran in February 1970, flew in the right pod of a Caravelle on 18 July 1973 and powered the Mirage F1-M53 in December 1974 (this aircraft was a contender for NATO orders won by the F-16). In March 1978 the Mirage 2000 began its flight trials. The M53 has a three-stage LP and five-stage HP spool rotating together, annular combustor and two-stage turbine. At 10,500 rpm pr is a modest 9.3, and thrust with full afterburner 9,000 kg, the P2 engine of 9,700 kg following delivery in 1985; a typical weight is 1,450 kg. To provide a newer and much lighter engine for future fighters SNECMA has since 1980 designed the M88. This augmented turbofan has variable inlet guide vanes, three-stage LP, six-stage HP, annular combustor and one-stage HP and LP turbines. The first M88 ran in January 1984, and low-rate production deliveries began in December 1996 for all versions of Rafale. The M88-2 weighs 1,970 lb and has dry and afterburning ratings of 11,250 lb and 16,872 lb. The M88-2K is a 15,740 lb version for single-engined aircraft, and the

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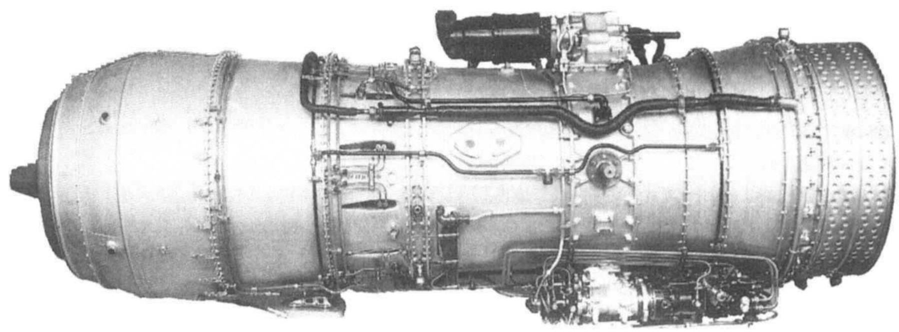
M88-3 is a growth version on test since December 1996 at thrusts up to 19,841 lb but the Rafale has yet to achieve an export sale. Snecma had been a partner in production of the Rolls-Royce Tyne for the Franco-German Transall military airlifter. From 1979 European nations discussed a Future Large Aircraft, to replace the Transall and C-130, and Snecma (as it was beginning to be written) tried to get its proposed M138 turboprop adopted as the engine. Wisely, when this aircraft began to move ahead as the A400M, Airbus Military demanded a better engine, and today Snecma is a 24.8 per cent partner in Europrop. It is also an equal partner with Saturn in PowerJet. Finally, despite the earlier links with Pratt & Whitney, today Snecma is the biggest partner of GE, notably in the CFM56, but also in the CF6, GE90, GE90-115B and all versions of GEnx.

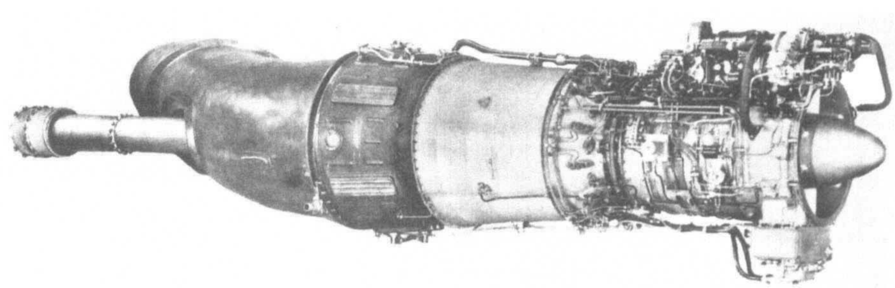
SOCEMA (FRANCE) In 1941 a team of engineers in the Unoccupied Zone, under P. Destival, began design of a turboprop called TGA1 ('Turbo Groupe d'Air', but as a cover said to mean 'Turbo Groupe d'Autorail', the actual contract being placed by the SNCF). Several examples were run from 1943, and in 1945 the TGA 1bis introduced improvements. Both had a 15-stage compressor of 3.6 pr, remarkably good cannular combustor, four-stage turbine and epicyclic propeller gearbox. Output was to be 3,000 hp (about 2,400 was achieved), weight being 2,100 kg. In 1945, using partly Jumo 004B technology, the TGAR 1008 turbojet was designed for SNCASE. Weighing 1,250 kg, it gave the required 1,900 kg thrust and was developed by 1949 to 2,000 kg before being abandoned. These were remarkable achievements with no special alloys and no outside help.

Soloviev (SOVIET UNION) P.A. Soloviev was unknown until the late 1950s, when his bureau was named as source of the D-15 engines fitted to the '201-M' record-breaking aircraft. This aircraft was later identified as a version of the M-4, normally powered by AM-3 (RD-3) engines much less powerful than the D-15 of 13,000 kg rating. It is an impressive two-shaft turbojet which probably influenced Soloviev's better-known airline engines. The D-20P is a two-spool turbofan with three-stage fan, eight-stage HP, 12-tube cannular combustor, single-stage HP turbine and two-stage LP. Airflow is 133 kg/s at 8,550 rpm, pr 13, bypass ratio 1, thrust 5,400 kg and weight 1,468 kg. The D-25V is the big turboshaft designed in early

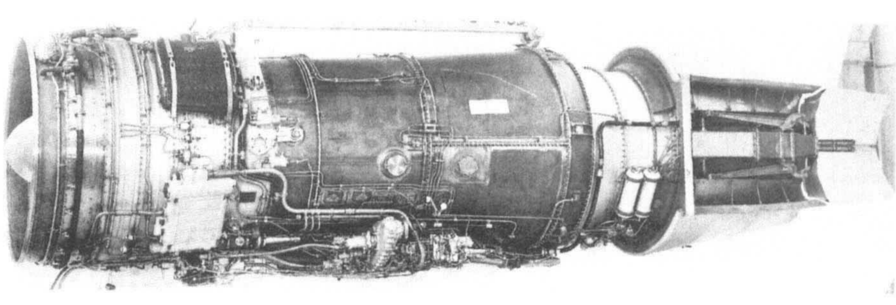
Soloviev's D-20P was the Soviet Union's first production turbofan. The first fan stage has supersonic tips, and the HP spool has automatic bleeds round stages three and four to avoid blade stall.



The huge Mi-6 helicopter was planned 55 years ago in parallel with P. Soloviev's D-25V engine. The front end is de-iced by hot oil, and the free turbine drives at the rear through the handed jetpipe.



The D-30KU Series II powers the Tu-154M; basically similar engines power the Il-62M and Il-76.



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1954 to power the Mi-6. It has a nine-stage compressor (pr 5.6 at 10,530 rpm), 12-tube cannular combustor, single-stage compressor turbine and two-stage power turbine driving to the rear. Weight is 1,325 kg (but the helicopter gearbox weighs a formidable 3,200 kg), and output 5,500 hp. The D-25VF has a zero-stage and gives 6,500 hp.

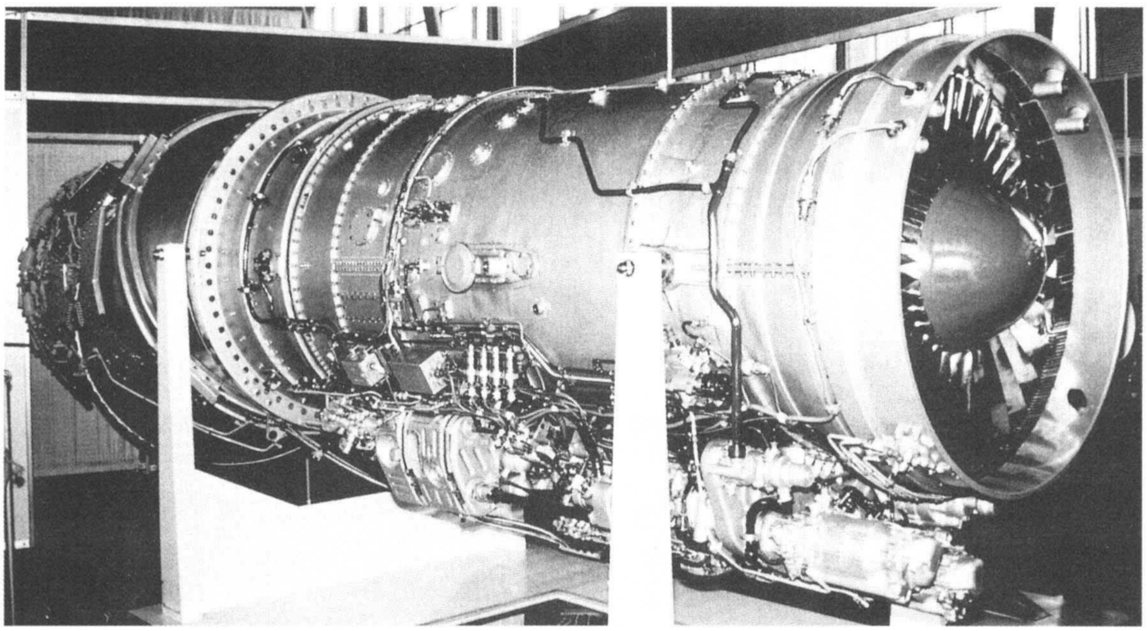
The D-30 is a turbofan derived from the D-20, with four-stage LP, 10-stage HP, 12-tube cannular combustor and two-stage HP and LP turbines. Weight is 1,550 kg and at 7,700 LP rpm airflow is 125 kg/s, pr 17.4 and thrust 6,800 kg. Despite its designation the D-30K is a totally different turbofan of much greater power. It has a three-stage LP, 11-stage HP, 12-tube cannular combustor, two-stage air-cooled HP turbine and four-stage LP turbine. Weight (without the usual reverser) is 2,300 kg, and at 4,730 LP rpm the airflow is 269 kg/s, bypass ratio 2.42, pr 20, and thrust 11,000 kg, other versions giving 12,000 kg.

In 1987 Soloviev was permitted to disclose the PS-90A, an advanced turbofan rated at 16 tonnes (35,275 lb) thrust. It has a single-stage fan (cruise bypass ratio 4.8), rotating with two LP core booster stages, 13-stage HP compressor (overall pr 35.5), annular combustor, two-stage HP turbine and four-stage LP turbine. A digital control system is fitted, and dry weight is 6,173 lb, with full-length bypass duct and mixer nozzle. Cruise rating at 36,000 ft and Mach 0.8 is 3,500 kg (7,716 lb), corresponding sfc being 0.595. Soloviev was succeeded by Yuri Reshetnikov, who is General Director of Aviadvigatel (*qv*).

Soyuz (RUSSIA) AMNTK Soyuz, with a name meaning alliance or association, is the successor to that Moscow group founded by Mikulin and then run by Tumanskii (1955–73), Favorski (1973–87) and now by Vassili Kobchenko and Mikhail Simonov (previously General Director of Sukhoi). Major AMNTK Soyuz engines have been mass-produced by TMKB Soyuz (see next). It has a heritage of colossal production of fighter turbojets, including some listed earlier under designers Gavrilov and Khachaturov. Kobchenko himself designed the R-79 vectored-thrust augmented turbofan for the Yak-141. This has five-stage LP and six-stage HP compressors, a vaporising combustor, and a short afterburner which can be used at full power even in hovering flight with the nozzle in the 95° position. The jetpipe contains two tapering-wedge sections which rotate in opposite directions to vector the thrust downwards. The R-79 weighs 6,063 lb and has ratings of 24,200 lb dry and 34,170 lb maximum, reduced to 30,864 lb when maximum air bleed is extracted for aircraft control.

Though the R-79 never achieved production, 27,000 earlier Soyuz engines powered MiG, Su, Tu and Yak aircraft of 44 air forces, as well as large numbers of cruise missiles and UAVs. Recently AMNTK Soyuz has produced a profusion of projected small turbojets, turbofans and turboprops, as well as the potentially important TV-O-100 developed with OMKB, all without finding customers.

Soyuz (RUSSIA) TMKB Soyuz, based at Moscow Tushino, was formed in 1942 as OKB-500, by Charomskii (*qv*). His successors were Vladimir Yakovlev (1946–53), Nikolai Metskvarishvili (1957–65), Konstantin Khachaturov (1965–82), Yuri Shvetsov (1982–87) and Roald Nusberg (from 1987). When the diesel engines were followed in 1947 by the Rolls-Royce Derwent the product was naturally named the RD-500, but subsequent work involved mass-production of the engines designed at what is now AMNTK Soyuz, bearing suffix 300. The most important were the R27-300, R29-300 and R35-300, which powered the MiG-23 and MiG-27. More recent engines include the RD-1700, designed to replace the Larzac in the MiG-AT, and the RD-2500 designed to power the rival Yak-130.



The R-79 is the most powerful vectored-thrust VTOL engine to have flown.

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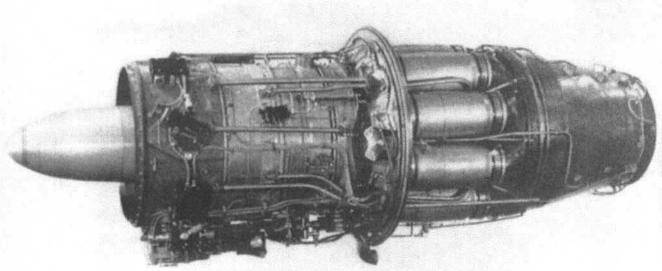
STAL (SWEDEN) The Svenska Turbinfabriks AB Ljungström began in 1946 to design a turbojet named *Skuten* (Witch). The firm had been in gas turbines since 1935 and the Skuten ran in early 1949, but did not fly. It had an eight-stage compressor, seven combustion chambers and single-stage turbine; weight was 780 kg and thrust 1,450 kg. In 1951 the *Dovern* went on test, flying in 1953 under a Lancaster. This engine had a nine-stage compressor, nine chambers and single-stage turbine, weight being 1,195 kg, airflow 55 kg/s, pr 5.2 and thrust 3,300 kg at 7,275 rpm. The Avon was picked instead to power the J35.

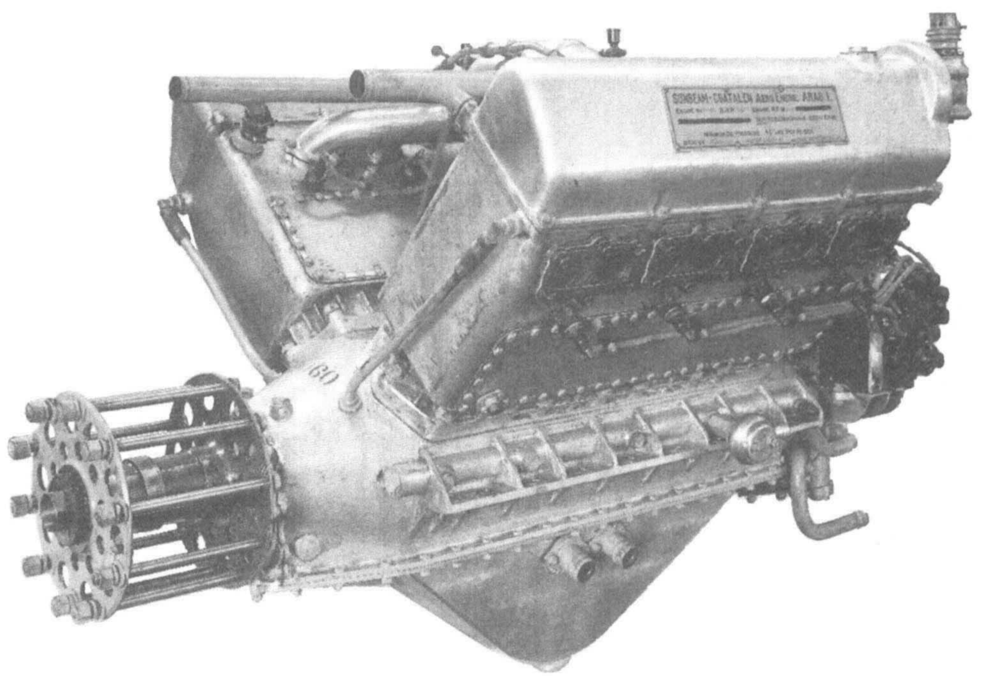
Sunbeam (UNITED KINGDOM) The Sunbeam Motor Car Company of Wolverhampton got off to a meteoric start after its formation in 1910, producing cars of many types including racers which quickly scored major successes. Technical expertise rested in Louis Coatalen, who came from his native France to build 'motors' in the widest sense. In 1913 he designed two aero engines, a 150-hp eight-cylinder and a 200-hp 12-cylinder. Both were water-cooled V-format engines, the bigger being intended for airships. They were of outstandingly modern conception, with cast cylinder blocks, twin carburettors each feeding one block, enclosed overhead valve gear and plenty of aluminium in the construction. Sunbeam added a 200-hp six-in-line which was described as 'the only British aircraft engine actually in production at the outbreak of war'.

