Developments of Aero-Engine in War 1915 to 1950: Impacts of Knowledge Management and Heuristics in the Configuration of Aero-Engine Architecture

Brian Price
Aston University

The development of technology is often observed to evolve along Darwinian lines, making use of available resources and responding to survival needs as a stimulus for change. Rapid development of piston aero-engine design for military applications during the period 1915 to 1950 provide an interesting study in a 'punctuated equilibrium' model of design, showing rapid developments during times of conflict that contrast with the relative stasis of design features and technologies during peacetime. This paper will examine a number of exemplar aero-engines developed during this period in Britain, Germany, Japan, USA, and Russia, attempting to draw general conclusions on the key drivers and constraints of piston engine evolution over this crucial period in IC engine history. The paper will review the limits of performance and show how engine configuration strategies developed for each set of national conditions prevalent at the time.

KEYWORDS: Aero, Engine, War, Knowledge, Design, Heuristics.

"It is not the strongest of the species that survive, nor the most intelligent, but the one most responsive to change."

Charles Darwin

Introduction

The development of aero-engines provides a useful exemplar of how competitive pressures, whether due to commercial competition, rival technological developments or the exigencies of war, are subject to a dynamic environment which can be thought of as analogous to a technological ecosystem. Throughout this paper the use of the term 'aero-engine' refers to piston engines used in aero applications from 1915-1950. The development of products can often be seen to progress along evolutionary lines. In this paper, we will look at a number of developments and the pressure for change and development. We will examine whether a biological model for change and evolutionary development can be applied to aero-engines and how knowledge of engines design features might be thought of as the coded DNA of the engine family.

Aero-Engine Requirements

From the earliest days of powered flight, the success, or otherwise, of airplane operation has been a function of balancing the design of airframe structure, engine performance, aerodynamics and controls systems. The need for reliable, high power-to-weight ratio engines has played a major part in enabling the expansion of the airplane's role in both commercial and military spheres. The engine and its associated systems such as fuel, cooling and controls have always been a significant proportion of the airplane take-off weight, accounting for some 15-35%, dependent upon application. This has been reasonably consistent throughout the period under consideration and specific power output has been a key metric for assessing performance growth. After the initial establishment of powered flight for regular operations, from 1920 onwards, a greater emphasis was placed on improving piston engine reliability. Considerable improvements in reliability and durability, including reduced need for regular servicing, ensured that confidence could be established in the nascent commercial flight industry. This provided not only a wider acceptance of powered flight, but also an opportunity, outside of the military, for investments into technology development, especially during the inter-war years.

Commercial operations, starting with postal delivery services and intercity commuting, progressed rapidly to longer haul international services. Airship services, through to the late 1930s, were seen as the primary means of rapid transport across oceans and to the edges of Empire. For commercial airplanes to compete with this, and given the limited establishment of aerodromes for landing and refuelling, a greater emphasis was placed on fuel efficiency for range and reduced take-off weight. Publicity for air travel through the 1920s to 1940s was boosted by a series of record breaking endeavours for range and speed, not least of these being the *Coupe d'Aviation Maritime Jacques Schneider*, more colloquially known as the Schneider Trophy. This competition formed a focus of high performance engine development for Fiat, with first the AS-2 V12 and latterly the AS-6 V24 supercharged engine of over 3,000 hp, the Curtiss V-1400 and Rolls-Royce. Most notable of these being the Rolls-Royce R engines which ultimately developed into the Merlin engine that saw such sterling service in military applications during World War II.

From this brief history, we can see that the primary measures of aero-engine success related to specific power-to-weight ratio, fuel consumption rate, absolute performance and operational acceptance as determined by reliability and serviceability, and production costs, which are related to both design features and production volume. We will use these measures as a means of evaluating the merits of designs from 1915 – 1950 and investigating the role that competition, both commercial and combative, played in spurring developments and the application of technologies.

Heuristics in Design

Heuristics are generic guidelines or rules-of-thumb, derived from previous experience and practice. They provide a framework for establishing product architecture and basic component sizing and functional specifications. Heuristics are generated from studies of similarity of successful design of earlier generations of the product, including those of the competition. Heuristics are most useful when specific information is scarce and where there is a need for rapid development, as under times of urgent progress when facing fierce competition. These are the circumstances that were faced by the aero-engines designers from 1915 onwards.

