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History of the Pegasus Vectored Thrust Engine

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THE cost of the development and production of strike-fighter aircraft increased rapidly in the 1950s because of the ever-increasing sophistication of the electronics and the bombs or missiles carried, together with the demand for supersonic performance of at least Mach 2. In a forlorn attempt to reverse this tendency in England, W.E.W. Petter, designer of the famed Canberra bomber, proposed the Gnat fighter, weighing less than 10,000 lb and limited to high subsonic performance, in the hope that such an aircraft would be inexpensive and easy to produce. Gen. Norstadt of the U.S. Air Force, Supreme Commander of NATO, supported the concept, but added that it should be capable of taking off and landing on 2000 ft grass strips, which he described as "cow pastures."

The specifications of the NATO Light Fighter, as it came to be known, closely followed those of the Gnat, except that this aircraft was to have high-pressure tires and thus could not operate from grass fields. Petter, being the obstinate fellow he was, steadfastly refused to change and, therefore, opened the field to D'Assault, Breguet, and Fiat; thus, the lightweight fighter competition began.

In the background, Col. John O'Driscoll of the U.S. Air Force was the driving force behind the competition and had inspired Gen. Norstadt to issue his requirements. At the time, O'Driscoll was the executive head of the Mutual Weapons Development Program (MWDP) in Paris, and had funding available for development projects of interest to NATO. He was also a man of great vision and experience, and the resuscitation of the German and Italian aircraft industries and air forces owes much to the vigor with which he pursued both the competition and selection of the lightweight fighter. He also held the purse strings and dealt most effectively with the competitors, despite the enormous pressures to which he was subjected.

The Bristol Engine Company had proposed the Orpheus engine as the powerplant for the Gnat. This engine had an air mass flow of 80 lb/s, a compression ratio of 4.5/1, a thrust of 4850 lb for a weight of 800 lb. As such, it was easily the lightest engine available and was subsequently adopted by all the aircraft competitors as the desired powerplant. Thus, Col. O'Driscoll had few problems in the choice of the engine, and after the technical details had been scrutinized at Wright-Patterson Air Force Base and Theodore von Kármán, he was able to give immediate financial support for the development of the engine. The arrangement was that MWDP would pay 75% of the development cost and the Bristol Engine Company fund the remainder.

A cross-sectional drawing of the Orpheus is shown in Fig. 1. It had a seven-stage axial compressor, an annular combustion chamber, and a single-stage turbine (the compression ratio having been chosen for this purpose).

The basic new feature was the large-diameter, thin shaft connecting the turbine and compressor, which eliminated all whirling problems and enabled two main bearings to be used—one at the front of the compressor and the other at the rear of the turbine. Hitherto, axial engines had always had a three-bearing arrangement, which necessitated a coupling in the center of the compressor-turbine shaft where the third bearing was situated. The Orpheus was the first jet engine to avoid this complication, weight, and cost. Additionally, the turbine was mounted on the shaft by Firth couplings. This simple device proved to be a very accurate centering mechanism, allowing the turbine to be removed and replaced without the need for dynamic rebalancing.

All of these features have now become standard design techniques in modern engines, but were initiated on the Orpheus and made a substantial contribution to its low cost, light weight, and reliability. The engine met all of its performance requirements, and ran like a "watch."

In the meantime, the aircraft competition had been won by Fiat, where Gabrielli had designed the G91. Hundreds of this aircraft were produced in both Germany and Italy, and the Orpheus engine was likewise produced by Fiat in Italy and Klockner-Humboldt Deutz in Germany. In fact, in the postwar era, the first 100,000 h of flying by the Luftwaffe were all with the G91 and the Orpheus.

Col. O'Driscoll had always considered short takeoff and landing to be a prime requirement in the European theater, which at that time was very short of concrete runways, all of which were highly vulnerable. Having launched the G91 and the Orpheus, he thus turned his attention to vertical takeoff and landing (VTOL).