Coatalen had a good reputation, and was the favoured engine supplier to the RNAS until late in the war. But designs proliferated. Bearing in mind that all used similar technology, and most had a deep V-sump looking like a Hispano, it was often hard to see which engine was actually fitted, especially as the arrangement of cowling, radiator(s) and exhaust(s) often differed as many as 17 times in one aircraft type. The following is an abbreviated list: 1914, unnamed 100-hp six-in-line, V-8 of 225 hp and prototype '300 hp'; 1915, 150-hp Nubian V-8 (often a pusher), prototype 310-hp Cossack V-12, 190-hp Saracen six-in-line; 1916, 200-hp Afridi, 100-hp Dyak six-in-line, prototype Arab V-8; 1917, production Arab at 200 hp (but prolonged difficulty with crankcase strength, cylinder attachment and severe vibration, throwing major programmes into disarray), production Cossack as the '310' (320 hp at 2,000 rpm) and '320' (345 hp at 2,000 rpm), and major production of Maori V-12s as the '240', '250' or Maori II and '275' or Maori III (actually 265 hp at 2,100 rpm); and 1918, 400-hp Matabele (with two Saracen blocks). Sunbeam made little effort to produce postwar aero engines and in 1923 Coatalen returned to France.

Svenska Flygmotor (SWEDEN) *See* Volvo.



The STAL Dovern was a plucky attempt at an advanced axial turbojet at a time when such an engine had almost defeated Rolls-Royce. Unfortunately for STAL, Rolls won through.



With a brass plate proclaiming it to be engine No. 19,060, this Sunbeam Arab I was rated at 234 hp at 2,000 rpm. Though similar in general layout to the V-8 Hispano-Suizas, Coatalen's engines were of totally different design.

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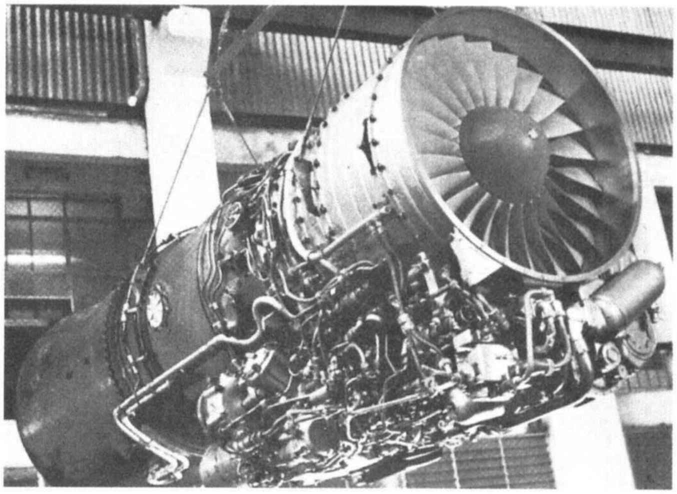
Teledyne CAE (USA) Continental Motors obtained a licence in 1951 for Turbomeca small gas turbines, the Marboré II turbojet being Americanised as the J69. From this stemmed a wide range of other engines. In 1967 CAE (Continental Aviation and Engineering) was formed as a separate division, and like the parent firm this became a division of Teledyne Incorporated in 1969. It was renamed Teledyne CAE, with headquarters at Toledo, Ohio, concentrating on small turbojets and turbofans for RPVs, missiles and small aircraft.

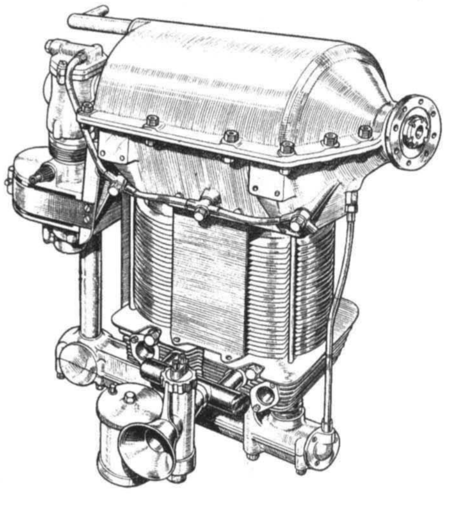
The J69 began life as the Continental Model 352, rated first at 660 and then 880 lb. Large numbers of J69-9s were built with pr 4, airflow 18 lb/s and rating 290 lb at 22,700 rpm. Smaller Turbomeca engines (6.6–7.5 lb/s) produced the Model 140 and 141 compressors and 220 (T51) turboshaft/turboprop. By 1956 Continental was engaged in adding transonic axial compressor stages, following Turbomeca's lead but doing its own design. This resulted in the J69-29 (356-7A), J69-41A (356-29A) and YJ69-406 (356-34A) RPV engines with airflow around 29.8 lb/s, pr about 5.45 and typically 1,920 lb thrust. Also for RPVs the J100 (356-28A) added two axial stages, each with replaceable blades (44.9 lb/s, pr 6.3) to give 2,700 lb at 20,700 rpm. A profusion of further engines followed, as well as a licence extension for the Larzac, but most failed to find markets. Work on lightweight lift jets led to the LJ95 (365) with thrust of 5,000 lb and weight less than 250 lb. Mass-production engines include the J402-400 (370) for the Harpoon missile, with precision-cast axial and centrifugal stages (9.6 lb/s, pr 5.8) rated at 660 lb at 41,200 rpm, and the J402-700 (372-2) RPV engine (640 lb at 40,400 rpm). There are several newer engines in the 1,000 or 7,000-lb class aimed at future missile/RPV/trainer markets and having no direct kinship with Turbomeca engines. In 1982 Teledyne CAE began second-source production of the Williams F107 cruise-missile engine.

Teledyne Continental (USA) *See* Continental.

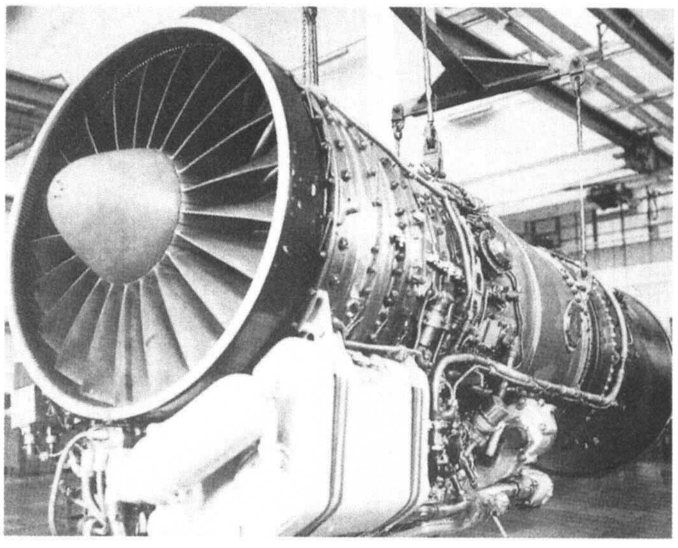
Textron (USA) *See* Lycoming.



Built in enormous quantities, Tumanskii's very attractive R-11F2S-300 is seen here in the Koraput plant of Hindustan Aeronautics, which has made this fighter engine under licence.



Not referred to in the text, this was the smallest of the French Train company's engines of the 1930s. A neat inverted twin, it was rated at 20–25 hp. Most Trains had four air-cooled cylinders and were rated at 40 hp.



An HAL-built R-25, a particularly neat two-stage afterburning turbojet. It has a two-stage afterburner which is said to make it suitable for air combat at high altitudes.

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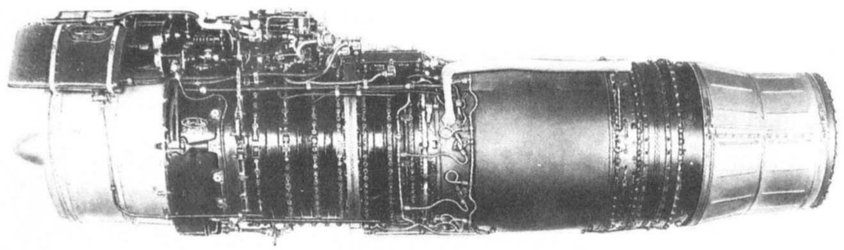
Tumanskii (SOVIET UNION) Academician Sergei Konstantinovich Tumanskii became famous for superchargers for high-altitude fighters in the Second World War (when he also began a partnership with the MiG bureau that has strengthened with time). He became deputy to Mikulin, easily made the transition to turbines, and on Mikulin's removal in 1956 was appointed General Constructor of the renamed bureau. Since then his engines have been produced in greater numbers than any other 'make', the total easily exceeding 70,000.

The first turbojet of wholly Soviet design to be mass-produced, the AM-5 was designed under Tumanskii in 1950. From it stemmed the AM-9, with nine-stage compressor (pr 7.14), annular combustor and two-stage turbine. In the chief application (MiG-19/J-6) all accessories are grouped above the engine and an afterburner is fitted. An engine with accessories on the underside, without afterburner, powered the Yak-25. In 1956 the AM-9 was redesignated RD-9, and seven major variants were produced until 1959, the RD-9BF-811 continuing in production in China as the Shenyang-built WP-6. All variants have a basic diameter of 32 in and a typical maximum rating is 7,275 lb.

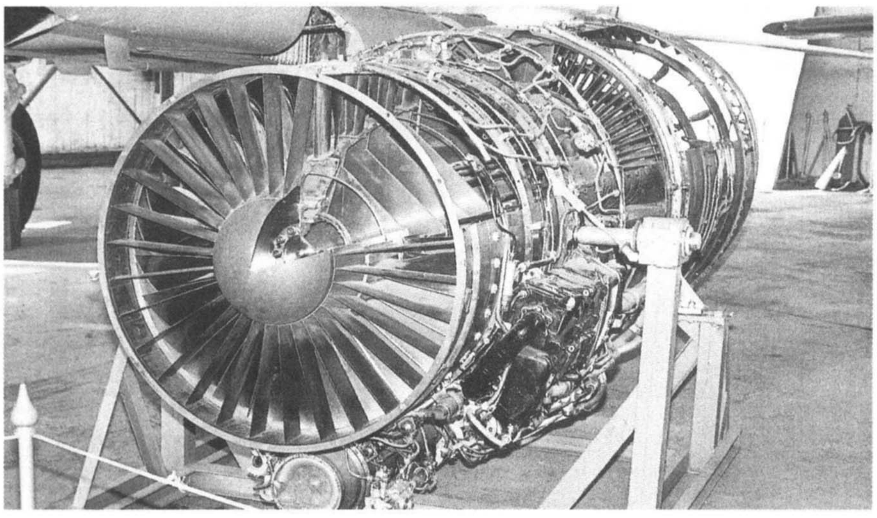
From this was derived the R-11, first run in early 1956, a slightly larger two-spool engine which pioneered the overhung first-stage without inlet guide vanes. All models have an excellent annular combustor and two one-stage turbines, and accessories are usually grouped under the compressor case. The initial series were rated at 8,600 lb dry and 11,243 lb with afterburner with full modulation and multi-flap nozzle. In the R-11-300 of 1959 an enlarged afterburner and new nozzle increased thrust to 13,117 lb. The R-11F of the same year ran at increased rpm with higher temperature, to give 9,480 lb dry and 12,676 lb with the original afterburner. The FS and F2S have large bleed manifolds for blown flaps. The final mass-production version was the R-11 F2S-300, of 13,668 lb thrust, also made by HAL at Koraput and at Chengdu, China, as the WP-7. Gavrilov (*qv*) developed it into the R-13.

The RU-19 is a small turbojet used as primary propulsion for RPVs, as a booster for transports and also as a combined booster and APU. Maximum thrust of the RU-19-300 is 900 kg. The R-25 is installationally interchangeable with the R-13 but is completely redesigned, uses much titanium, has a better pressure ratio of 9.55 and thus lower sfc, and thrust of 9,050 lb dry and 15,650 lb with afterburner; this Gavrilov engine powers the MiG-21bis and Su-15T.

To power the Mach-3 MiG-25 the bureau developed the R-15 all-steel single-spool turbojet with a five-stage compressor handling 318 lb/s at the modest pr of 4.75. The R-15K powered pilotless reconnaissance vehicles; the R-15-300 was qualified in 1959 at 15,080 lb dry and 22,380 lb with afterburner, for a weight of 5,710 lb; the R-15B-300 of 1962 had ratings of 16,535/22,510 lb; the R-15BD-300 of 1963 was rated at 19,400/24,700 lb; and the R-15BF2-300 was qualified at 29,760 lb, in all cases on special T-6 fuel. For Tumanskii's successors, *see* Soyuz AMNTK.



Designed by S.K. Tumanskii over 50 years ago, the RD-9BF is still very important in China as the WP-6. This Wo-Pen 6 is seen without afterburner.



A cutaway Tumanskii R-15B-300, displayed under a MiG-25R.

In 1972 the Rolls-Royce (formerly de Havilland) factory at Leavesden was busy producing the Turbomeca Turmo 3C4 for RAF Puma helicopters. Today it is just one of the 96 aircraft plants in southern England that no longer exist.

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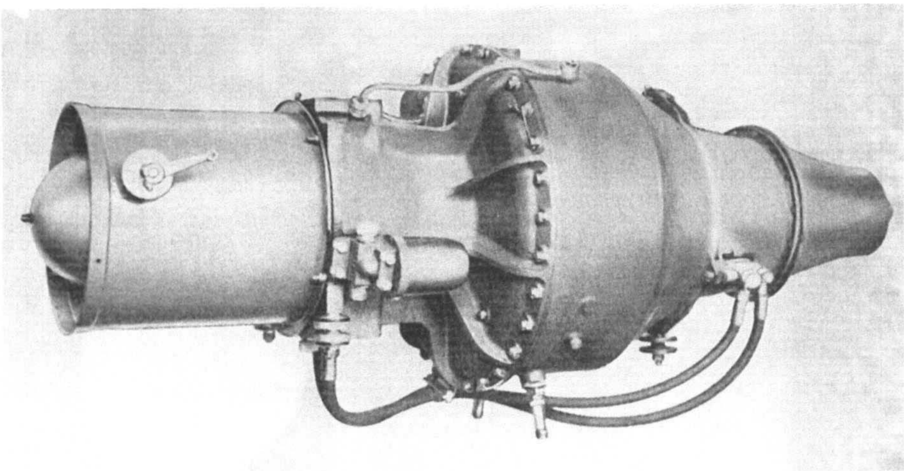
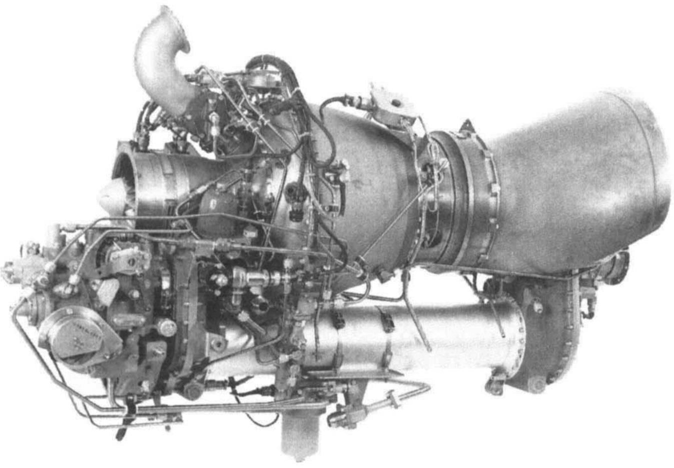
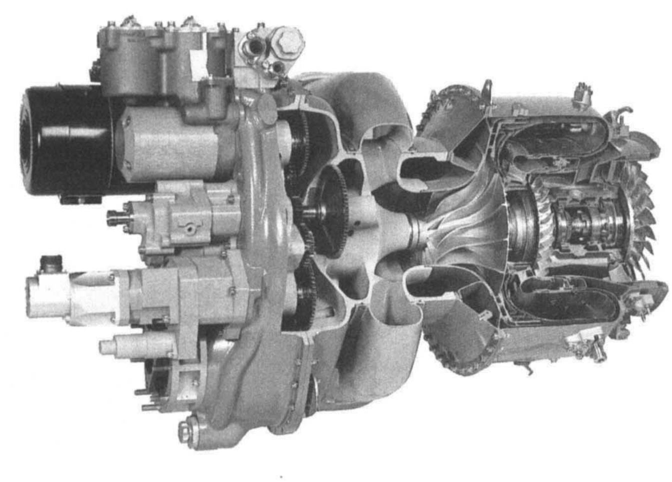


The Piméné was one of Turbomeca's first production engines, and the first small turbojet in the world to be built in quantity.



The Turbomeca Arriel 2S1 powers the Sikorsky S-76C+. Note the tube underneath enclosing the drive shaft.