In applying these product attributes to future engine design, the engineer must engage in some key decision making processes. During the course of designing a suitable aero-engine, the engineer is engaged in defining the specification of components through the selection of appropriate geometry, materials and finish. This may include specific reference to requirements such as heat treatment or other features required for successful component life and function. Throughout this process, the designer manages a range of competing attributes to achieve a balanced, overall architecture for the engine. These attributes include weight, size, performance, engine life, cost, etc. In order to achieve these objectives, it is necessary to make a large number of decisions concerning factors such as the required strength of components, materials, manufacturing capabilities (including surface finish and tolerances), geometric arrangements, etc. In each case, the designer relies on known inputs, such as component load conditions, operating environment, temperatures, materials properties, etc. Using this information, current best practice for design calculations is applied and an iterative process is followed in order to optimize the various characteristics or attributes of the component or system under consideration. Determination of the correct component sizing is done based on validated information through the use of detailed analysis calculations of formulae derived from empirical testing. In circumstances where information is unknown or definition of geometry is at an early stage, the use of design heuristics is employed.

The use of heuristics often becomes so embedded onto the engineering culture of an operation, such that, over time, there becomes a ‘house style’ for the configuration of products and the technologies that they apply. This can be both a strength, in that the deep knowledge and experience gained from specialization allows for a through understanding and application of the particular technologies adopted. But it can be a weakness, in that there can be a tendency to establish a monoculture of ideas, particularly at an architectural or configuration level. How an organization manages the information that it uses to direct future product development is central to the success of future product. With the benefit of history, we can look back over the development of key architectural configuration decisions in aero-engines through the first half of the last century, to assess their drivers and the outcomes of these decisions.

Natural Design

Use of analogy in design work has been long established as a means of concept generation, inspiration for specific problem solving and as a mechanism for thinking about function and needs. Observation of nature as inspiration for human artefacts is as old as history. In the early 1970s the use of biological analogy and direct copying of natural forms, materials and structures in human design has been formalised under the title of 'bio-mimicry'. In the area of aeronautical developments, some of the earliest pioneers of flight directed their work to observation of natural flight in birds, from Leonardo da Vinci (1452-1519) through to Sir George Cayley (1773-1857) and Otto Lilienthal (1848-1896). This continues to the present day, where bio-mimicry is a growing area for design inspiration, being further enabled by modern materials and processing techniques. We can also usefully apply biological analogy to understand the development of technologies as an ecosystem, subject to predator/prey interactions. The commercial and military application of engine designs can 'stress' the configuration. Those designs that are most suited to success go on to replicate through continued use of design features in next generations of product. Those that are less successful in achieving their objectives disappear from use and fade from the engine landscape.

To apply this approach, we should first review how nature manages the development of features in a biological context. Within the natural environment, the growth and development of plants and animals occurs on Darwinian lines. Under this model, organisms are continually tested by the process of predator/prey interactions and the use of natural resources, to determine fitness for purpose. We can use the claw of the Atlantic Blue Crab, *callinectes sapidus*, as an exemplar of this process, Figure 1. The Blue Crab is indigenous to the western edge of the Atlantic Ocean, from Nova Scotia down to Argentina. The crab is also found in Japanese and European waters, through the Mediterranean and into the Black Sea. In each of these regions, the crab has adapted to local conditions, altering size, colouring and shell thickness in response to both local predators and prey.

The crab's claw performs several functions, including defence from predators and for mating display, but it is primarily required for feeding, where it is used to crack open the shells of bivalves and molluscs. The shell of the crab claw is moulted several times a year in the early development of the crab and constitutes a considerable investment in energy. In a similar manner to animal bone, the thickness of the claw is determined by the loading requirements that will be placed upon it through its useful life – the higher the loads, the thicker the shell of the claw is required. If the crab damages its claw by using too high a crushing force, it can starve to death due to the claw being cracked. If it develops a claw that is

Figure 1. The Atlantic Blue Crab, *callinectes sapidus*, predates on its favourite food.

