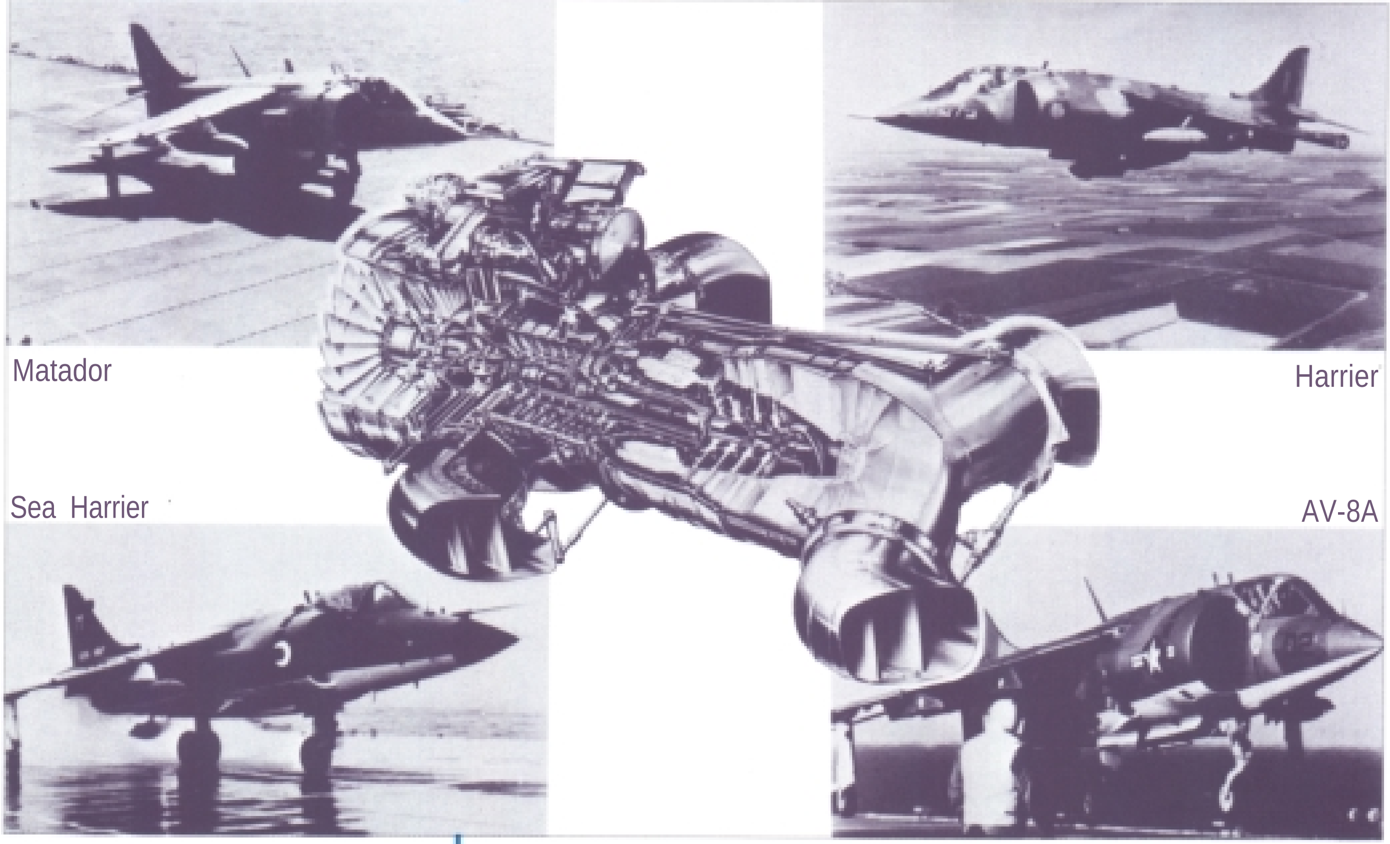
Pegasus Vectored-thrust Turbofan Engine



International
Historic Mechanical Engineering
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24 July 1993

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INTERNATIONAL HISTORIC MECHANICAL ENGINEERING LANDMARK
PEGASUS
VECTORED-THRUST TURBOFAN ENGINE
1960