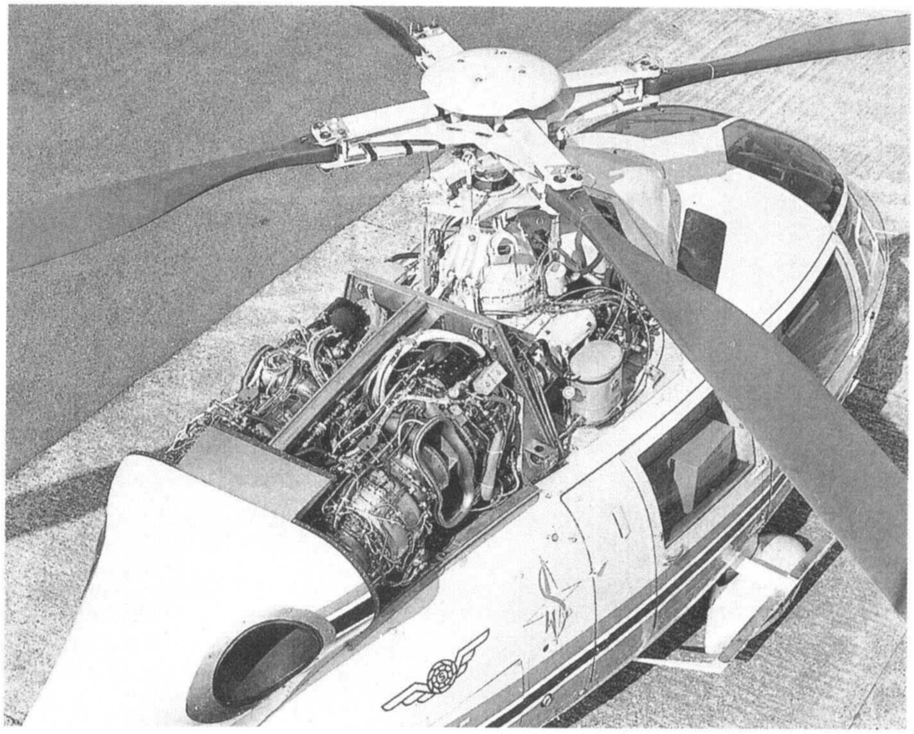
Smallest and simplest of the new-generation Turbomeca engines, the Arrius has an advanced centrifugal compressor without added axial stages. The accessories (left) are bigger and heavier than the engine itself.

Turbomeca (FRANCE) Nobody has run a major aero-engine company as long as the late Josef R. Szydlowski, who with André Planiol founded Société Turbomeca in 1938. Its business from the start involved compressors and turbines (originally HS12Y and Z turbochargers), starting in Paris (Billancourt) but moving in June 1940 to Bordes, Pyrenees. The factory was pillaged in 1944, but in 1945 work resumed on a wider front than before, and in 1947 the company designed two gas turbines, the Orédon of 140 hp and the Artouste of 220 hp. These were intended for many tasks including APUs and aircraft propulsion. In 1948 came the Piméné turbojet. These simple yet novel engines established the company as a pioneer of small gas turbines. They had a single-sided centrifugal compressor driven by a one-stage axial turbine with the blades integral with the disc, with fuel vaporised by being sprayed under centrifugal force from a perforated ring rotating with the main compressor drive shaft. This shaft was of large enough diameter to allow the rotating assembly to be supported between a ball bearing ahead of the compressor and a flexibly mounted roller bearing aft of the turbine. The turbine nozzle vanes (stators) were fabricated from welded sheet, with internal cooling by compressor delivery air. At low throttle settings the fuel delivery was mainly bypassed back to the pump.

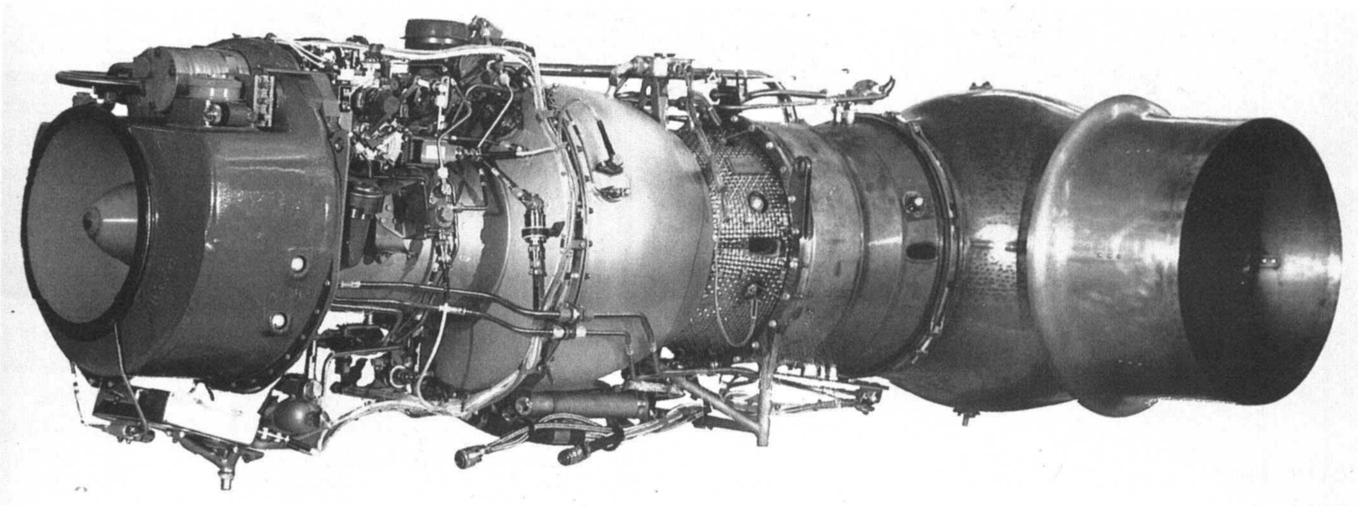
These features were repeated in almost all the 55-odd subsequent Turbomeca engine types. The only significant changes have been to add first one and subsequently one, two or three axial stages upstream of the centrifugal compressor, and use two-stage turbines with inserted firtree-root blades. The following condensed listing is roughly chronological.

The Orédon was developed to over 160 hp but did not propel aircraft. The Artouste was developed through the Artouste II (airflow 6.8 lb/s, pr 3.7) of 400 shp at 33,000 rpm to the Artouste III (added axial stage 9.7 lb/s, pr 5.5) and three-stage turbine, of 550 hp at 34,000 rpm, and thence to the IIIB flat-rated at 550 hp to 45°C. The Piméné weighed 119 lb, had airflow of 4.4 lb/s, pr 4, and gave 243 lb thrust at 36,000 rpm. The Palas was a scaled-up Piméné (airflow 6.8 lb/s, pr 4) weighing 159 lb and rated at 353 lb at 34,000 rpm. The Marboré I was a further enlargement to 661 lb thrust, flown on

Twin TM333s snugly installed in a Dauphin. This was Turbomeca's standard engine in the 1,000-hp class. Like Sikorsky, Turbomeca's logo is a winged S, standing for Szydlowski.

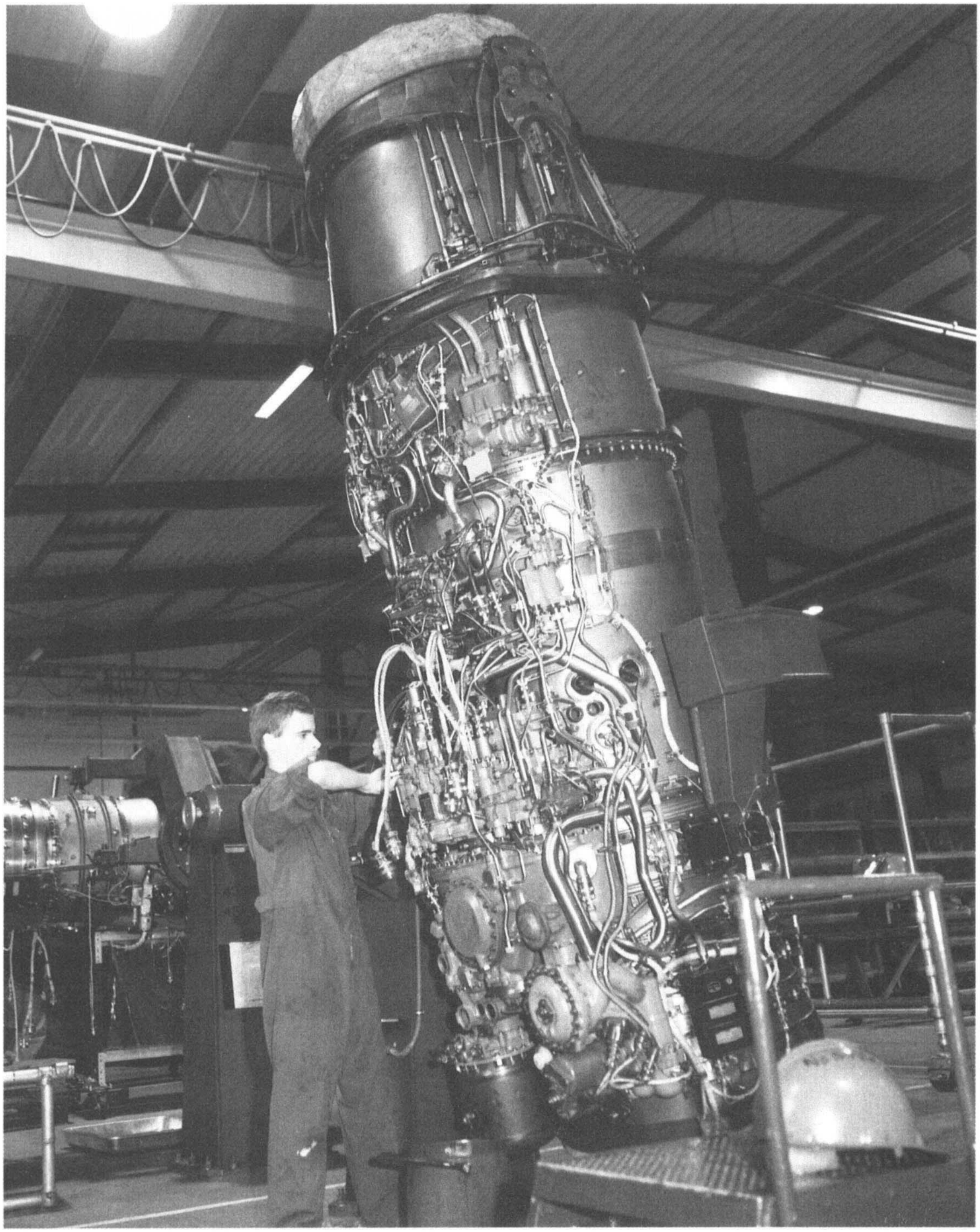


Turbomeca's standard 2,000-hp engine is the Makila, used in the Super Puma. It is a direct extension of the Turmo but with two extra axial stages.



the Gemeaux II on 16 June 1951. The same aircraft (redesignated Gemeaux III) flew on 24 August 1951 with the 838 lb Marboré II, and on 2 January 1952 with the production Marboré II (17.6 lb/s, pr 4) rated at 880 lb at 22,600 rpm. This was the biggest seller, licensed as the J69 to Continental (now Teledyne CAE) of the USA, and also to Israel, Spain, Romania and Yugoslavia. In Britain Blackburn took a licence for all Turbomeca engines, effecting considerable redesign but failing to find a market except for the Turmo. This was the first free-turbine engine, derived from the Artouste I in 1950 by adding a single-stage power turbine and gearbox. This was developed into the 400-hp Turmo II (1954) and then to many versions of Turmo III and IV with added axial compressor and two-stage core and power turbines (typically 13 lb/s, pr 5.9), weighing about 661 lb and rated up to 1,610 shp.

The Ossau was a turbojet rated at 1,763 lb thrust, with a diagonal (axial-cum-centrifugal) compressor, abandoned in 1952. The Pimédon was an air compressor (among other things, for tip-drive helicopters) derived from the Artouste, used in several versions. The Aspin I, rated at 441 lb thrust, was the first turbofan in the world to fly (Fouga Gemeaux IV, 2 January 1952); it had variable inlet vanes upstream of the single-stage fan, which was driven by a reduction gear from the compressor. The Aspin II, flown five months later, was rated at 772 lb thrust with sfc of 0.52. The Arrius I and II were air compressors larger than the Palouste, and the Autan of 1955



Highly qualified ground engineers at RAF Brüggen carry out maintenance on an RB.199 (tilted upright for easy access) from a Tornado GR.1A. Note the reverser buckets at the top.

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was a Palouste with an added axial stage giving 5.1 pr. The Soulor of 1954 never flew; it was a turbofan of 705 lb thrust. The Gourdon turbojet of 1955 weighed 379 lb and had thrust of 1,455 lb. The Marcadau turboprop of 400 hp was an Artouste II with 2.332 spur gear. The Gabizo turbojet of 1955 was a sharp upward jump in size, with an added axial stage (pr 5.2, airflow 48.5 lb/s) to give 2,425 lb thrust at 18,000 rpm or 3,395 lb with Nord afterburner. The Arbizon turbojet of 1956 had an axial-plus-centrifugal compressor and gave 551 lb thrust at 34,000 rpm. In 1970 the Arbizon IIIB appeared for the Otomat cruise missile, rated at 838 lb at 33,000 rpm, the simpler Arbizon IV weighing 132 lb for 809 lb thrust.

The Bastan of 1957 was the first axial/centrifugal turboprop, weighing 397 lb and initially giving 650 shp and being developed by 1965 to the 1,048-shp Bastan VII. The smaller Astazou of 1957, like the Bastan a constant-rpm engine with power varied by fuel flow, weighed 242 lb and gave

320 shp at 40,000 rpm. It became the company's best-selling turboprop, many versions with two axial stages giving powers in the l,000-hp class, and the Astazou XX (one of many turboshaft versions) having a third axial stage. The Turmastazou, also produced in Double form at 1,775 shp, was an Astazou XIV with an added free turbine. The Astafan of 1969 was an Astazou XIV with two-stage epicyclic reduction drive to a variable-pitch fan of 6.5 bypass ratio; weighing 507 lb, it gave 1,570 lb thrust with sfc of only 0.38. The Aubisque of 1961 was a turbofan larger than other Turbomeca engines except the Gabizo, weighing 639 lb and with a geared fan, its rating being 1,636 lb at 33,000 rpm. The Aubisque 6, not made in quantity was one of the first Turbomeca engines to have an air-cooled turbine (the other was the Astazou XVI); thrust rose to 1,852 lb. The name Orédon was resurrected in 1965 in Mk III form at 350 shp for helicopters, with Rolls-Royce reduction gear; the Orédon IV gave 420 shp at 59,100 rpm.

First run in 1974, the Arriel is one of the leading current turboshaft engines, with one axial and one centrifugal compressor made in titanium, strong enough for very high rpm giving a pr of 9. Weighing 240 lb, the Arriel 1 has a contingency rating of 698 shp and was developed in turboprop and turbofan versions. Its bigger partner is the Makila, first run in 1977; it has three axial plus one centrifugal, two-stage air cooled gas-generator turbine and two-stage power turbine, weighs 463 lb and gives 1,875 shp. First run in 1981, the TM333 is a free-turbine engine giving 912 shp, weighing 345 lb with two axial plus one centrifugal and one-stage gas-generator and power turbines. Launched in 1983 as the TM319, the Arrius is in production in turboshaft and turboprop forms. As it is a low-power engine it has no axial stages ahead of the centrifugal compressor. The Arrius 1 weighs 192 lb and has a contingency rating of 547 shp; the Arrius 2 will be rated at 634 hp for the McDD Explorer; the Arrius 1D turboprop weighs 245 lb and is rated at 420 shp.

In 2001 Turbomeca announced the Ardiden 'which completes our range of engines'. Rated at 1,600–1,800 shp, it breaks new ground in (like the Dart) having tandem centrifugal compressors, with no axial stage. One version, named *Shakti*, is being developed in partnership with Hindustan Aeronautics to power Indian helicopters. Other links have been forged with Russian companies, and TEC (Turbomeca Engines Corporation) in Texas makes 200 Arriels per year.

By 2006 Turbomeca had become part of Snecma, and thus a subsidiary of Safran. It had delivered 53,000 engines, some 33,000 of them for aircraft propulsion, delivered to customers in 125 countries. A further 14,000 engines have been made under licence in China, India, Israel, Romania, Spain, the UK, the USA and Yugoslavia.

Turbomeca collaborative engines The Adour and RTM.322 are described under RRTI (*qv*). The Larzac is described under SNECMA (*qv*) but is marketed by GRTS (Groupement Turbomeca-SNECMA). The TM251 turboshaft for the Agusta A106 was jointly developed with Agusta, who designated the 354-shp engine TAA.230. The MTR390 is described under MTR.

Turbo-Union (INTERNATIONAL) Turbo-Union Limited was formed in October 1969 to manage the programme for the RB.199 engine. Shares are held in the ratio Fiat (now Avio) 20 per cent, MTU 40 per cent and Rolls-Royce 40 per cent. The RB.199 is a three-shaft augmented turbofan of unprecedented compactness and light weight; overall length is typically only 127 in (3.23 m) including high-ratio afterburner and integral reverser. All versions have a three-stage LP (fan), three-stage IP, six-stage HP (airflow 155 lb/s, overall pr over 23), annular vaporising combustor, one-stage air-cooled HP and IP turbines and two-stage LP. Typical weight is 1,980 lb (with reverser, 2,390 lb) and ratings are: Mk101, 8,090 lb dry, 15,950 lb with afterburner; Mk 103 (standard Tornado IDS engine) 9,100 lb dry, 16,000 with afterburner; Mk 104 (Tornado F.3) 9,100/16,400 lb; Mk 105 (Tornado ECR) 9,656/16,800 lb. A total of 2,504 engines were produced.

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UMPO (BASHKORTOSTAN) Now named *Rossiya* (Russia), Ufa engine industrial association was established in 1925, and claims to be the largest aero-engine factory in the former USSR. Recent work includes production of different AL-31 versions, as well as the R-13, R-25, R-29B, R-35, R-95Sh and R-195. It is more slowly making the D-436 and AL-41, as well as main-rotor gearboxes for the Mi-26 and Ka helicopters.