unnecessarily large and powerful, it is at a disadvantage to competitors due to the larger amounts of energy required to lay the shell structure down and carry the extra weight. In this way, the claw needs to be thick enough to provide adequate crushing performance, but not so thick that it becomes a burden to the crab in weight, size or energy demand. An interesting observation that can be made concerning crab's claws is that the size and crushing force of the claw is usually closely aligned with the shell thickness of their prey. If the locality in which they feed consists of primarily thick shelled bivalves, the crab's claws will evolve to enable sufficient crushing force to open the majority of shells, but no higher. In turn, the bivalves most likely to survive will have thicker shells, resulting in the bivalve population average shell thickness increasing over time. This 'arms race' between predator and prey reaches a natural stasis, with the same species of crab and bivalve having matching crush strength and shell thickness that differs between regions i.e. weaker shelled molluscs, with weaker clawed crabs in one region and strong shelled molluscs, with strong clawed crabs in another.

The predator/prey model for biological interaction and its impact on the development of specific features can be seen as analogous to success pressures on competing product design. This is most acutely brought into focus with direct and intense competition under times of war, where protagonists are likely to develop unique technologies that are directly tested against one another and there can be clear indications of success. The question to be asked is therefore, can a biological model for product development be applied to aero-engine developments from 1915 – 1950?

Knowledge Management

If DNA is the information code that allows the optimal design of animal and plant features to progress to the next generation, then the design definitions in drawings and specifications can be thought of as the DNA of a particular aero-engine design. Those designs in terms of configuration, features and geometries, that prove most effective in use, will be carried forward to future generations of that type of aeroengine. Indeed, a distinct advantage of human knowledge management, compared to the process of biological DNA code transfer, is that the human agent is able to learn from and adopt a broader range of data sources through observation, assessment and application.

The knowledge to be used as the basis of further aero-engine developments can be from three distinct sources:

1. Original Knowledge
   Where new ideas are produced, tested out and validated, based on conceptual developments from first principles

2. Developed Knowledge
   Where extrapolations of current practice indicate the potential for improvements in performance

3. Reproduced Knowledge
   Where licensing, benchmarking or copying replicates previous successful designs

In his excellent book *What Engineers Know and How They Know It*, Walter Vincenti outlines the processes used in the early developments of aeronautical engineering knowledge from 1908-1950. In the early years of this period, enthusiastic pioneers were the wellspring of design information, based on empirical data from systematic trials. The work of the Wright brothers in building one of the first wind tunnels for wing shape developments, amongst other structured studies, are noteworthy in this regard. Gradually, with the growth of larger corporations with dedicated research and development departments, these activities became more formalized, using the mechanism of learned societies, such as the Society of Automotive Engineers and the Institute of Mechanical Engineers, to share and disseminate information. With the formation of national and industry research groups, such as the National Advisory Committee for Aeronautics (NACA – later to become NASA) in the USA, and the Royal Aeronautical Society in the UK, the development of generalized formulae for optimal aeronautical modelling became more common.

In the early period of aero-engine development, from 1915 through the 1920s, industrial enterprises still consisted of relatively small research and engineering departments. Engineering knowledge on engines configurations, such as it was, consisted of direct trial and error processes which evolved a body of knowledge that could be applied to the next generation of engines. Work progressed as a series of problem solving events, with little time or resources available to ground this in formulating theory. As organizations grew in size and had capacity to perform more structured studies, engineering best practice became codified into distinct design house styles. This was aided by the influence of a small number of key designers and engineers who played a major role in guiding engine architectures along paths that they perceived as most fruitful. Henry Royce at Rolls-Royce, Sir Roy Fedden at Bristol, F. B. Rentschler at Wright, Leonard Hobbs at Pratt & Whitney, A. A. Mikulin in the U.S.S.R., Takeo Doi and Shin Owadato of Kawasaki and Giuseppe Gabrielli at Fiat, to name but a few, took a leading role in defining the architectural arrangement of engine configurations, including the technology path that would be adopted. In some cases, companies such as Fiat & Kawasaki, were constrained by availability of in–house resources and focused on developing licensed designs. In other cases, such as the continued development of air-cooled sleeve valve engines at Bristol, this came out of a need to resolve specific problems, such as poppet valve durability and early promise indicated by testing. Once a company became committed to a technology path, it proved difficult and costly to alter direction due to not only the investments already made, but also due to the internal knowledge base being built around particular experiences of prior engines.