In Paris at the time, was a famous French aircraft designer, Michele Wibault, who was unattached to any aircraft company and was being supported by Winthrop Rockefeller. Wibault had an idea for a vertical takeoff fighter, which consisted of a turbine engine (in his case the Bristol Orion engine) driving through gearboxes and cross shafts four centrifugal compressors, two on each side of the aircraft (see Fig. 2). The volutes could be rotated through 90 deg, so the

One of the foremost figures in British Aviation, Sir Stanley Hooker joined Rolls-Royce in January 1938 and in the course of 40 years has held a succession of senior appointments, finally becoming Group Technical Director. As Chief Engineer at Barnoldswick during the war, he was responsible for the design and development of early jet engines. Later, at Bristol, he was closely involved in development of the two-spool Olympus engine and pioneered the vectored thrust Pegasus. A Fellow of the Royal Society, Sir Stanley has received many awards and decorations. He was Knighted in 1974.

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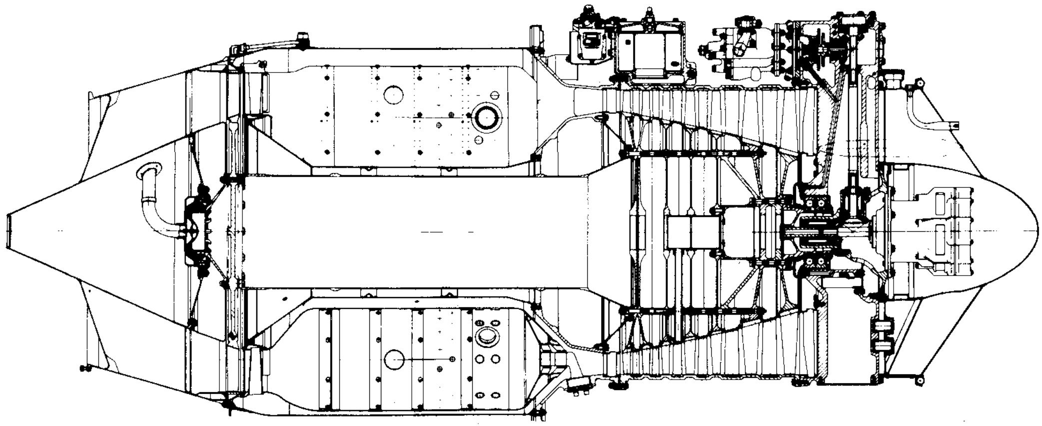

Fig. 1 Cross section of Orpheus engine.

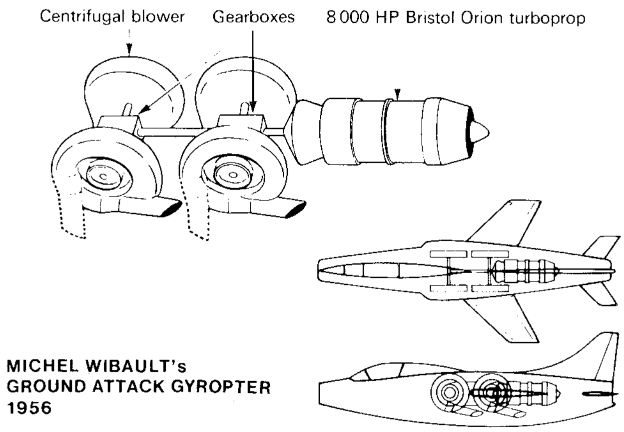

Fig. 2 Origins of thrust vectoring.

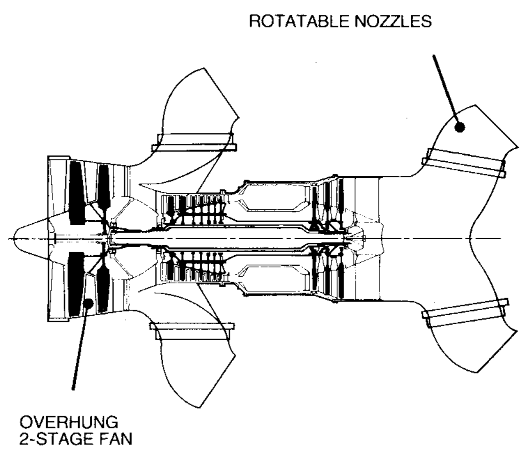

Fig. 3 Pegasus 1 engine.

jets of air from the four blowers could be directed vertically downward to lift the aircraft or rearward for propulsion. Thus, the idea of rotating nozzles was born.