THE BRISTOL AERO-ENGINES (ROLLS-ROYCE) PEGASUS ENGINE POWERED THE WORLD'S FIRST PRACTICAL VERTICAL/SHORT-TAKEOFF-AND-LANDING JET AIRCRAFT, THE HAWKER P. 1127 KESTREL. USING FOUR ROTATABLE NOZZLES, ITS THRUST COULD BE DIRECTED DOWNWARD TO LIFT THE AIRCRAFT, REARWARD FOR WINGBORNE FLIGHT, OR IN BETWEEN TO ENABLE TRANSITION BETWEEN THE TWO FLIGHT REGIMES. THIS ENGINE, SERIAL NUMBER BS 916, WAS PART OF THE DEVELOPMENT PROGRAM AND IS THE EARLIEST KNOWN SURVIVOR. PEGASUS ENGINE REMAIN IN PRODUCTION FOR THE HARRIER II AIRCRAFT.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
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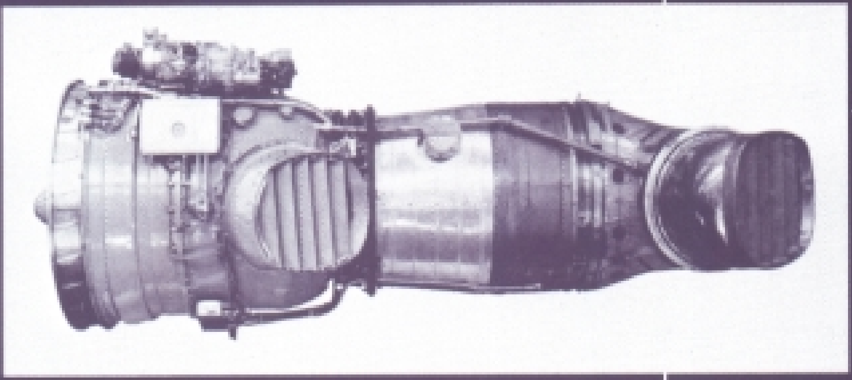
1993



Evolution of the Pegasus Vectored-thrust Engine

Introduction

The Pegasus vectored thrust engine provides the power for the first operational vertical and short takeoff and landing jet aircraft. The Harrier entered service with the Royal Air Force (RAF) in 1969, followed by the similar AV-8A with the United States Marine Corps in 1971. Both services have continued to operate developed versions of the basic aircraft, and it has been adopted by the Royal Navy and the Spanish, Indian, and Italian navies. More advanced versions of the engine and aircraft are still under development, to extend the capability of the weapon system and ensure continuing operation well into the next century.

The engine has the special characteristic of thrust vectoring, enabling the thrust to be directed rearward for propulsion, downward for lift, and forward for braking. The concept, which has remained basically unchanged since the first prototype P.1127 flew in 1960, enabled the goal of a single- engined VSTOL (very short takeoff and landing) jet aircraft to be realized.

The aircraft deliveries programmed for the present decade will ensure that the Pegasus engine, incorporating progressive development and refinement, will continue in service more than half a century after the first drawings were made in 1956.

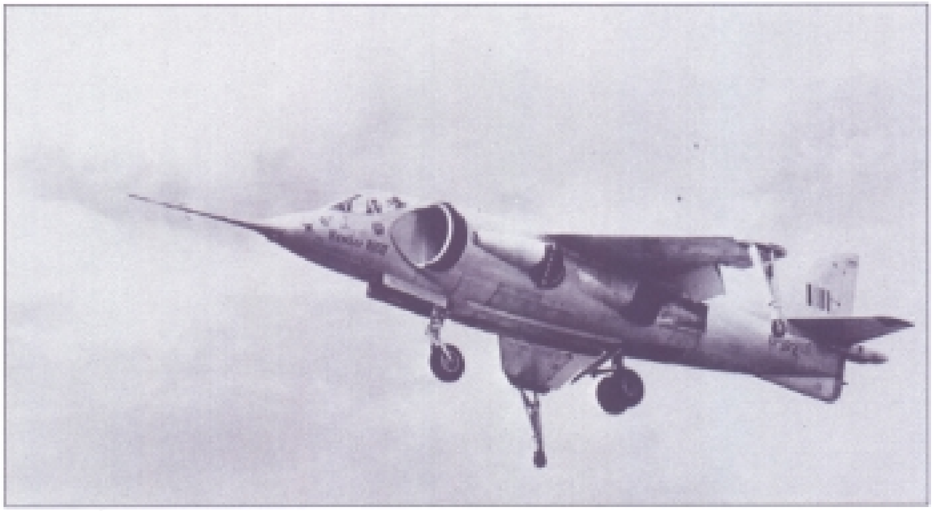
Background

In the late 1940s immediately following World War II, the development of ballistic missiles and sophisticated munitions led to concern in the Western Alliance regarding the vulnerability of North Atlantic Treaty Organization (NATO) airfields. This concern resulted in a perceived need for combat runways for takeoff and landing, and which could, if required, be dispersed for operation from unprepared and concealed sites. Naval interest focused on a similar objective to enable shipborne combat aircraft to operate from helicopter-size platforms and small ships, because of the high cost and expected vulnerability of large aircraft carriers.

During the 1950s, numerous projects and research programs were initiated in the United States and Western Europe to study and validate alternative means of achieving the required short or vertical takeoff (VTO) and landing characteristics. The advancing technology of the gas turbine offered steadily increasing values of engine thrust-to-weight ratio, which encouraged the study of direct jet lift systems and of the control and stability problems associated with the transition from hover to wing-borne flight.

The concepts examined and pursued to full-flight demonstration included "tail sitting" types exemplified by the Convair XFY-1 and mounted jet engines, while others used jet augmentation by means of lifting fans and ejectors.