Competitor Benchmarking

The use of intelligence based on developments by competitors is well established in industry. This may be as benign as keeping up with the latest developments in a particular industry by reading trade publications and attending conferences and presentations at learned societies, through to the deliberate acquisition of competitor industrial secrets. During times of war, the use of intelligence to gain information of the strengths and capability of the enemy is widely known to be a major factor in successful campaigns. Less well known is the role played in understanding technical matters of enemy equipment as a means of gaining tactical advantage and building on the knowledge base of the surveyors own capabilities. During World War II formalized knowledge capture of enemy technologies was developed further than previously, with technical intelligence units being built up by all the major Axis and Allied powers. This process followed several paths and is worth noting for the role that it played in influencing engines developments.

Beginning in World War I, units were established to recover and examine enemy equipment to assess relative strengths and weaknesses. Initially, this concentrated on operational characteristics and the seeking out of ‘weak spots’ in enemy armaments. During this period, a large number of aero-engines were based on a few highly successful design, such as the Gnome-Rhone rotary and its derivatives. There was relatively little difference in competing engine designs that was not already well known to all designers in the field.

During the inert-war years, the emphasis was on development of commercial aircraft, with the major effort put into improved durability and range. There was still a healthy licensing activity that was going on world-wide, and benchmarking was mainly completed through commercial assessment of demonstrator units. The area of most competition was in racing and record breaking, such as the Schneider Trophy, where the latest developments were closely guarded secrets.

It was with the Second World War that we see the establishment of a more structured approach to the assessment of enemy technology. For example, sufficient was known for the British to publish a book in 1943 covering “Steels in Enemy Aircraft” (A Metallurgical Study of German and Italian Aircraft Engine and Airframe Parts – Arranged by CA. Otto, Kennedy Press 1943).

This not only gave details of alloy compositions and metallurgical conditions, but it also showed photographs of gears, connecting rods and drive shaft arrangements, etc. By the mid-1940s the UK, USA, Japan, Russia and Germany had all established air intelligence units. Their responsibilities now went beyond gathering data on downed aircraft, to the planned acquisition of military technology, detailed appraisal of materials, features, designs and manufacturing, through to operation of captured aircraft for establishing flight capabilities. Captured aircraft were flight tested to the limits of their capability, and were then dissected to identify design and construction secrets, as in the “tear-down” procedure. An interesting feature of these procedures was that the Germans re-engined a Spitfire with a DB601 engine, Figure 2, and the British re-engined a Me 109 with a Merlin. The knowledge gained from these exercises was used to ascertain operational weaknesses. In some cases direct copying occurred.

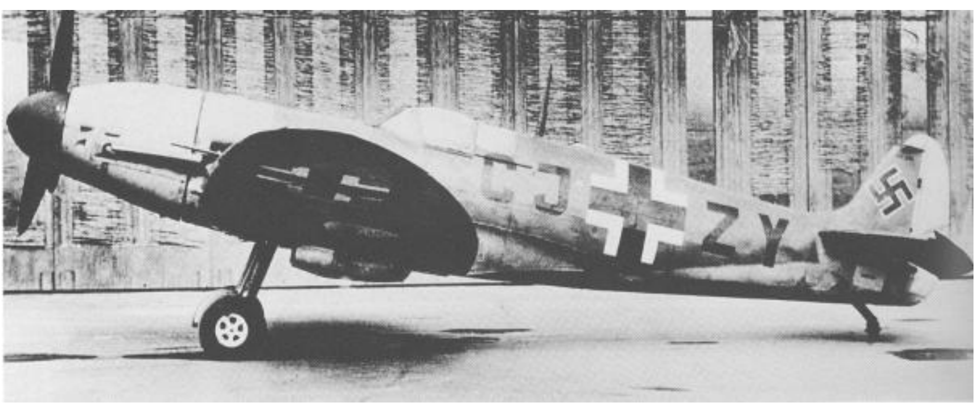

Figure 2. Captured Spitfire on test in Germany, but fitted with a DB601 engine.