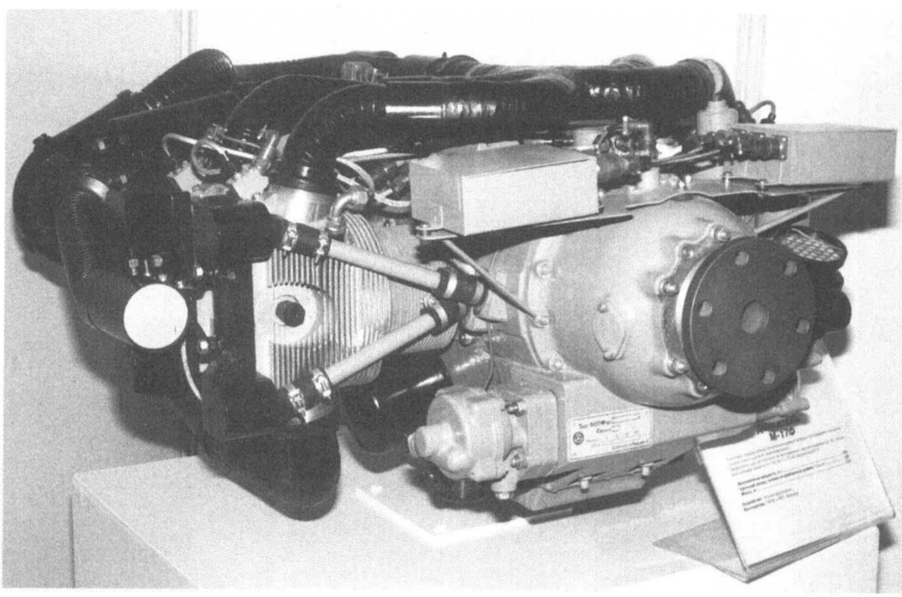
V

VM (ITALY) VM Motori produces a range of high-speed diesels, all with opposed air-cooled cylinders of 130 mm bore × 110 mm stroke. The TPJ 1304 has four cylinders, weighs 408 lb and is rated at 206 hp; the TPJ 1306 has six cylinders, weighs 536 lb and gives 315 hp; the TPJ 1308 has eight cylinders, weighs 657 lb and is rated at 424 hp.

VOKBM (RUSSIA) Founded by Ivan M. Vedeneyev in 1960, the Voronezh Bureau has been responsible for further development of the M-14 radial engine originally designed by Ivchyenko (*qv*). Current versions are the M-14PF, fully aerobatic, rated at 394 hp; the PM direct-drive pusher, rated at 311 hp; the PM-1 geared pusher, rated at 355 hp; the PT geared pusher, rated at 355 hp; and the NTK, standard in the latest aerobatic aircraft, with improved cooling, direct injection and designed for a turbo, rated at 424 hp for a weight of 474 lb. General Designer of VOKBM is Prof A.G. Bakanov, who has produced a range of light piston engines.

The M-16 has X-8 configuration, to give 296 hp; the M-17 is a flat-four of 173 or 200 hp; the M-18 is a flat-twin two-stroke of 39 or 54 hp; and the M-19 is a flat-four two-stroke of 80 hp.

Volvo Flygmotor (SWEDEN) Flygmotor was founded in 1930 to make the Bristol Pegasus. Subsequently it made the Twin Wasp R-1830 and DB 605, produced its own 145 hp flat-four (F-451-A) with bore 125 mm and stroke 105 mm (5.1 litres), and got into gas turbines by producing the DH Goblin and Ghost. Versions of the RR Avon followed with SFA (Svenska Flygmotor AB) afterburner, as the RM5 and RM6, followed by the RM8, a largely SFA-developed supersonic fighter engine whose basis was the P&W JT8D. Several hundred RM8As have a two-stage fan, four-stage LP and seven-stage HP (145 kg/s, pr 16.5), giving dry/afterburning thrusts of 6,690/11,790 kg for a weight of 2,100 kg (the reverser on the Viggen is part of the aircraft).



The most powerful production engine in Prof Bakanov's new range is the VOKBM M-17F, rated at 200 hp and weighing 287 lb.

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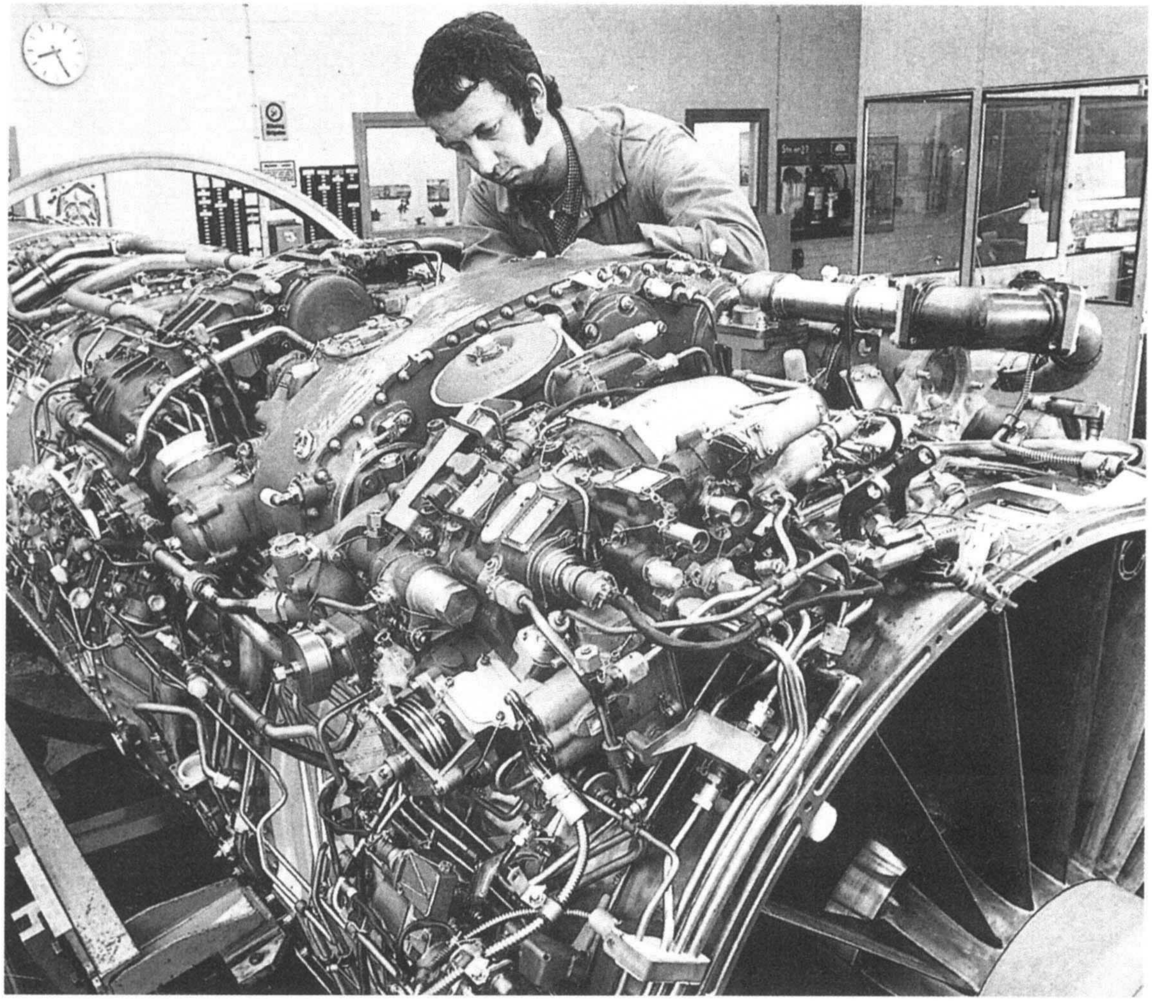
These were followed by the RM8B for the JA37 fighter with three-fan and three-LP design, revised combustor and new HP turbine, weighing 2,250 kg and with dry/augmented ratings of 7,350/12,750 kg. Volvo took over SFA in 1970, a major current task being a 40 per cent share in the RM12, a Swedish version of the GE F404 rated in the Gripen at 18,100 lb.

In 1978, Volvo Flygmotor had one product, the RM8, and one customer, the Swedish Air Force. Today it has a major share in the BR715, CF6, GE90, GEnx, CFM56, GP7000, JT8D, PW2000, PW4000, Tay, Trent and V2500. The company also has many other products including combustion chambers for the Ariane 4 space launcher and the supersonic pump turbines and engine nozzles for the next-generation Vulcain for Ariane 5.



Checking final details on a Volvo Flygmotor RM8A (rotated upside-down) before despatch from Trollhätten. One is reminded of what Lord Hives said when Whittle told him how simple jet engines were: 'Don't worry, we'll soon design the simplicity out of it!'

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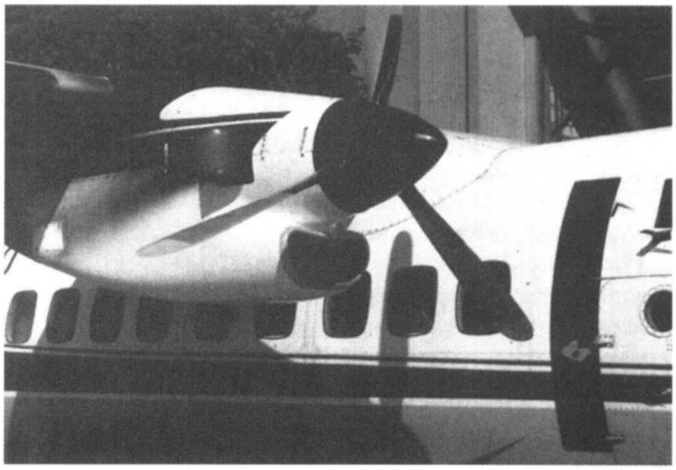
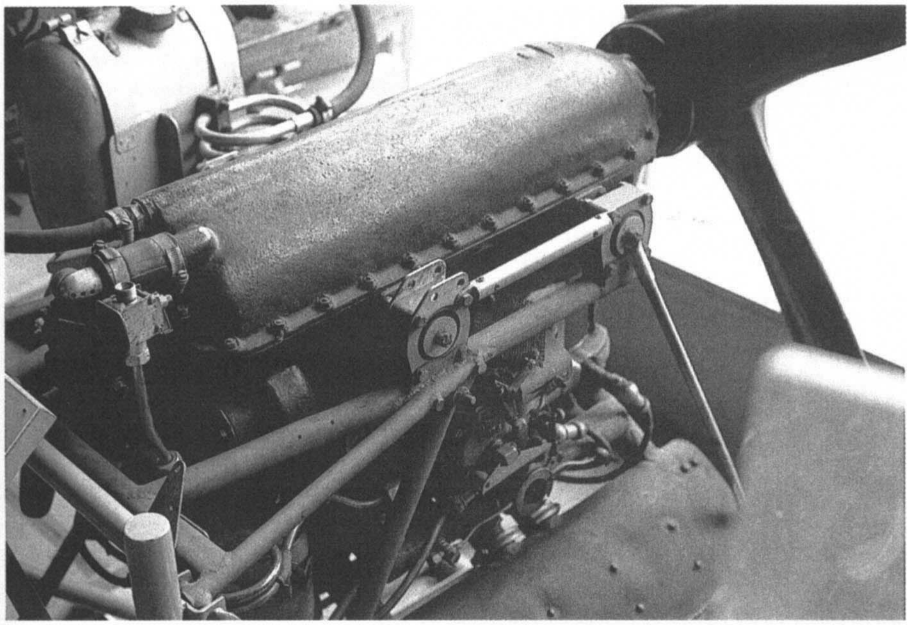
Walter (CZECHOSLOVAKIA) A.S. Walter of Prague-Jinonice, was established in 1920 soon after the country gained independence. Its first engines were water-cooled four- and six-in-lines, the W.IV being made in some hundreds at 220–240 hp or 300 hp in racing (high-compression) trim. From 1922 Walter made 17 distinct types of small radial, most with cylinders 105 × 120 mm, with three, five, seven or nine cylinders and initially with both valves parallel to the cylinder axis; from 1925 these had enclosed valve gear, a feature absent from the Jupiter which the firm made under licence. From 1929 Walter added air-cooled in-line engines, the most famous being the Minor and Mikron. These were inverted engines with steel cylinders, aluminium heads and pushrods to overhead valves; the Minor came with four or six cylinders of 105 × 115 mm, typical ratings being 105 and 160 hp, and the Mikron had gour cylinders 90 × 106 mm giving 65 hp. There were eight- and 12-cylinder versions, top of the range being the Sagitta inverted V-12 of 1937 with 118 × 140 mm cylinders (18.4 litres), weighing 360 kg in direct-drive supercharged form and rated at 500 hp at 2,400 rpm. Today's Avia inverted in-line engines (Minor 6-III, M 137 and M 337) are basically the pre-war Walter designs, and in 1984 the Mikron went back into production at the Aerotechnik works.

In 1956 design began on a turbojet to power military trainers. The resulting M701 externally resembles a jet version of the RR Dart, because it has a centrifugal compressor and seven combustion chambers mounted diag-onally. Rated at 1,962 lb thrust, this engine powers the L29 Delfin. Deliveries began in 1961 and eventually totalled more than 9,200.

In 1961 the Motorlet organisation started development of a small turboprop, and the resulting M601 – marketed as the Walter M601 – first ran in 1967. Development passed through various stages, but today the 691-hp M601B is in widespread service in the L-410 transport, the 724-hp M601D and 751-hp M601E are in production, and the M601Z powers the Z 37T agricultural aircraft, rated at 483 hp for propulsion and also driving a blower or pump for dusting or spraying. All versions have a rear air inlet, two axial plus one centrifugal compressors, annular combustor, single-stage compressor and power (output) turbines, as well as front jetpipes and reduction gear. A typical M601 weighs 440 lb. In late 2006 the M601 was still in production with deliveries having exceeded 4,450.



The famous Walter name has been perpetuated in today's Czech Republic in such engines as the Motorlet M601 turboprop in the 750-hp class, fitted to the mass-produced L-410UVP-E transport. Here it drives a V-508D propeller, but later examples drive the five-blade V-510.



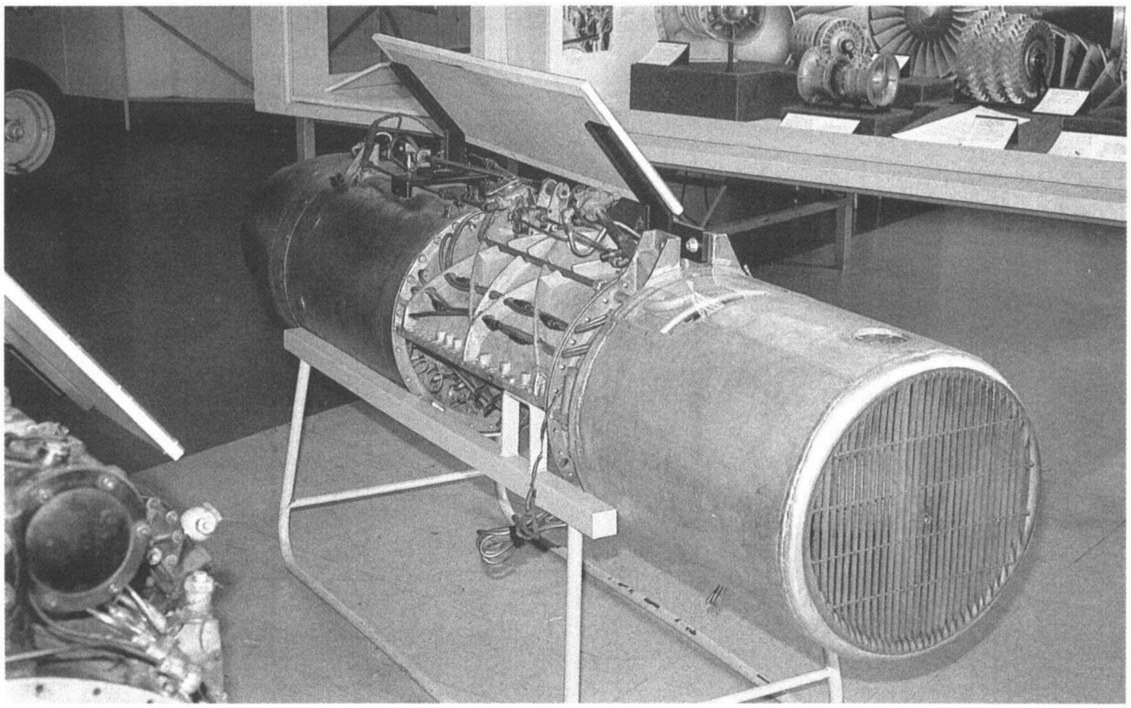
This Walter Mikron is typical of the Walters in having all the induction and exhaust piping on the right. A very similar engine is now back in production.

Motorlet has also been developing the Walter M602, to power the bigger L-610. This is extremely like the P&W Canada PW100, and is rated at 1,824 shp for a weight of 1,279 lb. Even though 34 M602 engines have been made, the L-610M was abandoned in 1996 and the production aircraft is the L-610G powered by the imported General Electric CT7-9D. Walter also produces the M202, a modern flat-twin two-stroke of 676 cc rated at 65 hp.