O' Driscoll was interested in the Wibault concept and invited the Bristol engineers to Paris to hear a presentation by Wibault. We were not impressed, except for the intriguing idea of rotating the jets. However, we came under pressure from O'Driscoll and Professor Markham of MIT (brought in by Rockefeller) to do something about the Wibault concept. Our first idea was to substitute one axial compressor (or fan) for the four centrifugal blowers.

The Orion turboprop engine specified by Wibault had been designed for future Brittania aircraft and, in the event, never went into production. Accordingly, we abandoned this and began to look at the Orpheus engine as the powerplant to drive the axial compressor, particularly as light weight was the essence of the exercise. The resulting thrust was much too low, unless the axial compressor or fan were increased in capacity and used to supercharge the Orpheus as well as supplying the rotating nozzles.

Thus, through several variants the Pegasus 1 engine, illustrated in Fig. 3, evolved. It consisted of a two-stage fan supercharging what was essentially the Orpheus engine, the fan being driven by a two-stage turbine by a shaft through the conveniently large-diameter shaft of the Orpheus.

At this stage, Col. O'Driscoll left MWDP, and was replaced by Col. (later Gen.) Willis Chapman of the USAF. We felt this might lead to the abandonment of vertical takeoff but, on the contrary, Chapman was just as enthusiastic and continued the encouragement of MWDP. von Kármán, whom I had known from my youth, was also enthusiastic and it was the great man himself who coined the phrase "vectored thrust" when he first saw the proposed Pegasus engine.

Chapman rapidly moved to the point of ordering six Pegasus 1 engines, four for bench development and two to be held in reserve for flight in a possible aircraft yet to be designed. Again, the arrangement as to funding was 75% MWDP and 25% Bristol,

It is now 1957 and although we were working on the proposal at Bristol, it had a low priority. In fact, at that stage we were not convinced that VTOL was a practical proposition since we had not yet managed to interest any of the reputable aircraft companies in the concept. The program took on more urgency when I was suddenly summoned by Sir Sidney Camm, chief designer of the Hawker Aircraft Company at Kingston-on-Thames, to appear in his office to see the general arrangement drawing of the P1127, later the Harrier and AV8.

At that stage, the Pegasus project had rotating nozzles at the front only, the hot gas from the turbine being taken in a straight pipe. This was simply because we felt that the disposal of the exhaust gas was very much bound up with the aircraft design and could not be finalized until that was forthcoming. Camm's proposal dealt with this point, because he split the exhaust gases into two parts, each issuing through rotating nozzles on each side of the P1127.

It is worth remembering here that Camm already had experience with divided or bifurcated exhaust pipes since his first jet aircraft in 1946. The Sea Hawk had used this arrangement with the Nene centrifugal engine. I had been associated with him on that machine, but it had slipped my memory over the years.

Thus, early in 1958, the design and manufacture of the Pegasus 1 engine began in earnest. At the same time and at their own expense, Hawker began the design and manufacture of the first prototype P1127.

The calculation of the gyroscopic forces on the fan due to fighter maneuvers compared with those on the propellor of a piston engine showed that these were much higher and that the fan could, therefore, with safety be overhung so that no bearing in front of the fan would be required. This conclusion can be verified almost by inspection of Fig. 3. The radius of gyration of the fan is about one-quarter that of a typical propeller and the weight less than one-half. The rotational speeds are in the ratio 6/1 and, consequently, very approximately the ratio of Iw in the two cases is

$$\frac{\text{Fan } Iw}{\text{Prop } Iw} \frac{M_F K_F^2 W_F}{M_p K_p^2 W_p} \frac{½ \times 1/16 \times 6000}{1 \times 1 \times 1000} = \frac{1}{5}$$

and the corresponding forces in maneuver could easily be taken by a single ball bearing.