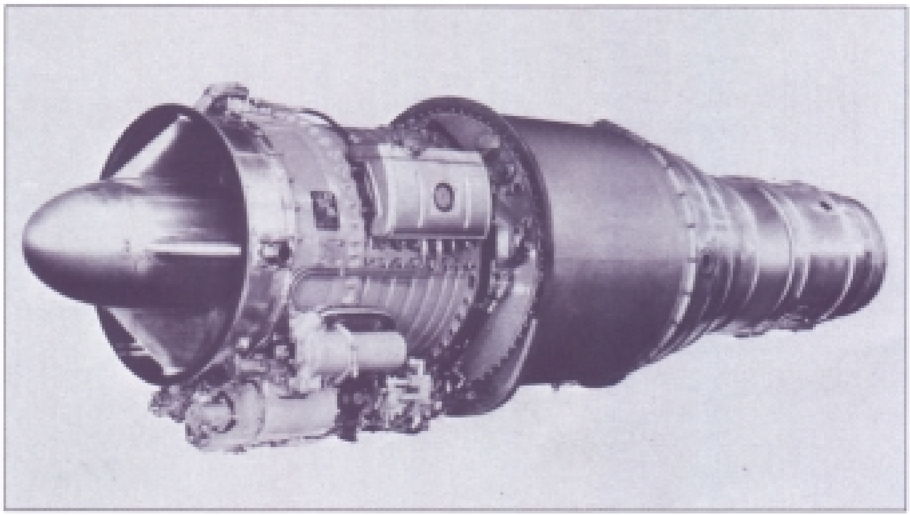
In the United Kingdom, effort was concentrated on the development and application of very high thrust-to-weight lift engines following the ideas put forward by Dr. A. A. Griffith. This work resulted, in 1954, in the launch of the Short SC1, a small VTO flat-rising research aircraft able to take off vertically with the thrust of four Rolls-Royce RB108 vertically mounted lift engines. The achieved engine thrust-to-weight ratio was 8:1, and a further similar engine was installed with a horizontal jet efflux



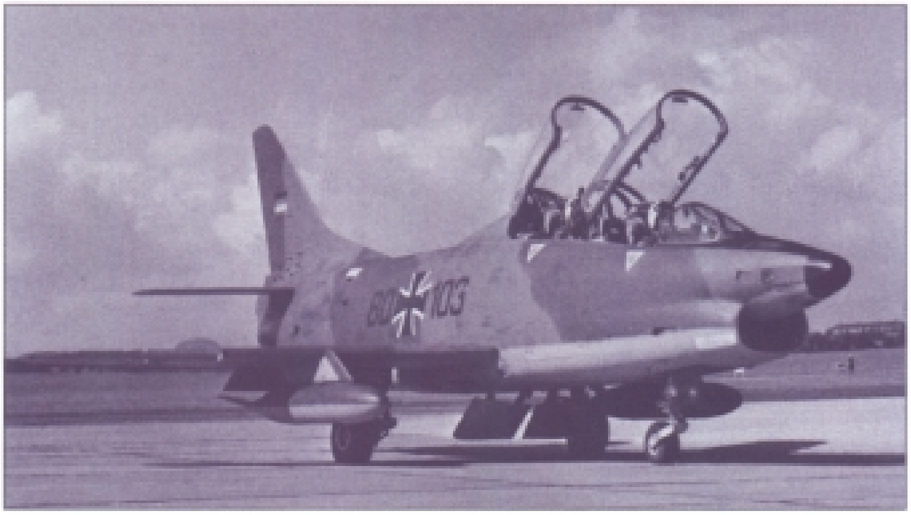
Hawker P.1127

for propulsion.

The two UK companies to become responsible for Pegasus and Harrier development were, at this time, not active in the field of VTO. The Bristol Aeroplane Company Engine Division, later to be absorbed into Bristol Siddeley Engines and then into Rolls-Royce, had responded to a requirement for a light-weight engine to power a NATO strike fighter, conventional in configuration but able to operate from relatively unprepared runways. This engine, the Orpheus turbojet, was selected for the Fiat G91 aircraft to meet the NATO requirement. The development program was managed and funded by the Mutual Weapons Development Program (MWDP), a United States agency with an office in Paris having the objective of supporting projects of potential value to the NATO forces. The Fiat G91, which later entered service with the German and Italian air forces, was to be followed in a second-phase program by an aircraft with enhanced performance and in a third phase by a strike fighter with short takeoff and vertical-landing capability.