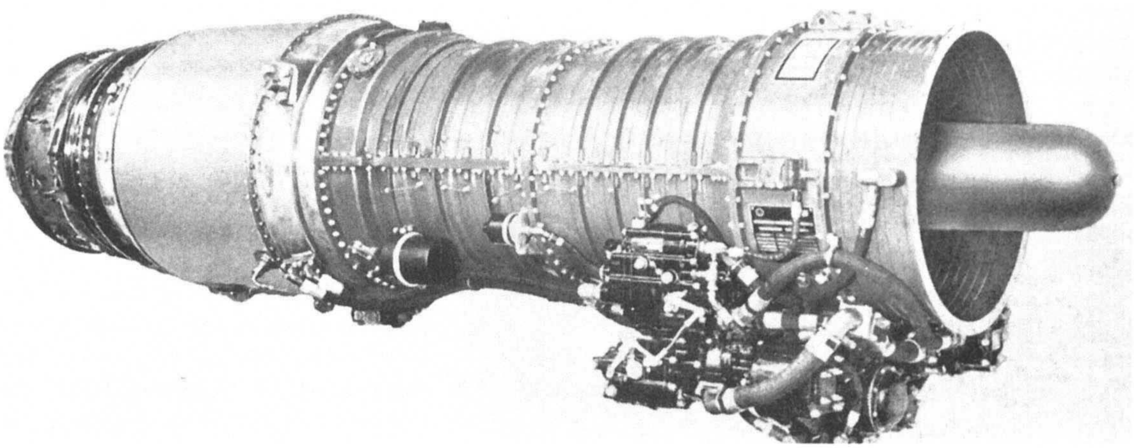
Walter (GERMANY) Professor Hellmuth Walter, a research chemist in Kiel, experimented with torpedoes driven by concentrated hydrogen peroxide. In 1935 he began designing a rocket engine for aircraft, founded the Hellmuth Walter Kommandit-gesellschaft (HWK) and received an RLM (Air Ministry) contract for a 40 kg thrust unit – in modern parlance, a 'bonker' – to be fitted to one wingtip of an aeroplane for roll dynamics research. This led in late 1936 to a unit of 100 kg thrust which boosted an He 72. Next came a profusion of assisted take-off rockets, and a contract for the RI-203 engine of 400 kg thrust, running on the spontaneous reaction of T-*stoff* (80 per cent peroxide plus a stabiliser) and Z-stoff (strong calcium permanganate solution). This powered the He 176 and DFS 194. This was developed into the RII-203 of 750 kg thrust, which powered the Me 163A. In turn this led to the still very dangerous R-II-211, with *Z-stoff* replaced by *C-stoff* (30 per cent solution of hydrazine hydrate in methanol). The highly reactive propellants were kept scrupulously separate until, fed by two turbopumps, they met in the reaction chamber. Weight was about 165 kg, and thrust 1,500 kg at sea level rising to 1,700 kg at high altitude. This entered production as the HWK-509A-2 for the Me 163B. Flight endurance was severely restricted by the propellant consumption of 8 kg/s, so the HWK 509C was developed with a cruise chamber of 300 kg and a main chamber of 1,700 kg. This powered the Ju 248 (Me 263) and Ba 349.

Warner (USA) Aeronautical Industries Incorporated was formed in Detroit in 1927, changing its name in the same year to Warner Aircraft. Its product, the Scarab seven-cylinder radial, ran in November 1927 and practically swept the board at the 1928 US Nationals. A conventional design, it had cylinders 4.25 in square with enclosed valve gear driven by pushrods behind the cylinders, making for a clean appearance. In 1930 the 90-hp five-cylinder Scarab Junior was added, followed in 1933 by the Super Scarab seven-cylinder which was made in two sizes, the R-500 (bore enlarged to 4.625, 499 cu in) and R-550 (4.875 in, 555 cu in), with respective take-off powers of 175 and 200 hp. ATA ferry pilots will remember the smoothness of these engines in the Argus (UC-61), but Warner was not included in the massive wartime production. In 1950 the assets were sold to Clinton Machine Corporation.

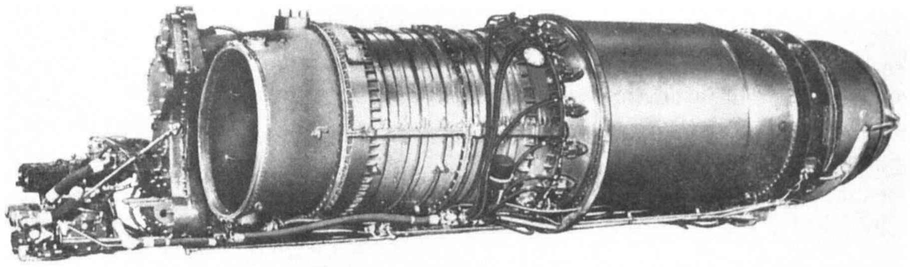
Westinghouse (USA) Westinghouse Electric Corporation, one of the world's biggest manufacturers of steam turbines, was one of the three turbine companies invited to be represented on the Durand Special Committee on Jet Propulsion. By sheer chance Westinghouse decided to recommend a turbojet (Allis Chalmers a turbofan and GE a turboprop). In July 1941 the company received go-ahead on its design, a Navy contract following on 8 December 1941 for the 19A (19 in diameter), an axial engine envisaged as a take-off booster. Under R.P. Kroon the team at South Philadelphia completed the design in 10 months, and



The Westinghouse J30, a turbojet of 19 in diameter, was contracted for on the day following Pearl Harbor. It was the first American-designed turbojet to run.



The one big success Westinghouse had with turbojets was the J34. This basically simple engine had a nominal (compressor) diameter of 24 in; the J34-WE-34 illustrated was a 3,250-lb engine that powered F2H Banshees.



In contrast, the big Westinghouse J40 caused the greatest upheaval in major aircraft programmes ever resulting from the failure of any engine. This J40-WE-6 was a 7,500-lb engine with no afterburner but still needed a twin-eyelid nozzle. Note the accessories grouped in the V between the aircraft inlet ducts.

had the X19A running on 19 March 1943. This was only the second type of axial turbojet to run outside Germany, and the first American-designed gas turbine to run. It set the pattern in being a simple and robust unit with six-stage compressor, annular combustor and single-stage turbine. It gave 1,200 lb thrust, and the No. 2 prototype was flown as a booster under an FG-1 Corsair in January 1944. By this time designs had been prepared for derived engines to give three sizes, the 9.5 in (diameter), 19 and 24 in. The 9.5A and B were for missiles and aeroplanes, respectively, receiving Navy designation J32. The 19XB for piloted aircraft became the J30, and this had a 10-stage compressor and was rated at 1,600 lb. It was tested under a Marauder and powered the FD-1 (later FH-1), 130 of the 261 production engines being made by Pratt & Whitney.

On 1 February 1945 Westinghouse established a separate Aviation Gas Turbine Division. So far this new field had proved a happy experience, and the 24C engine, the largest of the original family of designs, soon found a large and growing market as the J34. This had an 11-stage compressor (originally 50 lb/s, pr 3.65, and in later versions 55 lb/s at 4.35), a combustor of double concentric annular form with 24 downstream burners round the inner flame tube and 36 around the outer, and a two-stage turbine. Weight was typically 1,220 lb and thrust rose from 3,000 to 3,500 lb at 12,500 rpm. The J34 was conservatively designed and had a long career, a few surviving into the 1980s in P-2 and C-119 booster pods.

Westinghouse maintained a brisk pace of development and in spring 1947 embarked on two new engines, with US Navy BuAer support. These were the J40 (Model 40E, 40 in diameter) and J46, and it was expected that between them they would power almost all Navy fighter and attack aircraft of the 1950s. Because of its great importance the big J40 was timed earlier than the J46, and a prototype XJ40 ran on 28 October 1948. It had a 10-stage compressor, double concentric annular combustor with so-called 'step wall' construction with 16 duplex burners, and two-stage turbine. In the XA3D bomber the J40 was installed in pods with plain front inlets, with accessories around the underside, but in other applications (XF4D, XF10F, XF3H) all accessories were grouped between the bifurcated inlet ducts ahead of the engine, driven from a pressurised nose gearbox. An early J40 passed its 150-h qualifications test in January 1951, but by this time the J40 had revealed problems of many kinds – aerodynamic, combustion, structural and in detailed mechanical design – which prevented attainment of the design ratings and resulted in extreme unreliability. Development and pre-production engines weighed about 3,100 lb, or 3,620 lb with afterburner, and were planned to run at 7,600 rpm to give a minimum of 7,500 lb dry and 10,500 with afterburner. The best that could be obtained by summer 1952 was 6,000 lb. Douglas managed to switch to the J57 to power the A3D, and later did the same with the F4D. The XF10F finally ground to a halt, leaving the F3H Demon in terrible trouble. This fighter had its fuselage redesigned to accept the more powerful J40-10, but the only engines available were the Dash-8 (unreliable) and the Dash-22 with a constant-speed alternator drive but putting out only 7,200 lb. Flight development was punctuated by accidents and groundings, and the sorry saga finally ended with the last J40 flight on 7 July 1955. Subsequent Demons had the Allison J71 engine.

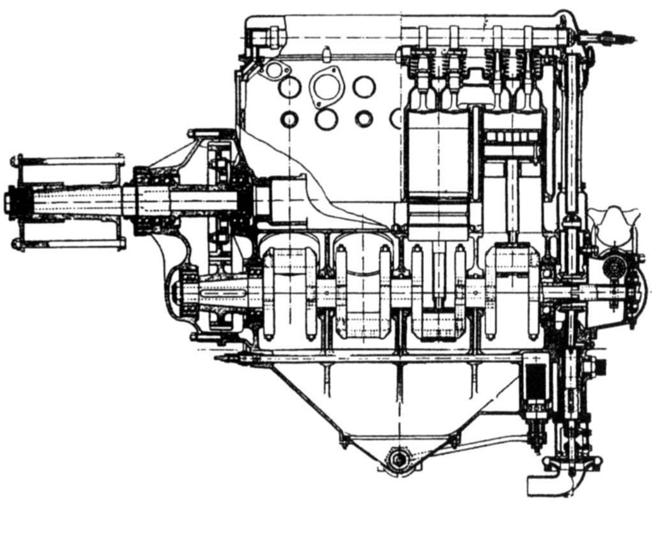
By 1955 Westinghouse AGT Division was raring to go in its great new facility vacated after the war by Pratt & Whitney at Kansas City. Having been made brutally aware of the difficulties of developing gas turbines, the division had on 15 June 1953 signed a 10-year technical collaboration agreement with Rolls-Royce. Had it simply taken licences, big sales might soon have resulted. Instead by 1955 it was announced that Westinghouse was working on the XJ54 and XJ81 turbojets, respectively in the medium and small thrust classes. The XJ81 was basically the Soar, intended for RPVs and missiles. Rolls were confident that the later Avons could find a large market via Westinghouse, but were horrified to learn that the XJ54 was an Avon scaled down to only 105 lb/s airflow, resulting in an engine weighing 1,500 lb and giving a thrust of 6,200 lb, with low fuel consumption. This was far better than the J46, the only engine of its own design that Westinghouse had left. It was a J34 scaled up to 75 lb/s, with an 11-stage compressor giving pr of 5.2. With afterburner it weighed 2,090 lb, and was rated at up to 6,000 lb. Only a handful were delivered for the F7U-3 and YF2Y, and the XJ54 was never sold at all.

Williams (USA) Sam Williams is the US answer to Szydlowski, though unlike Turbomeca almost all his output has gone into RPVs, targets, reconnaissance drones and cruise missiles. The WR19 two-shaft turbofan, which weighs 141 lb and gives 718 lb (wet rating), was used in Flying Belt, SAVER and WASP manned applications. In 1989 Rolls-Royce joined Williams on the FJ44 programme. This neat baby turbofan has an axial+centrifugal compressor, a bypass ratio of 3.28, and a full-length fan duct. The basic engine weighs 447 lb and has a rating of 1,900 lb. It is well timed, and already has been selected for eleven types of aircraft, one of them the unmanned Dark Star stratospheric spyplane. An important order was for 231 FJ44-1C engines to replace the Aubisque in 105 SK60 trainers of the Royal Swedish AF. Several other FJ44-powered aircraft are entering production.

Since 1995 Williams has produced turbofan engines of both greater and lesser thrust. The growth engine is the FJ44-2A, rated at 2,300 lb and already selected for the AASI Stratocruzer 1250-ER, Contender 303 and 606, Raytheon Premier 1 and Sino Swearingen SJ30-2. The best-selling FJ44 has now been developed in FJ44-3 and -4 versions, rated at up to 3,500 lb thrust. In 1995 Williams announced the FJX, rated at 700 lb thrust, whose main application (the Eclipse 500) switched to a more powerful engine. Better success has attended the FJ33, rated at 1,000 to 1,500 lb, which has attracted an avalanche of ultralight jet makers.

Wolseley (UNITED KINGDOM) In 1909 Wolseley Motors at Adderley Park, Birmingham, began building water-cooled aero engines, starting with a four-in-line with 4 × 5 in cylinders, weighing 242 lb and giving 30–36 hp at 1,440 rpm. Almost all subsequent versions were 90° V-8s, with cylinders cast in pairs with screwed-on aluminium jackets, left and right cylinders being staggered to allow two big ends on each crankpin. The 1909 engine had 3.75 × 5 in cylinders, weighed 350 lb and gave 50 hp at 1,350 rpm. In 1910 metric dimensions resulted in 94 × 138 mm cylinders, 326 lb and 90 hp at 1,750 rpm, followed by a 126 × 176 mm engine weighing 635 lb but giving 150 hp at 1,150–1,400 rpm. During the war the firm made the W.4 Viper family of engines derived from the Hispano, adding the 1918 Python to its own design. The market was abandoned until in 1933 a family of simple air-cooled radials was offered, and with sales and service backing by the Nuffield car organisation. The A.R.7 and A.R.9 had respectively seven and nine cylinders 4.1875 × 4.75 in, giving 130–145 and 165–180 (later over 200) hp. Few were built.

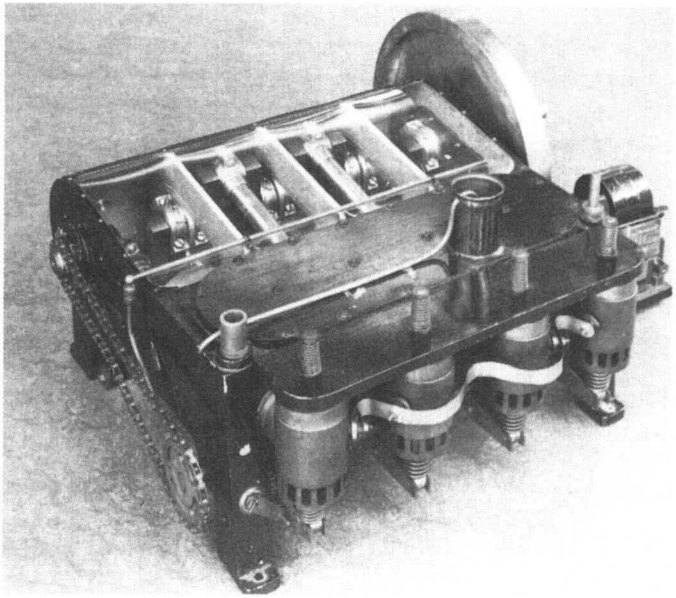
Wright (USA) Wilbur and Orville Wright were the first aviators to fly an engine. Their contribution to human flight was, however, mainly in solving the problems of how to build a controllable aeroplane and then learn to fly it. They carried out virtually all the serious research on propellers prior to 1905, and incidentally decided to propel all their early Flyers with two screws turning slowly in opposite directions by bicycle-chain geared drives. They did not want the bother of having to make their own engine, but got such a useless response from established builders that they were forced to do the job themselves. Unfailingly painstaking and methodical, they began by making a 'skeleton engine' with one cylinder, driven off a belt in their bicycle shop in Dayton. After carefully studying its behaviour they decided to go ahead with a complete engine in November 1902.



The Wolseley W.4b Adder, a 200-hp water-cooled V-8, was basically a Viper with a reduction gear. It replaced the Viper in some SE5as.

There is an amazing amount of inaccurate reportage on everything the brothers did. It has been claimed their first engine came from a Pope-Toledo car, that it was all-aluminium, that it had direct fuel injection, that fuel 'was allowed to drip into the intake ports', and that the pilot could speed up or slow down the engine by turning the fuel valve one way or the other, and much, much more. In fact the original engine, in the words of chief mechanic Charlie Taylor, who made almost all of it, 'had no carburettor, no spark plugs, not much of anything . . . but it worked'. It was a four-in-line lying on its side. The main body was cast in aluminium; the first casting fractured on an early run in February 1903 when the bearings seized. The steel cylinders were 4 × 4 in (201 cu in), and each screwed-on head had a vertical drum-like section containing a lightly sprung automatic inlet valve above and a strongly sprung exhaust valve below. The latter valves simply let the hot gas escape through surrounding apertures, and were opened by rockers from the chain-driven camshaft which was also geared to the petrol pump. Water jackets surrounded the cylinders, but not the heads, and as there was no forced flow the engine got steadily hotter, losing power. The top of the jacket area was cast in the form of a shallow tray, with a screwed cover, into which was slowly pumped the regular automobile petrol. This chamber was heated before the start, and subsequently got ever hotter, so that it was petrol vapour that mixed with the air induced through a kind of chimney above the cover. The crankshaft was machined from a single slab of steel and ran in five white-metal bearings. One end drove the camshaft sprocket and the other the flywheel and two propeller chain sprockets. The flywheel rim provided a friction drive to the low tension generator feeding simple make-and-break contacts inside the cylinder heads. Weight was almost exactly 152 lb, about 30 lb less than the brothers' target; with all accessories including radiator and piping (but not water) the weight was 174 lb. Power was hoped to be 8 hp, but on its first run on a brake, in February 1903, the engine gave an unexpected 13 hp. Later, at Kitty Hawk, it was tuned to give about 13 hp at a little over 1,000 rpm, but after about a minute or so output always fell to around 12 hp.