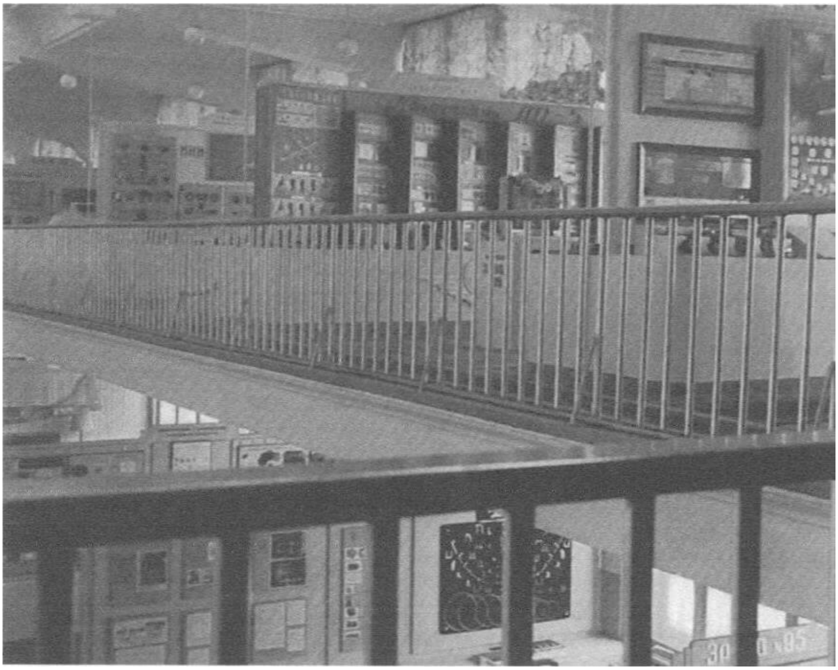

Figure 3. B-29 Tear-down and benchmarking exhibition in Moscow in 1946.

A notable example of direct copying came when several B-29 Superfortress bombers were forced to land in Russia, after completing a mission over Manchukuo and Japan in 1944. Three bombers were subsequently transported to the Tupolev design bureau in Moscow and under direct orders from Joseph Stalin, the Tu-4 “reverse engineered” copy was produced. One B-29 was stripped down to individual components for measurement and assessment. A comprehensive exhibition, Figure 3, of the components and systems was then established, so that engineers and suppliers could reference individual parts. A second B-29 was used for flight-testing and a third example was kept complete, in its original condition, for reference. The Russians already had a licence for the Wright R-3350 radial engine used in the B-29, but decided to use the Shevetsov Ash-73 18 cylinder radial, a version of the Wright R-1820 9-cylinder which they had developed, in the Tu-4. To facilitate the reverse engineering process and to help plan the programme, an exhibition of drawings and photographs was mounted at the Tupolev design offices in Moscow.

Development of Aero Engines

The development of aero-engines can be seen to follow several distinct phases. In each phase, roughly aligned with a particular decade, there were some primary drivers that influenced the direction taken for configuration and layout.

Aero-Engines Pre-1910

Early aero-engines were developed from automotive practice, adapting exiting engines for aero use or taking best practice to develop bespoke aero-engines, with an emphasis on high power to weight ratios. Power densities were relatively low, being typically 6-12 lbs. per bhp, but nonetheless sufficient for the slow airframes of the time, which required little in range or load carrying capacity. Aircraft of this era were still a novelty and used primarily for observation and short trips. Notable engines of this period were the five cylinder radial of Charles Manley, the V8 of Léon Levavasseur and in particular the Gnome five cylinder rotary designed by the Séguin brothers of France, which first appeared in 1908. With relatively simple designs, many engines had similar features and this period saw the beginnings of licensing arrangements that were to play such a large part in disseminating engine design features, in future decades, across disparate companies and regions.

Aero-Engines 1910-1920

Through the early part of the second decade of the twentieth century, progressive developments in airframe configurations, propeller function and materials improvements, meant that more could be expected of this new technology. The progress, which had been made even by 1915, in comparison to other IC engines is shown in Table 1 (by 1945 engine power densities had reached about one pound weight per horsepower). And also by 1915 there was an increased emphasis on range and load carrying capacity, as the use of airplanes for observation roles expanded into light cargo carrying and potential use as a bomber.