Orpheus Turbojet



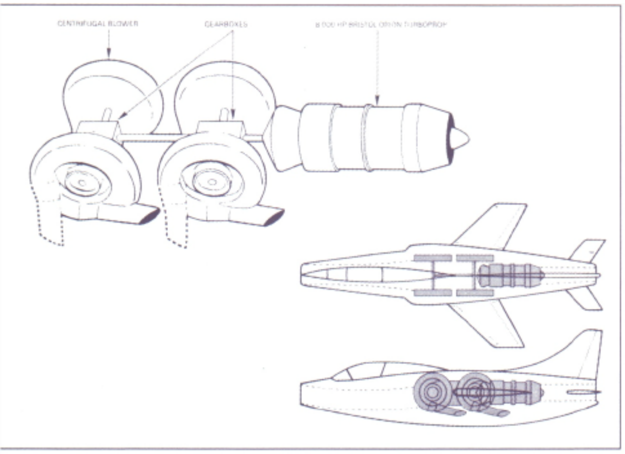
Fiat G91

The Evolution of Vectored Thrust

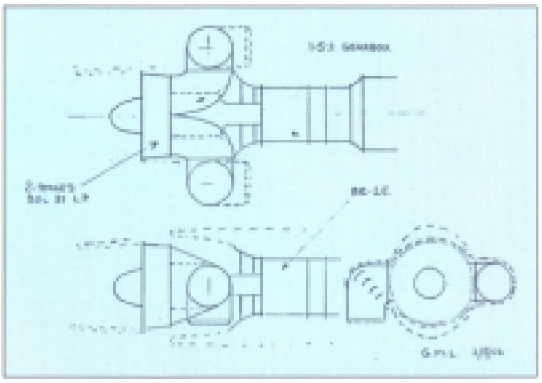
In March 1956, when MWDP was turning its attention to the third-phase NATO requirement, a proposal was submitted to the Paris office by Michel Wibault. Wibault was well known in aviation in the pre-war period, the company of that name having been responsible for a range of French transport and fighter aircraft. Post-war Wibault had been working on novel aviation projects and had produced schemes for a VSTOL strike fighter, which were entitled “Ground Attack Gyropter,” the subject of the March proposal.

This proposal introduced the concept of thrust vectoring and described the basic principles of operation that were subsequently incorporated into the Pegasus engine and the Harrier airframe. The system proposed consisted of a turboprop engine, the Bristol BE25 Orion of about 8,000 horsepower, driving four large centrifugal compressors, arranged like wheels at the sides of the fuselage. The blower casings could be rotated to direct the compressed air, and hence the thrust, through over 90 degrees. The air was directed downwards for vertical takeoff and landing, obliquely for climbing or transition, and horizontally for level flight. The exhaust gas from the turboprop was also used for vertical or horizontal thrust using a gas deviator mechanically connected with the rotation of the four blower casings. The proposed aircraft was stabilized in hovering and low-speed flight by means of air bled from the compressors and ejected from the wing tips and nose and tail of the airframe.

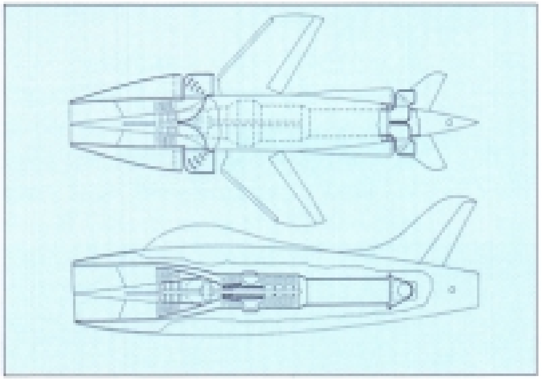
Col. John Driscoll, at the time head of the MWDP Paris office, sent the proposal to Dr. Stanley Hooker (later Sir Stanley) at Bristol Engines. It was studied by Gordon Lewis, who was responsible for new projects. Lewis recognized the importance of the thrust-vectoring principle but considered the Wibault mechanical arrangement of four compressors driven by shafts and bevel gear boxes to be complex and heavy. He proposed an alternative lighter and simpler arrangement, substituting a two-stage axial flow fan for the four centrifugal



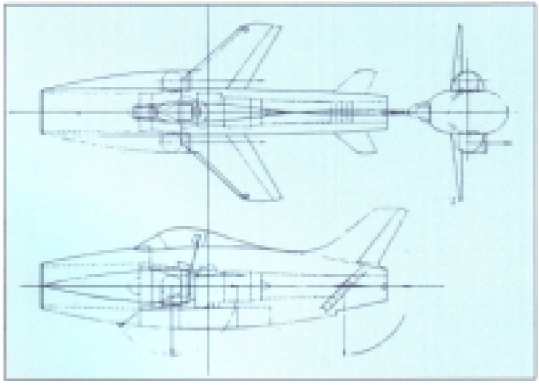
Michel Wibault's Ground Attack Gyropter, March 1956



Original sketch of BE 48, August 1956



Wibault-Lewis patent



Wibault Gyropter scheme using BE 48

blowers and vectoring the thrust through two rotating nozzles, one on each side of the engine.

This layout, designated BE 48, retained the Orion engine and a reduction gear to drive the fan Further weight reduction resulted from using a power turbine running at the appropriate speed, dispensing with the reduction gear, and replacing the turboprop with the simpler and lighter Orpheus turbojet. The resulting design, the BE 52, was further evolved into the BE 53 with a three-stage fan.