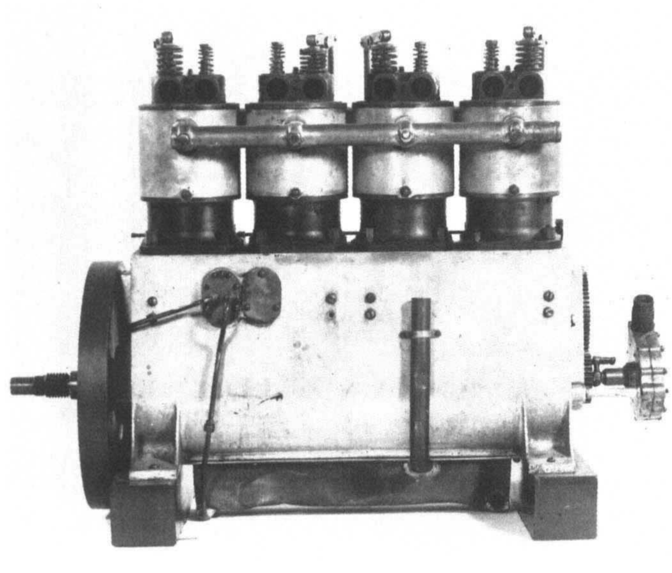
For 1904 the brothers designed two four-in-lines and a V-8, building both the four-cylinder engines. These had much better water cooling and many other improvements. The installed engine could put out full power for as long as the petrol lasted; indeed it grew more powerful with age: about 15 hp in 1904, 16.64 measured hp in January 1905 and over 20 hp by the end of the busy 1905 flying season. Gradually the brothers refined their engines, arranging the cylinders vertical fashion and adding six-in-line and V-8 patterns. Cylinder sizes varied, but did not depart far from the 4 in square of the original. Typical 1910 engines were rated at 30 hp (four-cylinder), weighing 170 lb, and 60 hp (V-8). High-tension magneto ignition was fitted, but direct fuel injection was more common than a carburettor, and inlet valves remained automatic. For various reasons the brothers (Orville alone after Wilbur's death from typhoid in 1912) failed to keep abreast of aeroplane and engine technology, and their last engine was made in 1915.



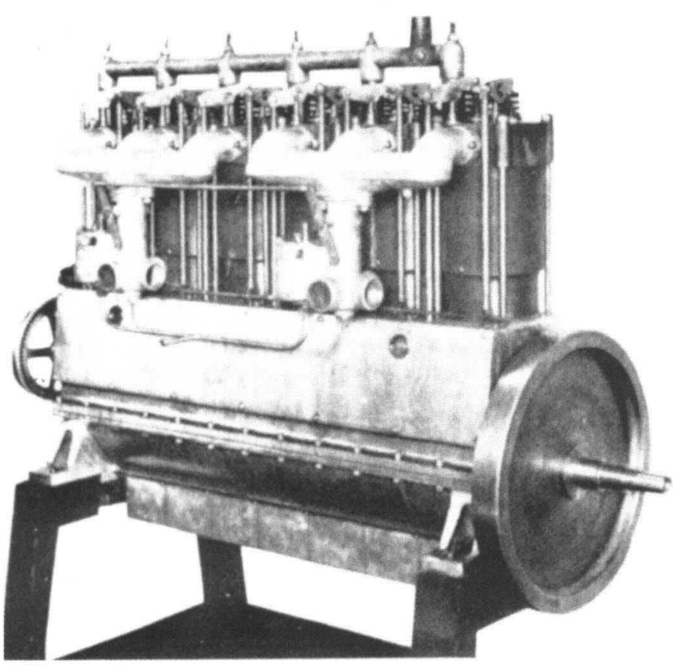
The 1903 Wright engine, with crankcase covered in transparent plastic. Left, the chain driving the camshaft and make/break contacts. Right, flywheel and DC generator. In front, the advance/retard controller, four vertical 'valve barrels' linked by the DC feed strap. On top, brass petrol pipe to the air inlet chimney brazed into the cover plate of the hot evaporative chamber.

In 1916 the Wright-Martin Aircraft Corporation linked two major US aviation firms to make Hispano-Suiza engines under licence. Large numbers were made of the Wright-Hispano E, a 180-hp V-8 of 718 cu in incorporating improved conrods and detail changes to the cylinder heads and valves. Small numbers were made of the H, of 1,127 cu in giving 300–325 hp. Almost all of the Wright-Martins were direct drive. In 1919 Wright-Martin was dispersed, most going to Mack Trucks, but thanks to F.B. Rentschler, a wartime officer concerned with engine production, substantial assets were used in October 1919 to form a new engine company, Wright Aeronautical Corporation, Rentschler becoming president. Wright continued improving the Hispano, the last model being the E-4 Tempest, rated at 200 hp and weighing 480 lb. It also designed two completely new engines. One was the T (Tornado), a large water-cooled V-12 of 1,947 cu in weighing 1,000 lb and intended to replace the Liberty in all heavy US Navy aircraft. Placed under contract in 1921, it began life at 500 hp, went into production in 1922 as the 525-hp T-2, reached 575 hp as the T-3 in 1923, and terminated in the 675-hp T-4 of December 1923. Wright tried to reach 700 hp, and also to produce a racing version to beat the smaller Curtiss D-12, but it was a dead end.

The other new engine was the R-1 nine-cylinder air-cooled radial of 1,454 cu in started in 1920 for the Army. This



In 1906 Orville Wright designed the engine which formed the basis of the brothers' flying until 1911. To reduce lateral shift of aircraft centre of gravity with and without a passenger the cylinders were vertical. This was the first engine sold to the US Navy for the B-1 seaplane of 1912. Note water pump on the right. The only 'production line' of such engines was by Bariquand et Marré in France, with cylinders 112 × 111 mm, rating 30 hp at 1,300 rpm..

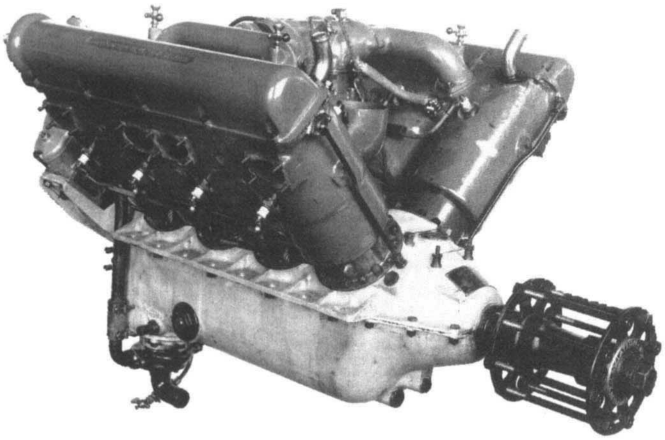


Typical of the last of the original Wright engines was the 6-60 (six cylinders, 60 hp) of 1913. With stroke lengthened to 4.5 in, this was a total redesign, with long studs holding down water-cooled cast-iron heads and twin carbs feeding on the side opposite to the exhausts. These simple engines were eventually developed to give about 80 hp, weight being about 280 lb.

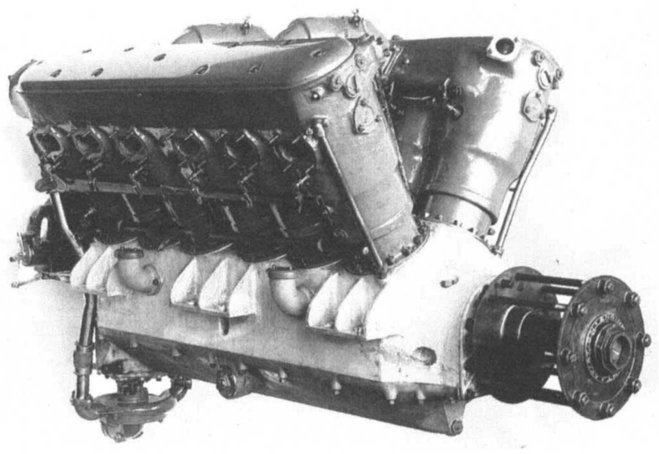
achieved its design power of 350 hp when run in 1921, but at 884 lb was heavy, and suffered from having poultice heads which had four valves and were copied from the Cosmos Jupiter. A famed expatriate Briton, Sam Heron, showed how to make better air-cooled cylinders, and when these were fitted the R-1 became the R-2, later the R1454, but the Navy handed this to Curtiss in 1923 as lowest-priced bidder. Wright had other problems: the Army settled on the Curtiss D-12, and the Navy announced it would buy no more Wright-Hispanos, and so under intense Navy pressure Rentschler agreed to take over Lawrance in May 1923, at once continuing development of the Lawrance J-1. The J-3 was strengthened and in 1924 the J-4 introduced an improved cylinder in which the hold-down flange was not on the cast aluminium barrel but on the steel liner. At this point the engine was named Whirlwind, and it quickly became the firm's main (almost only) product, still at 787 cu in and giving 215 hp. In winter 1924/25 Wright lost its president, chief engineer and chief designer (see Pratt & Whitney). The depleted team struggled on to improve cooling and fuel economy in the J-4B Whirlwind until, in 1926, E.T. Jones and Sam Heron joined and redesigned the cylinders and among other things fitted salt-cooled exhaust valves. The result was the J-5 Whirlwind, which achieved sudden fame when it took Lindbergh to Paris in May 1927.

In mid-1923 the Navy had awarded Wright contracts for two new air-cooled radials. It was increasingly convinced that such engines were preferable, and it had a high opinion of Lawrance, who became a Wright vice-president (and, in 1925, president). First came the P-1, a nine-cylinder engine of 1,652 cu in derived from a Lawrance Army design of 1919 but with a split master rod on a one-piece crankshaft and with valves fore and aft to try to restrict frontal area. In 1924 work began on the P-2, with much better Heron-type cylinders with laterally splayed valves completely enclosed, and with an integral supercharger. The P-1 gave 400 hp, and in early 1925 the P-2, by then named Cyclone, was type-tested at 435 hp. By this time Wright was also working on the intermediate 1,176 cu in Simoon, to give 350 hp, but this was knocked for six by the Wasp; in any case Wright's depleted engineering department did little in 1925.

In mid-1926 the Jones/Heron/Lawrance team, with chief engineer P.B. Taylor, set course again with improved Whirlwinds and Cyclones. The J-6 series of Whirlwinds had cylinders 5 × 5.5 in (bore having previously been 4.5 in), raising displacement from 787 to 973 cu in and power from (typically) 220 to 300 hp at 2,000 rpm. Valve gear and magnetos were moved to the rear, and there were many other changes. These bigger Whirlwinds, known as the R-975 in the new 'displacement' designations, were later joined by the seven-cylinder R-760. They were much used in transports and many other types, being developed to 350 hp (seven-cylinder) and 450 hp (nine-cylinder), large numbers being made by Continental in the Second World War. As for the Cyclone, this became the R-1750 with cylinders 6 × 6.875 in (1,749 cu in), type-tested in 1927 at 500 hp, soon raised to 525 hp at



When Wright Aeronautical was formed in 1919 this E-4 Tempest was the main product from the Paterson plant. From this point designer George Mead departed from the basic Hispano V-8.

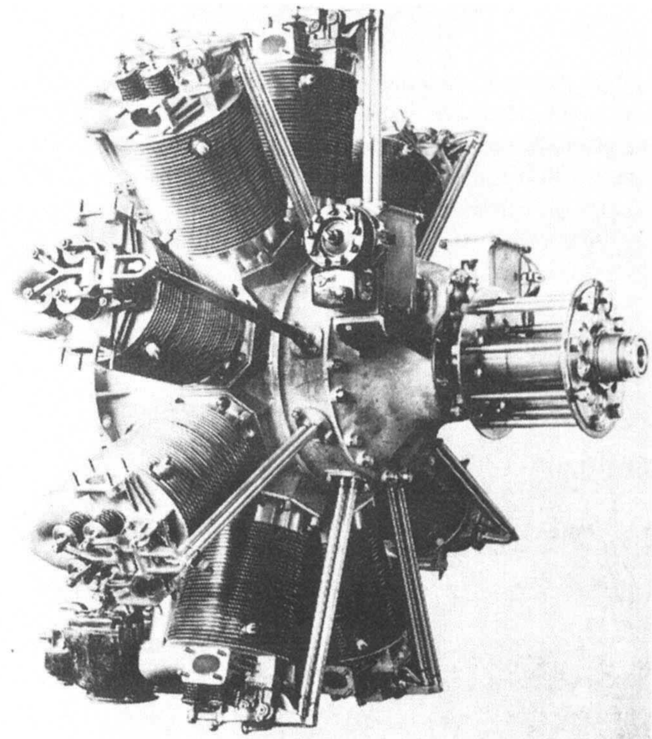


One of Mead's fresh designs was the T-4 Tornado, a hefty water-cooled V-12 used in US Navy seaplanes. Its exterior is so clean it looks unfinished.

1,900 rpm, and put into production. This began to offer some competition to Pratt & Whitney, and a further shot in the arm was the merger with Curtiss in 1929. The resulting Curtiss-Wright Corporation kept Wright Aeronautical unchanged until 1931, when the engine teams were merged at the Wright plant at Paterson, New Jersey. Taylor remained chief engineer, but now reported to the new vice-president (engineering) Arthur Nutt, from Curtiss.

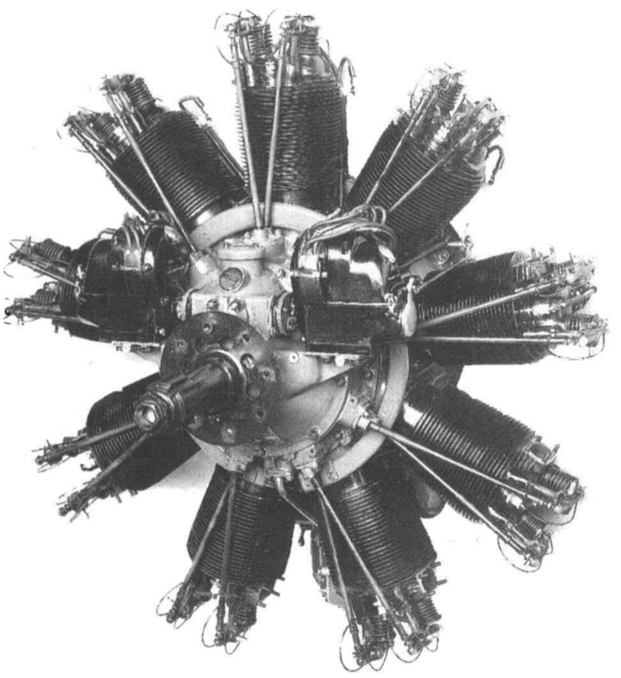
In 1932 the united team produced an outstanding new Cyclone, the F. This had bore increased to 6.125 in, giving capacity of 1,823 cu in; it was known as the R-1820. It had better cylinder finning, a forged crankcase and every modern refinement, including provision for a Hamilton variable-pitch propeller and it was picked by Douglas for the DC-1. Later Cyclones had a near-monopoly in pre-war Douglas Commercials, and it was sheer chance that almost all wartime-derived versions had the rival R-1830. In 1930 Wright also embarked on its first two-row engine the R-1510 with 14 Whirlwind cylinders (and retaining the name Whirlwind), which slowly developed at 750–775 hp but failed to find a market. An even bigger challenge was the H-2120 for the Navy. Intended to replace the Curtiss H-1640, this was to be a very slim flat-12 liquid-cooled engine of 1,000 hp which was to lead to the X-4240 of 2,000 hp with four blocks of six cylinders. Yet another diversion of effort from 1932 was the Navy V-1800, an advanced V-12 tested at 800 hp but dropped through lack of funds in 1934 (historian Schlaifer notes that this design was sold to the Soviet Union and there taken to 900 hp, but this is news to the Russians).

Throughout the first half of the 1930s Wright achieved increasing success with the R-1820 Cyclone, which did much to compensate for the failure of new designs. The F-series was made in large numbers at ratings up to 900 hp at 2,350 rpm on 91-grade fuel. By 1937 the G-series featured detail improvements throughout, and increased cooling-fin area to 2,800 sq in per cylinder to give the magic 1,000 hp, and in 1940 the G200 with even deeper fins and twin dynamic counterweights went to 2,500 rpm, giving 1,200 hp. Vast numbers were made, many of them by Studebaker, one major application being the B-17. By 1944 Wright had begun



Wright's first radial, the R-1 of 1921, was the first successful high-power radial in the United States. Many features came from the British Jupiter, which returned the compliment by later using a close tandem pair of rods to drive the four valves in each head.