At the same time, the intake guide vanes, which were a standard feature of axial compressors and whose original function had been to keep the Mach number at entry to the compressor below 1.0, could be deleted, since the age of the supersonic fan was just beginning. This was a great simplification, since not only was a bearing eliminated but the complication of anti-icing the vanes was also eliminated.

With some trepidation, but ultimately with complete success, we decided to use an intershaft bearing at the turbine end of the Orpheus high-pressure unit. Thus the main bearings on the Pegasus were reduced to the irreducable four in number.

In consultation with Camm, we decided to go all the way and counterrotate the fan and the high-pressure unit, this being essential for the elimination of the gyroscopic forces on the aircraft during the hover and transition phases of flight. By luck and the Grace of God, the greater weight and radius of inertia of the fan and two-stage turbine was just about compensated for by the different rotational speeds of the two units and the net overall gyroscopic forces were reduced to negligible proportions.

Again, by inspection of Fig. 3, the weight of the fan and low-pressure turbine is about 1.5 times that of the high-pressure compressor and turbine and the radii of gyration in the ratio 1.5/1. The rotational speeds being approximately 10,000 rpm for the high-pressure unit and 6000 rpm for the fan, we have

$$\frac{\text{Fan}Iw}{\text{HP}Iw} = \frac{1.5 \times 1.5 \times 6000}{1 \times 1 \times 10{,}000} = 1.35$$

For counterrotation, the net force is the difference between the two angular momenta, i.e., 35%, and for the same rotational direction 235%. Thus the net gyroscopic force on the aircraft during any perturbation is reduced roughly to one-seventh by counterrotation.

We felt able to take the design risks of these untried features, and many other more minor ones, because of the experimental nature of the VTOL concept and, thus, not working to a rigid timetable or definite production schedule.

The original concept of the P1127 was that the aircraft would be stabilized during the period of hover and transition to wing lift by air "puffer" jets at the wing tips, nose, and tail, and that these would be supplied by low-pressure air from the fan and thus not affect the thermodynamic cycle of the engine. However, the size of ducts required was so large that they could not be accommodated in the wing; thus, high-pressure air direct from the combustion chamber had to be used. This inevitably involved a loss of thrust, so to recoup this, the capacity of the core, i.e., the old Orpheus axial compressor, was increased by redesigning the blading.

However, the first engine did not have this feature, and first ran in September 1959 at a derated figure of 9000 lb thrust. It served to prove that the new design features worked satisfactorily.

We gave great consideration to the nozzle operating mechanisms, since we realized that malfunctioning of these was a killer. The Plessey Company evolved a twin servo/motor unit driven by high-pressure air from the engine combustion chamber, which operated through a differential gearbox to rotate the nozzles. Thus if one motor failed, the other could still drive the nozzles, albeit at only half speed. The drive was taken from the motors by shafts and, ultimately, by chains to rotate the nozzles. There was one extra positioning lever required in the cockpit so that the pilot could set the nozzles at any desired angular position from vertically downward to the horizontal.

We had had qualms about the nozzle bearings on the rear hot nozzles. They were destined to operate in a very hot environment, since the exhaust gas temperature in the nozzles was on the order of 700°C. We discovered by chance that the fan air pressure was always greater than the jet pipe pressure, and hence a pipe from the fan outlet to a volute surrounding each bearing allowed cool fan air (about 100°C) to pass through the bearing into the exhaust nozzles, and there was no possibility of a reversal of flow. Thus the bearings were cooled and functioned perfectly.

The second Pegasus engine had the increased capacity high-pressure compressor and first ran in February 1960. It was cleared for flight, initially at 11,000 lb and subsequently at 12,000 lb with a life of 15 h.