Wibault quickly accepted the changes to his mechanical design and produced a scheme of a strike fighter using the new proposed engine. This was presented to MWDP, where Col. Willis Chapman, later Brigadier General, had replaced Col. Driscoll. Chapman encouraged Bristol to proceed with the design, and a joint patent was registered at the end of 1956 in the names of Wibault and Lewis. This patent identified the main feature of rotating nozzles, including a pair at the rear of the aircraft to deflect the turbine exhaust gas, and contra-rotation of the engine spools to minimize the effect of gyroscopic couples on hovering stability. By this time the benefit of using a proportion of the fan delivery air to supercharge the engine compressor had been realized, resulting in the necessity for only a single air intake. This aspect was covered in the patent, and the engine emerged as a turbofan, or bypass engine, an arrangement used extensively in later commercial engines.

In May 1957 Sir Sydney Camm of Hawker Aircraft contacted Sir Stanley Hooker to discuss possible VSTOL projects. The BE 53 schemes were presented, and Ralph Hooper of Hawkers carried out a series of project designs aiming at a VSTOL fighter with real military capability. His work contributed much to the refinement of the engine design, including the major feature of rotating rear nozzles, exiting on each side of the fuselage and closely integrated with the engine. The nozzle rotation mechanism had received much attention by F. C. Marchant, in charge of the Bristol design office, and he evolved the scheme of using large diameter bearings to support the nozzles with air motor driven chains round the periphery of the bearings to affect rotation.

By the autumn of 1957, the Hawker designers had prepared the initial schemes of the prototype P.1127, and the engine design, named Pegasus, had become a compact and light thrust vectoring engine, with the thrust line passing through the center of gravity in all angles of deflection. The engine configuration at the commencement of joint MWDP and company-funded development in 1958 comprised a two-stage fan, seven-stage compressor, and three stages of turbine.

The program moved forward rapidly when Hawker launched the P.1127 prototype with UK funding, and in September 1959, the first engine ran on the test bed, giving 9,000 lbs of thrust. The Hawker Chief Test Pilot, Bill Bedford, flew the P.1127 for the first time in the hovering mode in October 1960, by which time the engine thrust had been increased to 12,000 lbs.

John Dale, who had been responsible for development of the Orpheus engine in the Fiat G91, took charge of Pegasus development engineering and led the team that progressively raised the engine thrust to over 21,000 lbs for the RAF' Harriers and US Marine Corps AV-8As.

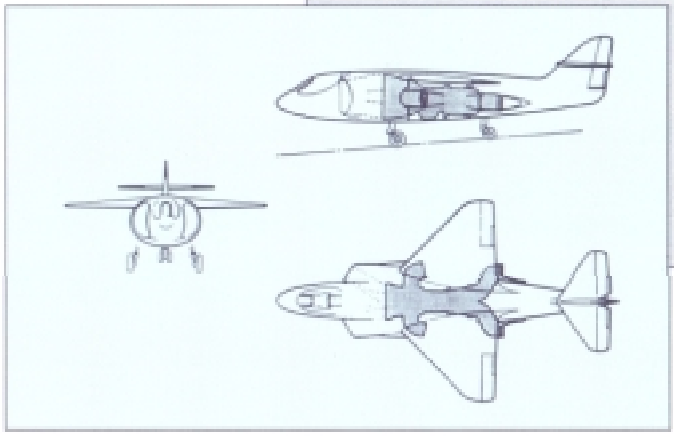
In the process of thrust enhancement, the engine passed through several phases of evolution to the present-day configuration of three fan stages, eight-stage compressor, and four stages of turbine with an annular combustor. Special features of the engine include contra-rotation, provision for air bleed for the aircraft stabilization nozzles, and a transonic fan with no inlet guide vanes. This latter type of fan was subsequently adopted for large turbofan commercial engines.

Development Problems

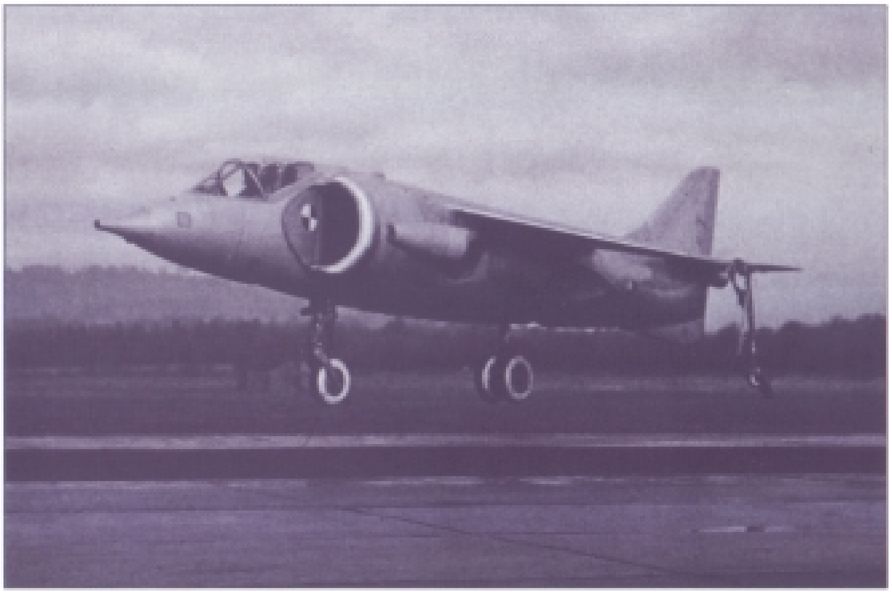
The Pegasus Harrier combination has been very successful, but nevertheless there have been design and development problems to be solved during its career. The early problems emerged under the following headings:

Intake ducting and fan outlet system. Because the engine has to be located at the aircraft center of gravity, the intake duct is only about one diameter long. Connecting the two large fuselage side intakes with the engine face required short high curvature ducting, which introduced air flow distortion at the fan inlet and led to excessive blade vibration. To keep the vibration frequencies of the blades outside the revolutions-per-minute (RPM) range of the engine, they were machined with interblade supports and made in titanium for added strength. This also solved the problem of further air distortion caused by the fan outlet ducting. The early faired ducts to the nozzles were replaced by a plenum chamber to insulate the fan from the upstream effect of the two nozzles.

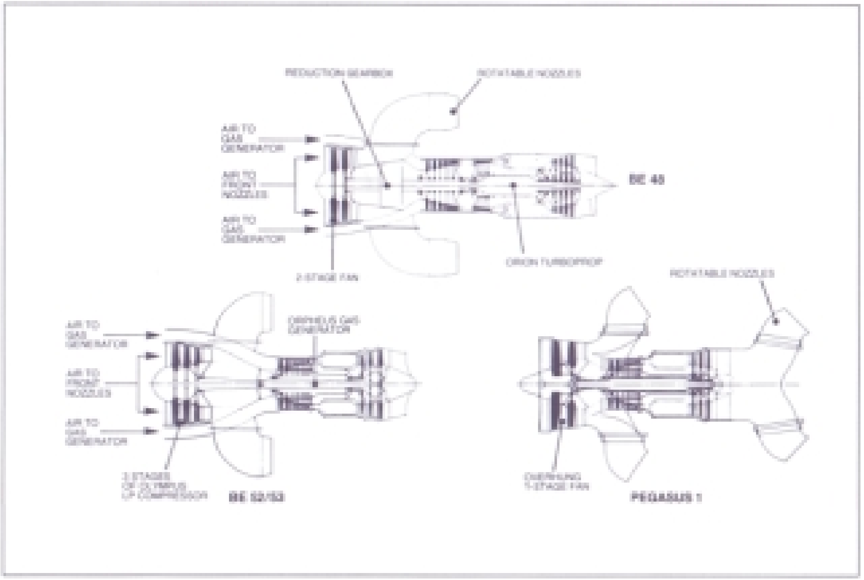
Pegasus 2



Early Hawker P.1127 configuration



P.1127 first flight October 1960



Exhaust duct. The task of the exhaust duct is similar to that of the plenum chamber, that is, to split the flow of gas from the turbine into two nozzles. This induced vibration in the final-stage turbine blades, and the development engineers introduced wire lacing as used in steam turbines to restrain the blade movements. Later in the program, the turbine was redesigned with shrouded blades, also similar to steam turbine practice.

Ground erosion. With nozzles down, the jets impinge on the ground and can cause erosion of the surface and throw up debris with damaging effects. The technique of rolling takeoff, making use of the thrust vectoring principle, enabled this issue to be brought under control by accelerating the aircraft forward before directing the nozzles downward.

Hot gas recirculation. During jet-borne flight close to the ground, the exhaust gases recirculate round the aircraft and can enter the engine intake and produce temperature rise and flow distortion effects, which reduce engine power. These effects are caused mainly by "fountains" of exhaust gas that form between pairs of jet streams. The Pegasus, with four nozzles, produces two fountains, the one nearest the intake comprising relatively cool air from the fan, which effectively forms a barrier preventing hot exhaust gas from reaching the intake. Problems of this nature are intrinsically associated with a VTO system, and the Pegasus configuration has been demonstrated to have particular advantages over most alternatives. The engine and airframe companies have worked closely together throughout the program to solve such problems associated with engine installation. This close collaboration has been a special feature of the Pegasus Harrier program.

Thrust Growth

The Hawker designers continually demanded increases in thrust from the engine to mature the weapon-carryingcapability and range of the aircraft. The Pegasus 5 was designed for the Kestrel, a development of the P.1127 for which a thrust of 15,500 lbs was required. In 1963 the United States, United Kingdom, and West Germany signed the Tripartite Agreement to fund a squadron of nine Kestrels, which carried out trials in 1965 to evaluate the feasibility of dispersed operations and establish practical procedures. To achieve the necessary thrust, Bristol introduced most of the design features that were to be incorporated in the later production engines.

Tripartite Squadron Kestrel

The Pegasus Mk101 was the first full-production Pegasus and entered RAF service in the Hawker Siddeley Harrier in April 1969 with a thrust of 19,000 lbs. The Pegasus Mk102 was an interim production standard pending introduction of the Mk103, which powered all Harriers of the RAF and the corresponding AV-8A of the US Marine Corps. This engine was also acquired for the Matador, the name given to the aircraft purchased by the Spanish Navy. Thrust of the Mk103 was increased to 21,500 lbs using an increased air flow fan and improved turbine cooling. The later Mk104 had some changes to resist salt-water corrosion for the Royal Navy version of the aircraft, the Sea Harrier.