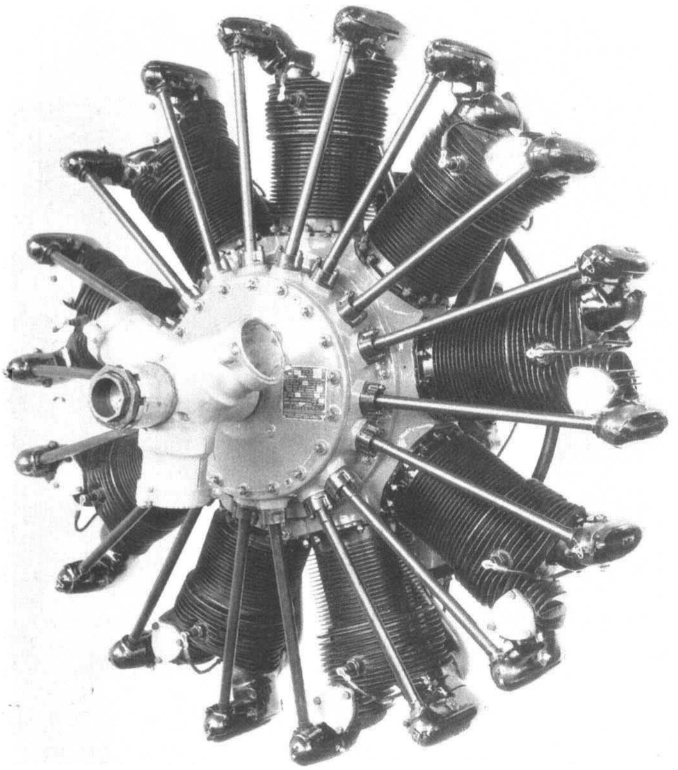
W



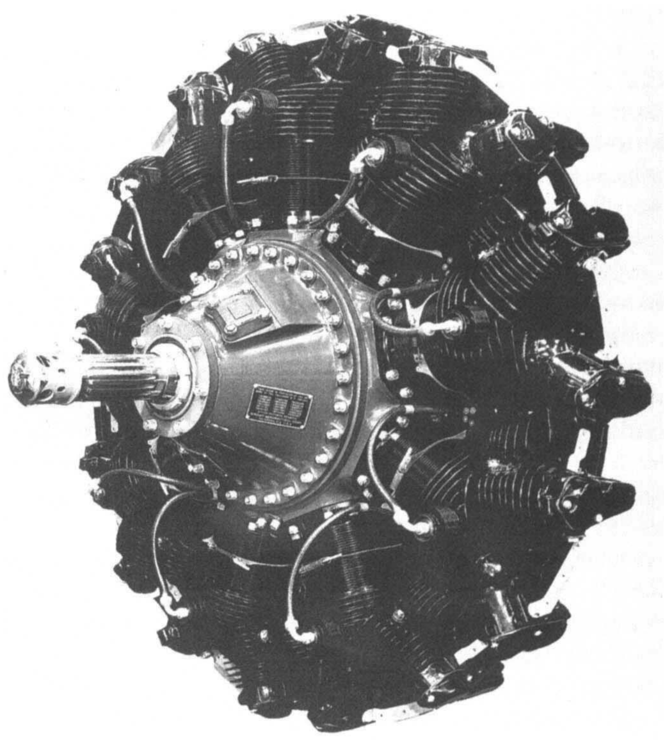
In 1924 Lawrance and Mead set Wright on course with the J-4, the first J-series radial to be named Whirlwind. It had two-valve cylinders, the gear being exposed, and two Scintilla magnetos on the front.

introducing its W-fin made of aluminium sheet rolled and caulked into fine grooves cut in the barrels. This led to the H-series Cyclone of 1,350 hp at 2,700 rpm, which remained in volume production (not by Wright but by Lycoming and Canadian P&W) for aeroplanes and helicopters throughout the 1950s at 1,525 hp at 2,800 rpm. Last of the single-row engines was the 1942-designed Cyclone 7, marketed from 1945 as the R-1300, based on the Cyclone H but with stroke reduced to 6.3125 in. The 800-hp production engines were licensed to Kaiser-Frazer and then to Lycoming, many going into blimps; the turbocharged version was dropped.

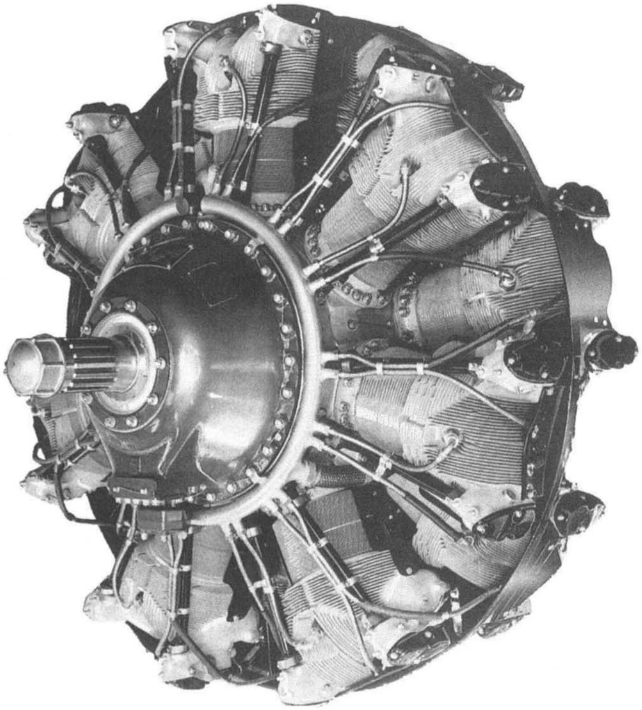
Wright's key to the future was the belated start in November 1935 upon the design of a modern but conventional two-row engine much bigger than the Cyclone. This was the Cyclone 14, or R-2600, with 14 cylinders of regular 6.125 bore but a new stroke, 6.3125, giving 2,603 cu in. The first run in September 1936 caused Pratt & Whitney to drop its R-2180 and enlarge its own R-2600 into the R-2800, but by this time Wright was about to run a much bigger engine still, the R-3350 Duplex Cyclone, or Cyclone 18. This had 18 cylinders of Cyclone 14 size, giving 3,342 cu in, and while the 14 was aimed at 1,500 hp the 18 was aimed at 2,000. The smaller engine was certificated at 1,500 hp in June 1937 and was in production by December 1937. PanAm accepted the high fuel price to use 115-grade fuel in the



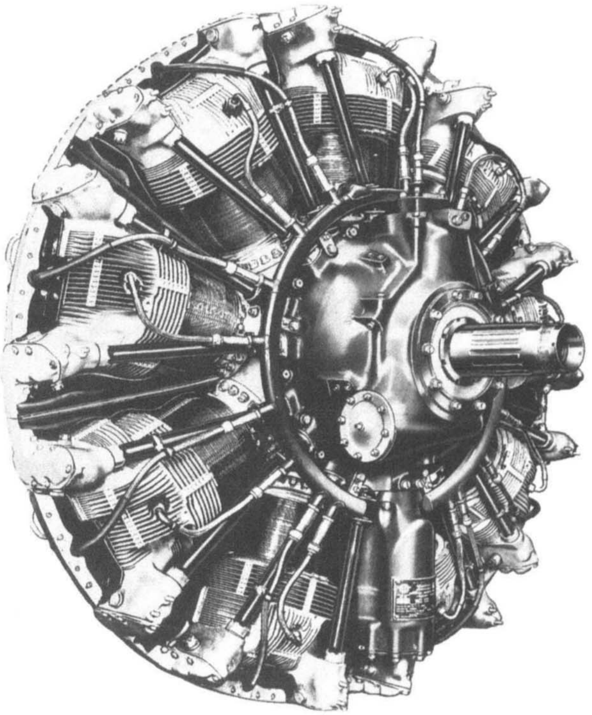
The first production Cyclone was the 525-hp R-1750 of 1927. It had more and deeper fins, enclosed valve gear, and all ignition equipment moved to the rear.



A Second World War R-975-E3 of 450 hp, the last of the Whirlwinds. In most installations the propeller drive was surrounded by an exhaust collector ring. Note that the valve gear has gone to the back.

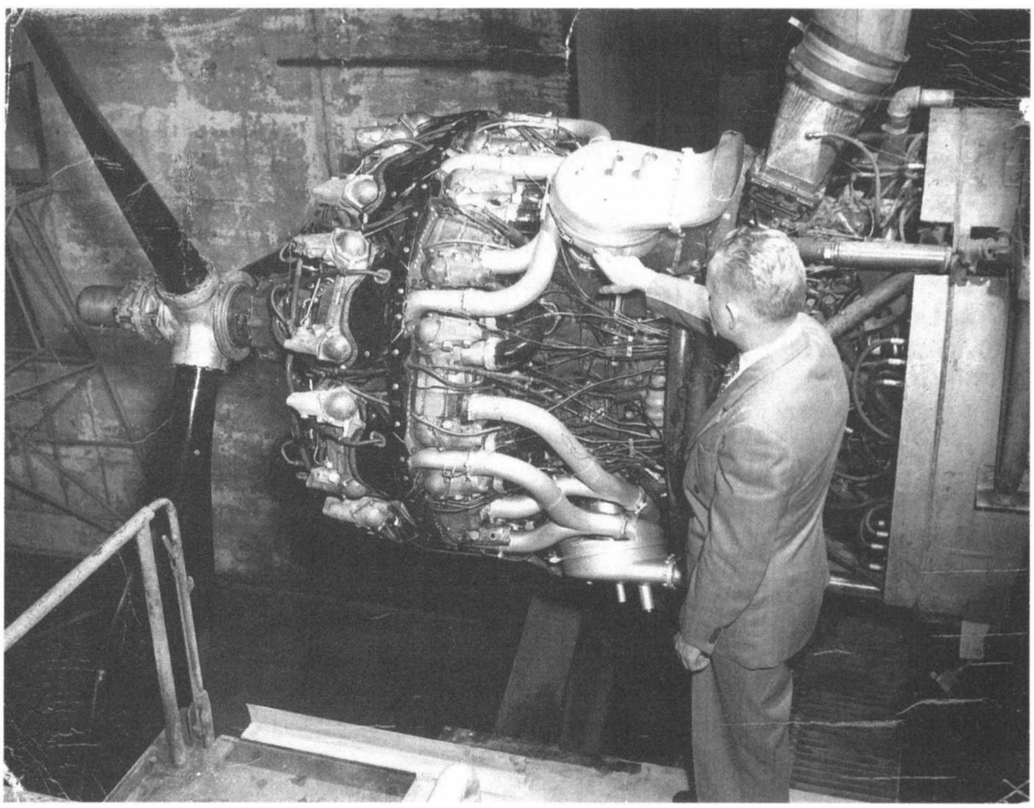


One of the war-winners was the R-2600, or Cyclone 14. This is one of the BB-series, with W-fin cylinders and uprated to 1,900 hp for such machines as the TBF and SB2C.



The Cyclone 9 family terminated in the mid-1950s with the H-series of 1,525 hp, made possible by the very closely pitched W-fin cooling. Made by Lycoming and P&W Canada for such aircraft as the S2F Tracker, these Cyclones gave just 1,000 hp more than the 1927 Cyclone.

Chief engineer Wilton G. 'Bill' Lundquist points to one of the three turbines, each driven by white-hot exhaust from six cylinders, that turned the R-3350 into the Turbo-Compound. This prototype was on test in January 1949. He never meant it to be the end of the road for Wright Aeronautical.



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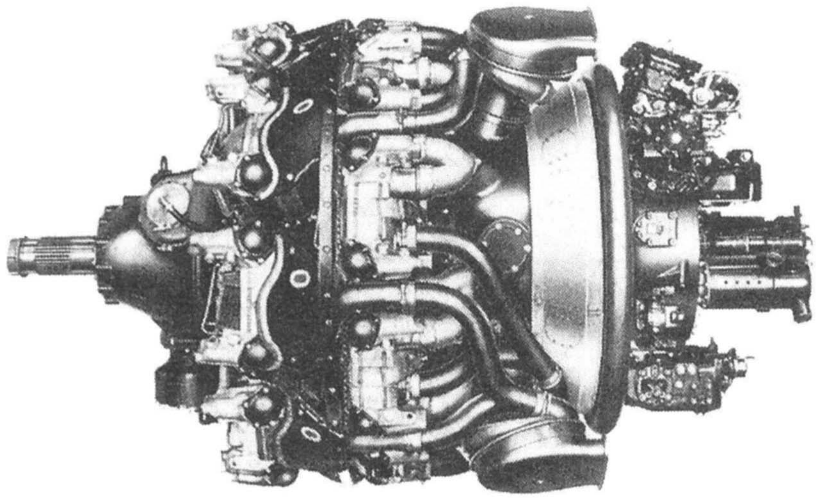


Perhaps the ultimate classical type of piston aero engine, the Turbo-Compound sought to extract more useful work from each unit of fuel, and incidentally was tightly baffled to make the cooling air work harder as well. Note the pale pipes conveying mixture to the 18 cylinders and the dark pipes taking white-hot exhaust to the three turbines.

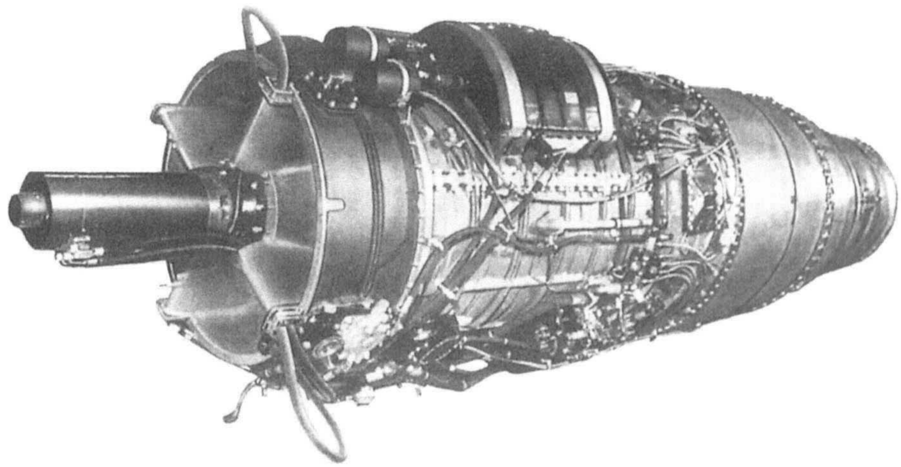
The author is grateful to Kimble D. McCutcheon, President of the Aircraft Engine Historical Society, for this picture of the surviving Wright R-2160 Tornado.

special high-compression version, called Wright 709C-14AC1, fitted to the transatlantic Boeing 314A from late 1938. The R-2600 became a major wartime engine, rated at around 1,700 hp in the B-series, of which over 50,000 were made by Wright at a plant in Cincinnati. By 1944 the BB-series of 1,900 hp went into production at Paterson with a forged steel crankcase and W-finning, but the R-2600 stopped dead at VJ day.

In contrast, the giant R-3350 grew in importance for almost 20 years from 1938. Design began in January 1936, and the first engine ran in May 1937. It was quickly adopted for all the largest US aircraft, but development was troubled by poor mixture distribution, catastrophic backfires in the capacious induction system, inflight fires and other problems. The crucial application was the B-29, where a very high degree of supercharging was necessary. Each engine had two General Electric turbosuperchargers feeding the gear-driven blower inside the magnesium case on the rear of the steel crankcase. By March 1938 Wright had decided to design its own superchargers (previously assigned to GE) and immense efforts transformed the altitude performance of the R-3350 by 1943. The one thing missing was direct fuel injection, which would have solved several problems; water injection to boost power on the arduous B-29 take-offs also had to wait until after the war. The wartime R-3350-23 was rated at 2,200 hp at 2,800 rpm and weighed about 2,670 lb. Related engines powered early Constellations, the L-649 and 749 having the 2,500-hp BD series and the A-1 Skyraider the 2,700 hp, 2,900 rpm, CA series (R-3350-26WB), weighing about 2,850 lb. By this time fuel was injected either through holes in the supercharger impeller or direct into the cylinders. Late R-3350s gave 2,800 hp on 115/145 fuel.

During the Second World War Wright was inevitably caught up in the Army programme for unconventional high-power engines. After dropping the H-2120 and V-1800 the merged Curtiss and Wright teams ignored liquid cooling until in about March 1938 work began for the Army on a 1,800-hp flat-24 to fit inside wings. This was soon found to be an impractical concept, and in early 1939 Wright proposed a compact liquid-cooled radial with six rows, each with seven tiny (51 cu in) cylinders. This was adopted as the R-2160 Tornado, a contract

Seen here in the more common non-afterburning form, the Wright J65 was a much-redesigned US version of the AS Sapphire. Large numbers were made for B-57s, F-84Fs and A-4s. An experimental J65 was the first engine to fly on liquid hydrogen.



for a 14-cylinder unit being awarded in June 1939. Tests with this showed that the use of multiple high-speed shafts linking the divided crankshaft to the propeller gearbox was sound, and the Lockheed XP-58 and Republic XP-69 were designed to use this promising engine in 1941. But the very short stroke, constriction of inlet manifolds and major problems with valve gear brought termination in 1943, the engineers being desperately needed on the R-3350.

Gas turbines

In 1944 Wright was awarded a USAAF contract for its first gas turbine, the XT35 Typhoon turboprop. This uninspired engine had an 18-stage axial compressor and was to give 5,500 hp. Flight testing with an XT35 in the nose of a B-17 began in September 1947, but after 17 engines had been built the contract was cancelled.