Table 1. Comparison of Aero-Engine with other IC engines in 1915

Engine Class circa 1915	*Lbs. per BHP*
Stationary Diesel	300-600
Marine Diesel	200-300
Submarine Diesel	60
Marine Petrol	50-80
Automotive Petrol	16-25
Aero Petrol	2-6

By 1910 more than 70 aero-engine manufacturers had sprung up, mainly in Western Europe. At the outbreak of war in 1914, lightweight and reliable aero-engines had been developed in a number of configurations, including inline, vee, rotary and radial. Rotary engines gained an early lead in terms of being a dominant form for engine configurations, the action of the cylinders rotating about a fixed crankshaft provided good air-cooling when the aeroplane was idling or taxiing in preparation for flight. Rotary configurations were successfully adopted by many airframe manufacturers and accounted for some 80% of all aero-engine installations by 1917.

The dominance of the Gnome rotary and its derivatives was challenged by manufacturers finding ways to work around the Séguin brothers patents. The Le Rhone rotary had a separate inlet and exhaust value operated by a single pushrod and rocker arrangement and the Clerget rotary used an individual pushrod for each valve. Thousand of these engines were manufactured not only by their originators, but by licensees in England, Sweden, Germany, France and the United States. Licensing provided manufacturers with a number of advantages. It allowed them to reduce their development times, as they enter production immediately with a proven design, reduced the risk in having to develop their own technology and gave some scope for cost reductions through economies of scale at a component level. There were also some distinct advantages in the ready availability and inter-changeability of parts for service and support. Eventually, manufacturers began to see some of these initial benefits as constraints. They grew to resent paying licence fees and chaffed against the limitations of not having their own technologies to provide distinction and competitive advantage. Licensees would often develop the products further, allowing them to obtain their own patents and intellectual property, which they could then exploit through onward licensing, including back to the original licence holder.

Inline engines continued to be developed, particularly in Germany, where the engines of Mercedes, Maybach, BMW, Benz and Austro-Daimler were solid and reliable. The Mercedes car, which won the TT race in 1914, was acquired by the Admiralty and provided to Rolls-Royce, where it provided the inspiration for the Hawk, Falcon and Eagle range of engines. This is yet another example of competitive intelligence at work in the industry.

The Liberty engine was produced by the USA in the early part of the war, was based on best automotive practice of the time. A V12 water cooled design, the Liberty utilized a simple structure, with interchangeable parts, for low cost and easy servicing. Other notable engines of this period were the range of Hispano-Suiza V8 & V12 water cooled engines made in France, Britain and the USA, the Curtiss OX-5 water cooled V8 and the Italian Fiat V12 water cooled A20 engine.

Aero-Engines 1920-1930

At the end of the First World War, the dominance of the rotary air-cooled format was beginning to wane. Increasingly, engines were configured with geared drives to the propeller, allowing the engines to develop higher speeds for improved power outputs, whilst matching propeller tip speed to suit airframe limitations. During this period, the development of improved cooling systems, gas and electric starters and improvements in materials and manufacturing, allowed significant strides in performance and reliability.

The range of engines developed during war conditions generally proved unsuitable for peacetime use, where the premium was on reliability and durability. Engines in the 400-450bhp range, such as the Liberty V12, BMW inline 6 and Siddeley twin radial 14, proved popular. The Aircraft Disposal Company (ADC) developed engines from surplus Renault and RAF parts. This strategy allowed production of the Cirrus 80hp four cylinder inline, later developments of which led to the Gipsy, and when inverted became the Gipsy Major. With a power output of 130hp, this became the primary light airplane engine of the 1930s. Rolls-Royce scaled up the WWI Eagle, adding four valve cylinders, to produce the Condor, with later developments producing over 650hp. European manufacturers such as Lorraine, Hispano-Suiza, Farman, BMW and Junkers, stayed with inline six water cooled engines, which proved reliable, robust and cost effective. In the USA, air-cooled radials were the norm, with the Wright Whirlwind produced in 5, 7 and 9 cylinder variants. The new Pratt & Whitney Aircraft Corporation developed the 400hp radial Wasp, which soon came to dominate US military applications. The US Navy was particularly interested in air-cooled engines as they saw the reduced weight, better reliability and lower costs as distinct advantages compared with liquid cooled designs. The initial Wasp was shortly followed by the R-1340 Wasp and R-1690 Hornet.