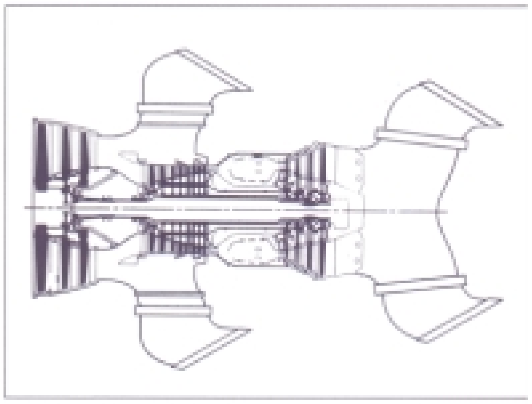
The McDonnell Douglas Company, which had formed a collaboration with Hawker Siddeley to support the AV-8A program, carried out an extensive redesign of the aircraft to meet the requirements set for the AV-8B. This necessitated further thrust increase and detailed engine changes to improve reliability and engine life and modified exhaust nozzles to integrate with the aerodynamic changes that greatly increased the takeoff weight capability. Large orders were placed for the AV-8B, and parallel developments in the United Kingdom resulted in the Harrier Mk2 for the Royal Air Force.

An engine demonstrator program established the basis for more thrust increase, enablingfurther developments of the AV-8B and Harrier Mk2 to be introduced for ground-based and naval applications. The engine is now equipped with digital electronic control, replacing the original hydromechanical system.

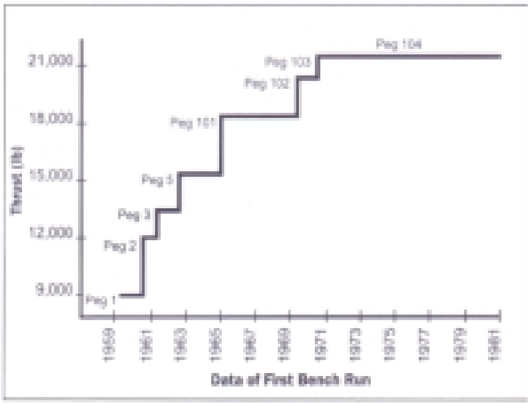
Operating Experience

The deployment of RAF Harriers to dispersed sites, the flexible operation of the US Marine Corps AV-8A and AV-8B, and the naval operations from small aircraft carriers have all vindicated the claims made for vectored thrust VSTOL in the original Wibault proposal and detailed in the submissions made for funding of the P. 1127 and early Pegasus engines.

In 1982 in the South Atlantic and 1992 in the Persian Gulf, these characteristics have been demonstrated in action.



Pegasus 11 (Mk 103)



Pegasus Engine thrust progression

Why Vectored Thrust Succeeded

During the 1960s and into the 197Os, many extensive programs were committed in the United States and Europe to evolve VSTOL systems using a variety of concepts. These included lifting fans installed horizontally in the wing section, ejector augmentor systems, multiple lift engines, and rotating engine nacelles. None of these was developed to operational status.

One powerful reason why the single-engine solution embodied in the Harrier was pursued was the essential simplicity of the concept. The basic principle of vectored thrust is that all the powerplant thrust can be orientated in any direction between horizontal and vertical, so that it provides lift as well as propulsion. Given sufficient thrust to lift off vertically, the aircraft can make a smooth transition from hover to forward flight. Vectored thrust, as represented by the Pegasus-Harrier combination, has the following characteristics and advantages:

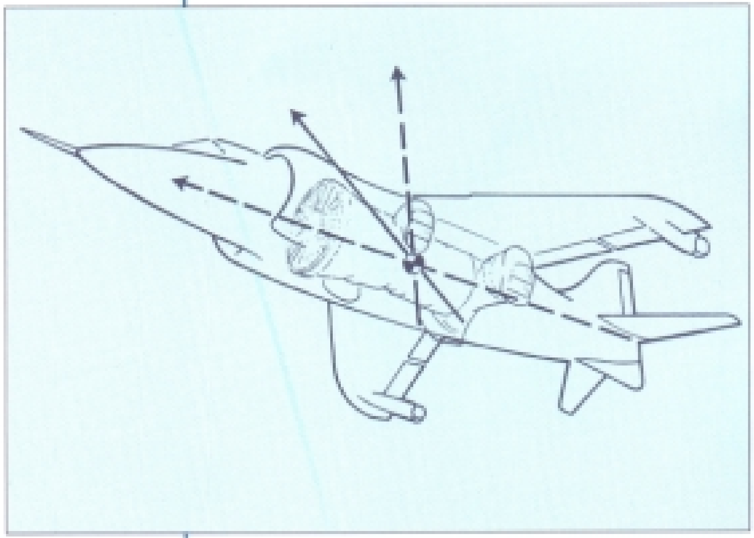
- A single engine located near the aircraft center of gravity, with a rotating nozzle system producing a thrust resultant that can be vectored between horizontal and vertical.
- Engine and nozzles together forming a compact, self-contained power unit,
- Rapid nozzle vectoring (over 90°/sec) actuated by a powerful air motor drive system using engine-supplied air.
- Short takeoff, at weights substantially greater than those that would be possible for VTO, is effective and easy, since all the thrust is available for ground acceleration, lift-off and transition. Also, rolling vertical takeoff and short takeoff techniques minimize the impact of jets on the ground or ship's deck.
- The pilot has only one extra lever in the cockpit, to affect nozzle rotation. Since the engine spools rotate in opposite directions, there is virtually no gyroscopic effect, and control of the aircraft during hover and transition is not totally dependent on electronic controls and auto-stabilization.
- Thrust vectoring in forward flight can be used to increase maneuverability in combat.