In 1949 president Guy Vaughan retired, the company moved its HQ from Paterson to its vast wartime plant at Wood-Ridge nearby, and under a new president, Roy T. Hurley – reputedly the highest-paid US executive of the period – set course for the future. It realised it needed to get into gas turbines, but chief engineer Bill Lundquist was an experienced and forceful man who was convinced the R-3350 would 'go on for ever'. He was strongly reinforced in this view by the Navy's funding of a significant new development, the R-3350 Turbo-Compound. This harnessed as much as possible (say, 21 per cent) of the energy normally wasted in the exhaust gas, by piping it through three blow-down turbines, spaced 120° apart and each fed by six cylinders. The turbines had Haynes Stellite blades welded to an Inconel X disc, and via a stainless-steel radial shaft and fluid coupling were geared to the rear of the crankshaft. Each put in about 200 hp at full power, so the engine output rose from some 2,700 to 3,250 hp, without burning any more fuel; weight rose to about 3,600 lb. The Turbo-Compound passed its Navy 150-h test in January 1950, and went into service on R7V Super Connies. Later versions found wide civil and military markets with wet ratings up to 3,700 hp.

These massive assemblages of precision machinery were the pinnacle of the art of the piston aero engine. Lundquist realised too late that 'for ever' was in reality going to end in 1957. Fortunately dynamic Hurley had seen the light in 1950 and bought licences for the Armstrong Siddeley Sapphire and Bristol Olympus. The former was subjected not only to Americanisation but also to a redesign process that, for example, replaced the Sapphire's main mid-section diffuser frame, machined from a solid forging, by a dimensionally similar section welded from pieces of nodular (spheroidal-graphite) iron. This all took about two years longer than expected, so that the author, for one, gave up counting the number of engineless F-84Fs parked on the airfield at Farmingdale when he got beyond 100. Delivery of the J65 Sapphire at last got going in 1953, from Wright and from Buick. The Dash-3 version in the F-84F had a Bendix fuel/air starter which screamed up to 100,000 rpm, to crank the J65. It always lit with a mild explosion, and this was sometimes followed by a much bigger explosion as it disintegrated at over 200,000 rpm, the clutch having failed to disconnect the drive to the accelerating J65. The B-57 engine starter had a solid-fuel cartridge; this poured black smoke as well. A few J65-6 and -18 Navy engines had afterburners.

Director of engineering Jack Charshafian boldly had a vast gearbox designed which, with extra turbine stages, turned the J65 into the T49 turboprop. There was even a TP51A2 commercial version. This began bench testing in December 1952 at 8,000 shp, and at 9,710 ehp began flying in an XB-47D on 26 August 1955, which was about the time that it became evident the T49 was not going to find a buyer. As for the Olympus, Wright tore it apart even more than they had the Sapphire and tried to redesign it into the J67 for the USAF and JT38 Zephyr for the airlines. By the time they were putting the engine together again the J57/JT3 had scooped up the entire market.

The decline of Wright in engines was as rapid as had been that of its partner Curtiss in aircraft. In 1958 it bought a licence for NSU-Wankel RC (rotating-combustion) engines, but efforts to find aviation markets proved disappointing, and the once mighty company sold out in 1985 to Deere (*see* Lycoming).

X–Z

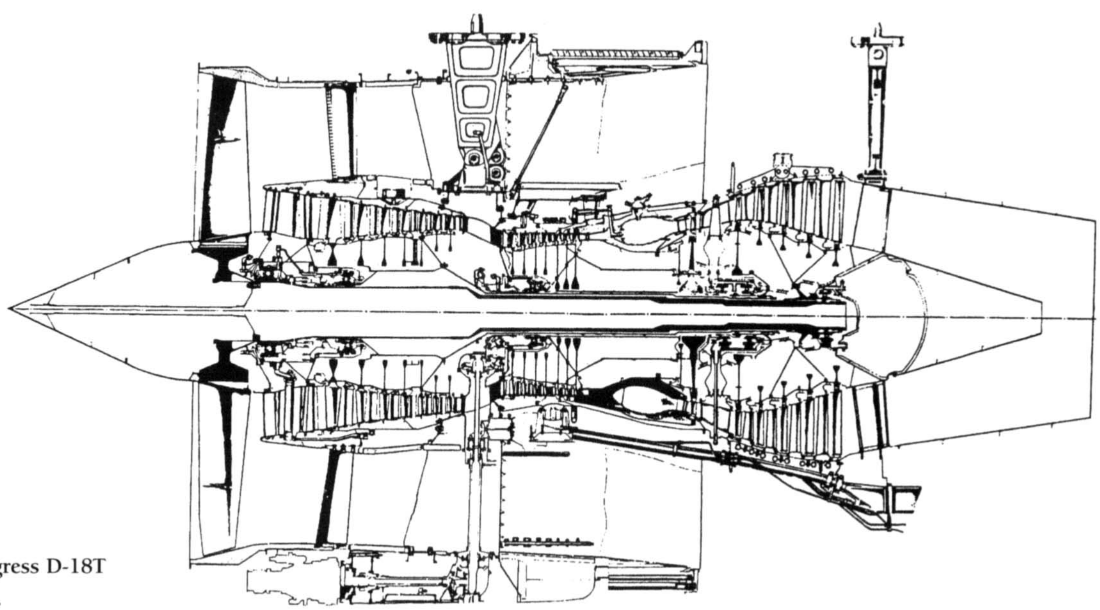
X

XAE (CHINA) Based at what is now called Shaanxi, Xian Aero Engine Corporation was created in 1958 to make under licence the RD-3M-500A turbojet to power the H-6, derived from the Tu-16. Soon XAE was also mass-producing the WP5 (VK-1, derived from the Nene). This gave a link with Rolls-Royce, and in 1975, despite the Cultural Revolution, work began making the Spey 202 fighter engine under licence as the WS9. Rolls-Royce supplied 50 engines, to get production of the JH-7 fighter started, and in 2001 about 90 more British-made Speys followed. XAE is kept solvent by making large numbers of parts for all Rolls-Royce companies, General Electric, Honeywell and Pratt & Whitney.

Z

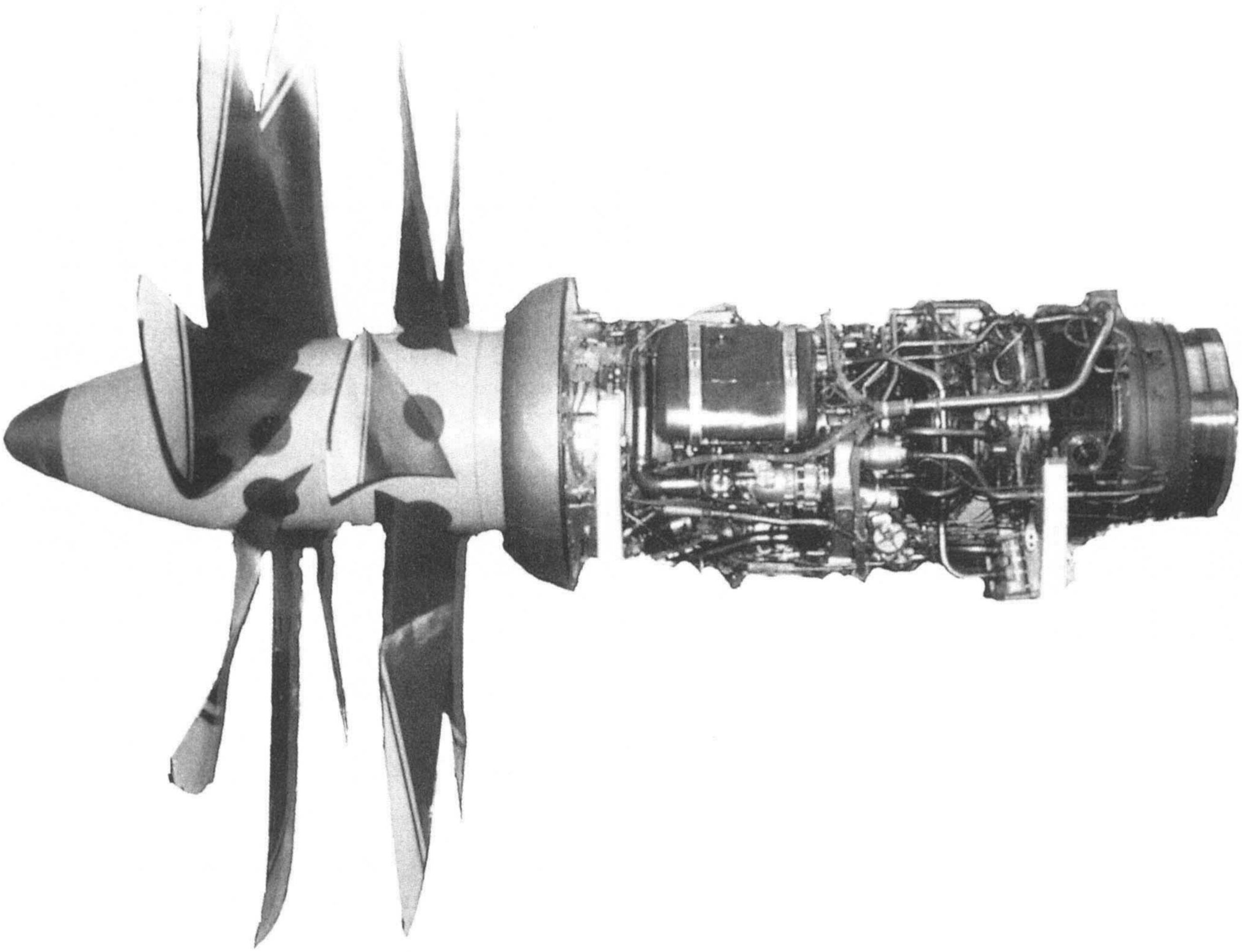
ZMKB (UKRAINE) The great design bureau at Zaporozhye was founded in May 1945 by Ivchyenko, and from 1968 its chief constructor (i.e. chief designer) was Lotarev. Most of its products have been described under their names, and (M-14) under VOKBM. Today's leader is F.M. Muravchenko, but the full name of the bureau is 'Ivchyenko Progress Zaporozhye Machine-Building Design Bureau', or ZMKB for short. The DV-2 turbofan was developed in partnership with PS (*qv*).

From the D-36 (see Lotarev) have been developed not only the D-136 and 236, but also a new shaft-drive D-336 and the D-436, an improved turbofan being tested in several forms with ratings from 13,227 to 20,613 lb. The most important are the D-436T1, which powers the Tu-334-100, and the D-436-148, which powers the An-148, an updated An-74, fitted with underwing engines unlike the An-72. In 1980 the former Lotarev bureau tested the first big Soviet turbofan, the D-18T. This again has three shafts, the single-stage 91.73 in fan of bypass ratio 5.6 being followed by a seven-stage IP and seven-stage HP spool. Weight is 9,039 lb, rating 51,660 lb, and cruise sfc as low as 0.570. Today, the biggest development programme is the D-27 propfan, using a core derived from the D-236 but driving new Stupino SV-27 contra-rotating propfan blades. The tractor D-27, rated at 13,880 shp, powers the An-70 airlifter, first flown on 16 December 1994, which on paper is superior to the A400M but has had a troubled and cash-strapped development.



The three-shaft ZMKB Progress D-18T powers the An-124 Ruslan.

Zoche (GERMANY) Michael Zoche's company in Munich specialises in diesel piston engines. So far there have been two main types for aircraft, the ZO 01A with four radial cylinders spaced at 90°, and the ZO 02A with two such rows giving an eight-cylinder engine. Cylinders are 95 mm bore and 94 mm stroke, giving capacities of 2,665 and 5,330 cc. The 01A weighs 185 lb and is rated at 150 hp at 2,500 rpm, while the 02A weighs 260 lb and gives 300 hp. Three 02A engines drive ducted propellers in the Sentinel 1240 airship. The largest airship currently planned, the Sentinel 5000, is designed for three 2,000-hp ZO-04A compound engines, two of them pivoted for thrust vectoring. Specific consumption of Zoche engines is an excellent 0.32–0.385 (most aircraft piston engines are around 0.5). A further selling point is the ability to use any jet fuel, which today is far more widely available than Avgas.



The Ukraine's An-70, powered by four of these D-27 propfans, forms an airlift combination with an efficiency no other country can even approach.

Z

GLOSSARY

Afterburner Enlarged jetpipe with variable nozzle in which extra fuel can be burned to boost thrust.

Aft fan Fan, with extra drive turbine, added downstream of core engine.

Air-cooled Piston engine whose cylinders have no cooling other than radiant fins.

Annular Pure body of revolution, with no separate flame tubes.

APU Auxiliary power unit.

Augmented Boosted by additional fuel injected in bypass air as well as in core gas.

Axial With airflow passing between alternate fixed and moving blades, sensibly parallel to engine axis.

Bank One line of cylinders in V, X, H or W engine.

Bare weight Without accessories, cooling baffles, etc.

Big end End of conrod encircling crankpin.

Bipropellant Using two liquids, a fuel and an oxidant.

Block Single casting or a forging containing one bank.

Bore Internal diameter of cylinder.

Broad arrow Three banks in W form.

Bypass Air compressed by fan or LP compressor ducted past core and expelled to atmosphere, sometimes mixed with core jet in common nozzle.

Can-annular Annular chamber with separate flame tubes.

Capacity Total area of all pistons multiplied by stroke, also called displacement or swept volume.

Centrifugal Accelerating air expelled radially outward at high speed, diffuser then converting speed to pressure.

Compression ratio Ratio of cylinder volume at BDC (bottom dead centre) to entrapped volume at TDC (top dead centre).

Contraprop Two propellers in tandem rotating in opposite directions about the same axis.

Core Gas generator providing power for gas-turbine engine.

Diffuser Expanding duct in which subsonic flow slows down while increasing in pressure.

Downdraught Supplied with air from above.

Dry weight Without water, fuel or oil.

Dual ignition With independent sources of spark.

Ducted fan Early term for turbofan.

Emissions Exhaust gas, visible smoke, noise, etc.

Fan Multibladed rotor driven by core to produce thrust by accelerating fresh air to rear: if at the front of an engine it also supercharges the core.

Flame tube Thin-walled perforated container(s) inside combustion chamber in which fuel is burned: it controls mixing of dilution (cooling) air.

Flat twin Twin-cylinder horizontally opposed engine (hence flat-four, flat-six).

Free turbine Power turbine driving output shaft only, not connected to gas generator.

Fuel injection Injection of metered supply of fuel into inlet system or (direct injection) of measured doses straight into each cylinder.

Gas generator Basic power-producing part of gas turbine comprising compressor, combustor and turbine.

H engine Cylinder banks form H seen from end: left/right vertically-opposed engines geared to one output.

HP The high-pressure spool in a two-shaft engine forms the physically smaller central portion, with the compressor and turbine separated only by the combustion chamber.

Inlet guide vane One row of radial vanes (blades) immediately upstream of a compressor or turbine.

In-line Engine with single linear bank of cylinders.

Inverted With cylinders hanging down from crankcase.

Jacket Container for cooling water surrounding cylinder.

Liner Wear-resistant tube inside (usually softer) cylinder, in which piston runs.

Liquid-cooled Cooled by liquid other than pure water.

LP The low-pressure spool comprises a compressor upstream of the HP compressor and a turbine downstream of the HP turbine.

Mass flow Measure of airflow through engine.

Monobloc Cast or forged in one piece.

Monocoque With all strength in outer shell.

Overhead valves Normal (poppet) valves in top of cylinder, stems projecting outwards.

PN Performance number (below 100 called octane number), measure of fuel's resistance to detonation (knocking).

Power turbine Providing useful output shaft power only: not driving compressor.

Pressure ratio Ratio of pressure at compressor delivery to that at inlet.

Propfan Propeller designed for jet speeds, with many broad but thin curved blades like scimitars.

Pulsejet Air-breathing engine with valves or resonant duct giving rapid-fire intermittent combustion.

Ramjet Air-breathing engine which, after being accelerated to high speed by some other means, acts like a turbojet without need for compressor or turbine.

Ratings Permitted maximum powers.

Reverser Device for deflecting engine jet(s) forward, to slow aircraft after landing.

Row Radial cylinders lying in one plane like spokes.

sfc Specific fuel consumption is basic measure of efficiency (fuel flow for given power or thrust).

Single-shaft One main rotating assembly; no separate power turbine or LP/HP spools.

Stage One row of radial blades, all in same plane.

Stator Row of fixed blades upstream of moving compressor or turbine rotor blades (vanes).

Stroke Distance from BDC to TDC (see compression ratio).

Supercharger Blower or compressor increasing density of mixture (in diesel, air) supplied to cylinder.

Turbocharger Supercharger driven by exhaust gas.

Turbofan Core plus large fan driven by extra turbine.
Turbojet Core plus nozzle only.
Turboprop Core plus propeller reduction gear driven by extra turbine or turbine stages.
Turboshaft Core plus output shaft driven by extra turbine or turbine stages.
Two-spool Also called two-shaft, a core having LP and HP spools rotating at different speeds.
Updraught Fed with air from below.
V engine Two banks forming V when seen from end.
Water injection Spray of water, or water/alcohol, to cool airflow and postpone detonation or, in gas turbine, increase density and hence power.
Zero stage Stage added upstream of original compressor.

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