In Europe, the Jupiter air-cooled radial was dominant in 1920s and flown in 229 types of aircraft – being licensed to every airplane maker in the UK. The short stroke Mercury (550-950hp) was derived from this, as was the 1000hp Pegasus, demonstrating the linkage between designs, based on successful experience. Problems with engine operations could also be used as a spur for new developments. Roy Fedden at Bristol had problems with the development of twin-row four-valve engines. His solution to this was to remove the poppet valve and adopt a sleeve valve arrangement, as suggested by Harry Ricardo. Ironically, later research into the knock characteristics of fuels by Ricardo, improved valve metallurgy and designs and engine airflow regimes meant that the short term advantages of sleeve valves were surpassed. However, by the mid-thirties, Bristol had made significant commitments perfecting the sleeve valve and the company was reluctant to go back to poppet valve designs.

It was during this period that the Schneider Trophy races played such an important part in development of high specific output aero-engines. Whether from Curtiss, Fiat or Rolls-Royce, these were invariably V12 water cooled units fitted into streamlined aircraft built entirely for speed. A Curtiss D-12 engine, which powered the USA to success in 1923, was loaned to Air Ministry. Rolls-Royce examined the Curtiss engine and based features of the F-X Schneider challenger on this in 1926. Developments of this ultimately led to the ‘R’, which powered the Supermarine S.6 & S.68 to victories in 1929 and 1931 respectively. The Schneider Trophy was won outright by Britain in 1931 with the 2,783hp (0.58lbs/hp) boosted R engine, partially derived from the earlier Rolls-Royce Buzzard (825hp) and influenced by the Curtiss D-12. Great emphasis was placed on absolute power output and in this engine supercharging reached a high level of development. Materials, fuels and cooling techniques all received a boost from this focused race activity; the knowledge gained during this period later proved invaluable in development of not only the Rolls-Royce Merlin, which as derived from the Rolls-Royce R, but in other inline developments.

Aero-Engines 1930-1940

The key challenge of the 1930s was the desire to avoid issues with engine knocking. Development of fuels became critical to engine performance and ultimately, durability. The introduction of tetraethyl lead (TEL) into gasoline gave increased tolerance to detonation, but required changes to spark plugs and valves. Supercharging, although in use since the 1910s, became more widely used as a means of improving high altitude performance.

Further developments of the R-1820 Wright Cyclone took it from 500hp to over 1200hp. This in part depended on the use of 100-octane fuel. In parallel came the R2600 Cyclone 14 cylinder two row radial of 1300-1900hp. The R-3350 Duplex Cyclone was rated at 1750hp in 1939 and was to go on to develop twice as much over time. Other notable engines of the period are the Pratt & Whitney R-1830 Twin Wasp 14 cylinder, Allison V-1710 V12 cooled with a mixture of water-glycol, and the Hispano-Suiza 12Y 860-100hp, made in France and Russia. The Germans stuck with direct injection inverted V12 DB600 690hp from 1935 and the DB601 1000hp 1938, which became the mainstay of their aero-engine production. These engines, and their derivatives, proved not only successful for the German war effort, but were licensed to other Axis powers, such as Japan, where they were further, independently developed. The Junkers Jumo 210 & 211 two-stroke diesels are a rare example of the application of diesel technology to aero-engines. The initial attraction of diesels goes back to early applications in airships and a desire for low volatility fuels and efficient engines for range. Although the Junkers diesels were fuel efficient, they were considered heavy and did not extend beyond limited roles in bomber applications.

Major technical issues during the interwar period were engine cooling, especially in air cooled radials, Figure 4, and the necessity to achieve good reliability with poppet valves. Starr, in a paper in this volume, has shown how the internal cooling of valves and materials needed to evolve to cope with increased power outputs and with the introduction of fuels containing tetraethyl lead. In this paper we also highlight the improvement in the finning of air-cooled radials. Although finning had been required on rotary engines, the actual dimensions were not too critical since the engines were of low output and the rotation of the cylinders ensured a good airflow at all times. When engine designers moved over to radials, fin design became absolutely critical. The only source of cooling air was