The MacRobert Award

In 1969 the first MacRobert Award was shared by a team of five persons associated with the early design and development of the Pegasus engine. This award was set up in 1968 by the trustees of the MacRobert Trusts, to be allocated in recognition of engineering innovation leading to the benefit of the United Kingdom. The Council of Engineering Institutions initiated the process, and the award is now presented annually by the Royal Academy of Engineering.

Leading the team was Dr. Stanley Hooker, in charge of engineeringat Bristol in the 1950s. He had been responsible at Rolls-Royce for the development of the Whittle jet engine to production status. Sir Stanely, together with Sir Sydney Camm at Hawker Aircraft, placed his considerable reputation behind the Pegasus concept and laid the foundations for subsequent success.

AV-8B



Vectored Thrust Principle

Left to right: Frank Marchant, Gordon Lewis, John Dale, Sir Stanley Hooker, and Neville Quinn

Gordon M. Lewis was responsible for the conceptual design of the Pegasus, emerging from the original ideas of Michael Wibault. He was originally a specialist in axial flow compressor design and later managed major engine programs before retiring as Technical Director

N. R. Quinn, having been in charge of supercharger work at Bristol in the piston-engine era, was heading the performance department in 1956. Quinn's perception of the merit of the Pegasus concept and execution of many performance studies made a major contribution to the engine definition.

F. C. Marchant was in 1956 Chief Designer at Bristol Engines, and he carried out the mechanical design of the Pegasus to achieve the high thrust-to-weight ratio needed for VSTOL. He introduced innovative design features that were later widely adopted in the aero gas-turbine industry.

John H. Dale had been responsible for the Orpheus jet engine at Bristol and took charge of Pegasus development from the start of the program. He carried Pegasus engineering onward for about 20 years, earning great respect from operators for engineering integrity and attention to flight safety.

The above were nominated in 1969 as having particular involvement in Pegasus. However, a major engine development program requires a large team of engineers over several decades to mature and improve the product. Many of the engineers involved made significant contributions to the design and took part in the solution of problems as they arose. It is not possible to do justice to all these people in this brochure.

It should be emphasized again that the close partnership between the engine and airframe engineers has always been and still is a very special feature of the Pegasus Harrier program.

-- Dr. G. M. Lewis, CBE, MA, F.Eng., F.R.Ae.S., F.I.Mech.E.

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The History and Heritage Program of the ASME

The ASME History and Heritage Recognition Program began in September 1971. To implement and achieve its goals, ASME formed a History and Heritage Committee, initially composed of mechanical engineers, historians of technology, and curator (emeritus) of mechanical engineering at the Smithsonian Institution. The Committee provides a public service by examining, noting, recording, and acknowledging mechanical engineering achievements of particular significance. The History and Heritage Committee is part of the ASME Council on Public Affairs and Board on Public Information. For further information please contact Public Information, American Society of Mechanical Engineers, 345 East 47 Street, New York, NY 10017-2392, (0101) 212-705-7740.

Designation

The BS 916 Pegasus Engine is the 38th ASME International Historic Mechanical Engineering Landmark to be designated. Since the ASME Historic Mechanical Engineering Recognition Program began in 1971, 156 Historic Mechanical Engineering Landmarks, 6 Mechanical Engineering Heritage Sites, and 4 Mechanical Engineering Heritage Collections have been recognized. Each reflects its influence on society, either in its immediate locale, nationwide, or throughout the world.

It is the sixth international landmark designated in conjunction with IMechE: SS Great Britain in Bristol, the Newcomen Steam Atmospheric Engine in Devon, and the Steam Turbine Yacht Turbinia in Newcastle-upon-Tyne as well as the Cruquius Steam Drainage Pumping Station in Haarlemmermeer, The Netherlands, and the Boulton and Watt Rotative Steam Engine in Sydney, Australia.

A landmark represents a progressive step in the evolution of mechanical engineering. Site designations note an event or development of clear historical importance to mechanical engineers. Collections mark the contributions of a number of objects with special significance to the historical development of mechanical engineering.

The ASME Historic Mechanical Engineering Recognition Program illuminates our technological heritage and serves to encourage the preservation of the physical remains of historically the divergent paths of discovery.

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