In August 1960, the prototype P1127 complete with engine was wheeled from its hangar at the Hawker airfield in Dunsfold, Surrey, and in September 1960 the Hawker chief test pilot, Wing Commander Bill Bedford made the first historic hover flight. (See Fig. 4.) I remember suggesting to

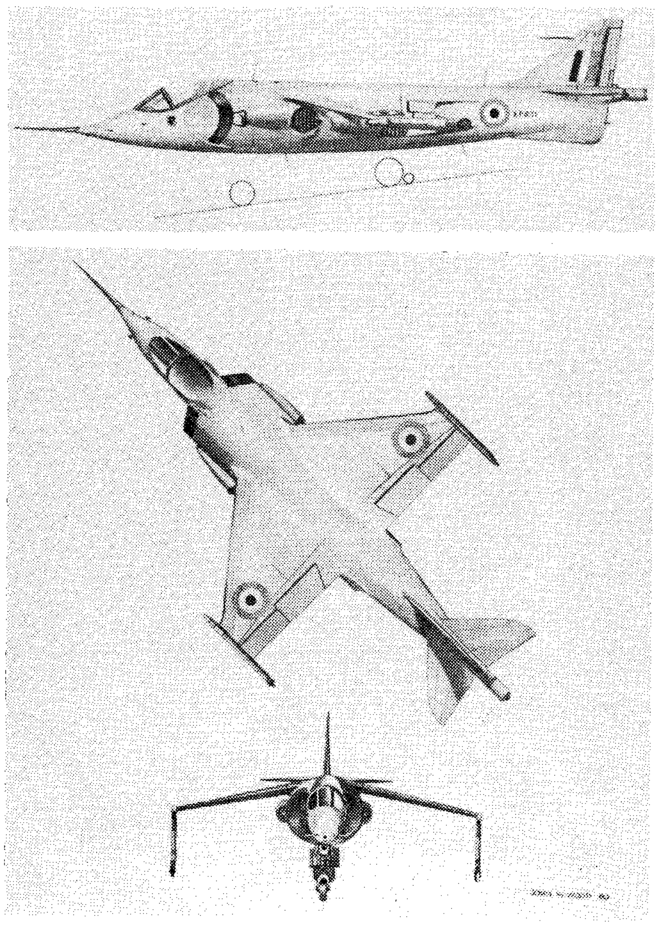

Fig. 4 Prototype of P1127 aircraft with Pegasus engine.

Camm that the first flight ought to be with conventional takeoff and landing to establish the flying qualities of the P1127. He was highly indignant! "What's that?" he said, "Hawker aircraft always handle perfectly. We shall start immediately on vertical takeoff."

However, it was not until a year later in September 1961 that Bedford made the first transition from hover to wingborne flight. I asked him what it was like, and he replied: "The aircraft went like a brick on ice!"

Much of the success of the Harrier must go to that early work by Bedford and his colleague Hugh Merryweather. They flew the P1127 with great elan and ventured into the unknown with calculated daring. Their critical experiences were of great value, particularly with regard to the necessary response rates required from the engine thrust and nozzle actuation, and also the required amount of "puffer" force for "stability" in the hover and transition modes.

As mentioned earlier, while Bristol was supported financially by MWDP, Hawker proceeded with the prototype P1127 at their own expense. We had gaily promised Hawker to supply the flight engines, when we suddenly remembered that these belonged to MWDP and were not ours to give. A meeting was arranged immediately between Col. Chapman and Sir Sydney Camm at Kingston, and immediately Chapman came through with "Of course, Hawker can have the flight engines." Thus the show was legitimately put on the road.

On the initial design of the engine, the plenum chamber which collects the air from the fan and passes it to the two front rotating nozzles was specified in fiberglass, as were the two front nozzles themselves. It seemed an ideal application for this man-made material, since the air temperatures and pressures were well inside the operational limits for fiberglass.

The early flight engines were so equipped, until Bill Bedford had a strange failure in flight. He was on a straight, level speed run when the aircraft began to vibrate badly. Not knowing what had happened, he prepared for an emergency landing; but, when he put down the nozzles for landing, the aircraft went into an uncontrollable roll. Bedford ejected safely, but the aircraft was completely destroyed.

We were still debating the cause of the accident a few days later, when a local farmer walked in with a complete fiberglass nozzle in his hand, asking if it belonged to us! All was now clear. The fiberglass nozzle had failed at its attachment flange and had been blown off. Thus the air jet came out at right angles to the flight path and, when the nozzles were put down for landing, only the undamaged one rotated, causing the aircraft to roll.

We rapidly changed the design from fiberglass to titanium, but this cracked badly on test. After a further attempt using aluminum sheet, we finally settled for steel, as on the hot nozzles which had never given any problems.

Once the P1127 had successfully made it transition flights from hover to wingborne flight, immediate attention was given by Camm and his colleagues Hooper and Fozzard to transforming the empty shell of the P1127 into a fighting machine. Naturally, much more thrust than the 12,000 lb of the Pegasus 2 would be required, and I remember Camm and Sir John Lidbury of Hawker taking me to one side and asking if 18,000 lb could be guaranteed from the engine. I replied that considerable internal modifications would be required, but the possibility was definitely there.

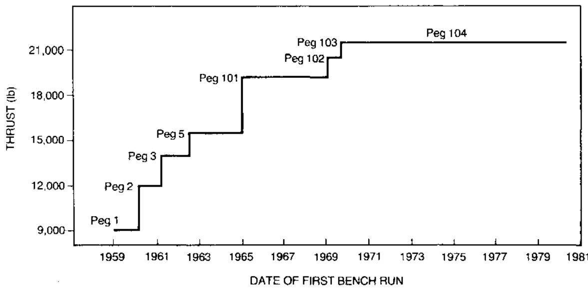

Fig. 5 Pegasus engine thrust progression.

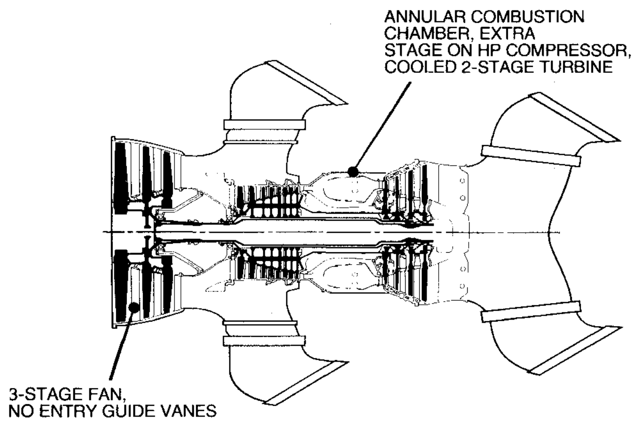

Fig. 6 Final configuration of Pegasus Mark 103.

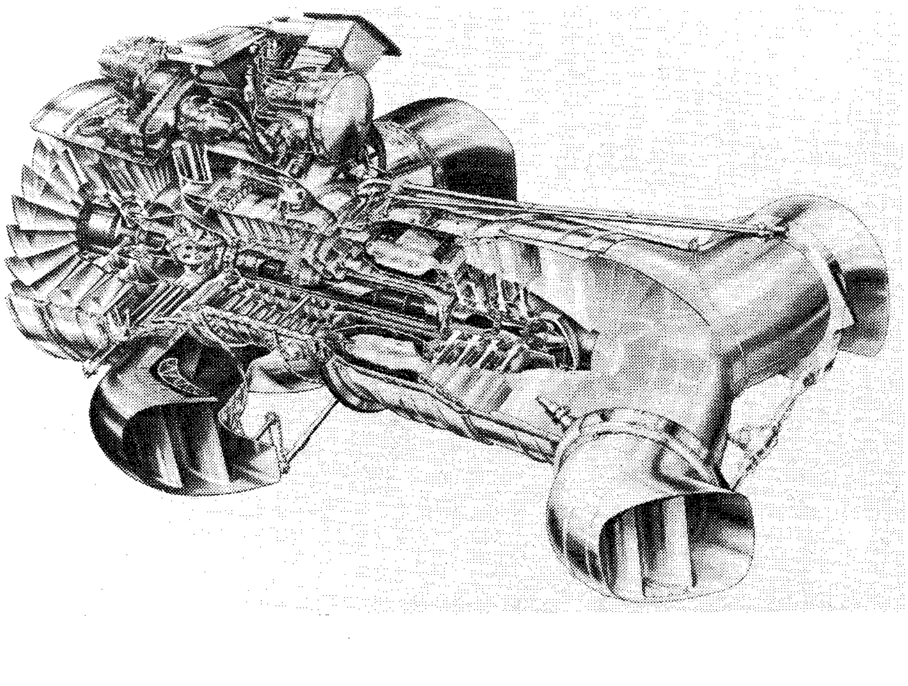

Fig. 7 Pegasus Mark 103.

Table 1 Pegasus Mark 103

Airflow	430 lb/s
Velocity and temperature of air:	
Through front jets	1200 ft/s, 110° C
Through rear jets	1800 ft/s, 670° C
Fan compression ratio	2.4/1
Overall compression ratio	Nearly 15/1
Thrust/weight ratio	Nearly 6/1

We had already modified the Pegasus 2 to give 13,500 lb thrust by adding one extra stage to the front of the high-pressure compressor and one to the high-pressure turbine (Pegasus 3), but more was required.

The fan was changed from two to three stages and the airflow increased. Variable intake guide vanes were added to the front of the high-pressure compressor, the tubular combustion chamber was changed to the annular vaporizing type (a technique we acquired when Bristol were amalgamated with Armstrong-Siddeley to form Bristol-Siddeley), and the first-stage high-pressure turbine blades were aircooled. The resulting engine was designated the Pegasus 5, giving 15,500 lb thrust.

Later, the second stage high-pressure turbine blades were aircooled, and water injection added, thus allowing the combustion temperature to be raised.

By 1965, the production specification of the Pegasus 101 was available, and the thrust raised to 19,000 lb. The final version, the Pegasus Mark 103 has now been in service for 10 years at 21,500 lb and powers all Harriers in service with the RAF and U.S. Marine Corps.

The progression of thrust over the years is illustrated in Fig. 5, and the final engine configuration Mark 103 in Figs. 6 and 7. The latter includes the gas turbine starter, which can also run and test all of the systems on the engine and aircraft for ground checks, and makes the Harrier independent of ground services and capable of operating from forward areas remote from ground bases.

Some aerodynamic and performance details are given in Table 1. With a thrust-weight ratio of nearly 6/1, the engine has maintained its preeminent position in the VSTOL field for the past 10 years.

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

1) A single engine located near the aircraft center of gravity, with a rotating nozzle system producing a thrust resultant vectorable between horizontal and vertical.

2) Engine and nozzles together forming a compact, self-contained power unit.

3) Rapid nozzle vectoring (over 90 deg/s) actuated by a powerful but lightweight air motor drive system, using engine-supplied air.

4) Short takeoff, at weights substantially greater than those which would be possible for vertical takeoff, is effective and easy, since all of the thrust is available for ground acceleration, liftoff, and transition. Also, rolling vertical takeoff and short takeoff techniques minimize the impact of jets on the ground or ship's deck.

5) The pilot has only one extra lever in the cockpit. Since the engine spools rotate in opposite directions, there is no gyroscopic effect and control of the aircraft during hover and transition is not dependent on electronic controls. Loss of power resulting from engine failure is not accompanied by asymmetric forces.

6) The single engine also means minimum development, procurement, and operating costs, as well as minimum volume which leaves more room for fuel and stores.

7) Thrust vectoring in forward flight (VIFF) can be used to increase maneuverability in combat.

Thus the vision of O'Driscoll and Chapman, and the financial support they supplied has been returned to the United States in full measure, with the U.S. Marine Corps our most enthusiastic customer. I am glad to have this opportunity to pay tribute to those two officers and their colleagues and to acknowledge the generosity of the United States government in setting up the MWDP Organization in Paris which led to two European military aircraft taking their place in NATO defenses—the Fiat G91 and the Harrier, in both of which the ancestry of the engine is so closely associated.