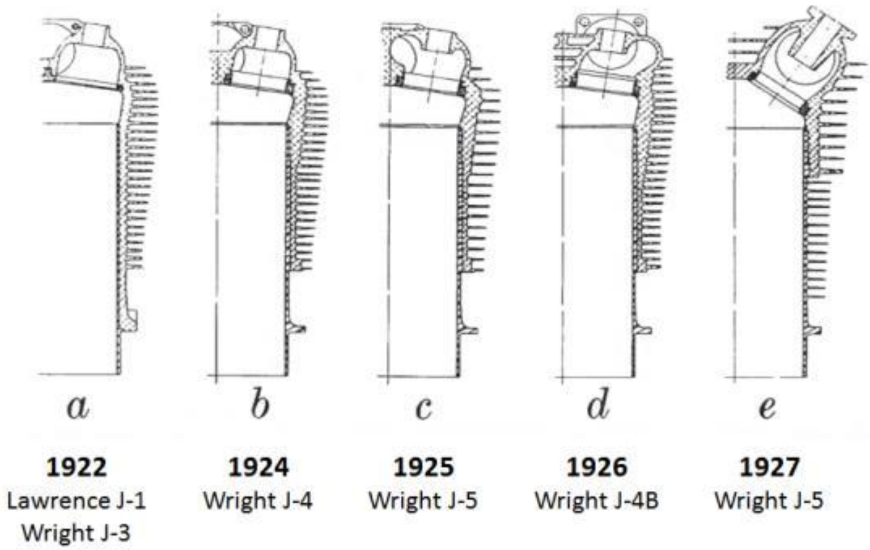

Figure 4. Evolutionary developments of Wright cooling fins.

from the forward motion of the aircraft. Too much airflow represented a drag penalty, too little, engine overheating. The switch from rotaries to radials can therefore be represented as the need for engines of a "mutated" radial form to have to survive in a vastly changed environment.

However, once initial success had been achieved in the new environment, evolution continued, as can be seen with the first few years of development of the Wright radials, which were developed from the semi-successful Lawrence. The whole subject of the cooling of radial engines can be analysed from the point of view of evolutionary pressures, as severe competition was coming from the streamlined liquid cooled in-line. Survival depended on a major genetic change, namely the Townend ring, and its subsequent evolution by NACA.

Aero-Engines 1940-1950

Under the intense pressures of war, evolutionary developments of existing engine designs reached their zenith. The Rolls-Royce R developed into the Merlin V12 with two-stage supercharging and a host of detail improvements for reliability and durability. Over this period, power output of the Merlin progressed from just over 1200 hp in 1939 to over 2800 hp by the final years of the war, assisted by increased boost pressures up to 30lbs/in^2 and use of 115/145 grade fuel by 1945. Both Rolls-Royce and the American Packhard company continued developments of the engine for fighter and bomber applications. The Packard V-1650 versions were rated at over 2000hp, despite reductions in costs and improvements in quality by applying high volume automotive best practice being used to simplify many design features and reduced use of high tolerances for geometry and surface finish. Radial engines continued to play a role, with the Hercules and 18 cylinder Centaurus radials providing Britain's most powerful piston engine at 3,270hp. Both the Hercules & Merlin were mass-produced in standard cradles, allowing either to fit the Lancaster, Halifax or Beaufighter bombers. Moves to rationalize inter-changeability of complete engines like this were also used by Germany, an example being the Ju 88 bomber, which could take either a DB801 radial or a Jumo 211 and 213 inverted vee configuration, mounted on common location points. There was continued interest in novel engine configurations some of which reached production. The chief example was the Napier Sabre, an H type. The Sabre also incorporated sleeve valves, which were only made to work properly after assistance from Bristol, this being a good example of the transfer of heuristic knowledge from one manufacturer to another. It is extremely doubtful whether this would have occurred unless wartime needs had been more of a competitive spur than normal commercial threats. However, in general innovative engines were less successful and never achieved the volumes of the radial and vee types.

In the USA, Pratt & Whitney R-2800 Double Wasp 18 cylinder of 1800-2800hp was superb and used in large numbers of military and civil aircraft. Even larger numbers of R-1830 Twin Wasp were used in Consolidated B24 and Wright R-1820 Cyclone being used in Boeing B-17. The benefits of higher volume manufacturing were seen in reduced cost, easier field support and a more steady supply of material for the war effort. One of the mainstays of US engine production was the Wright R-3350 18 cylinder twin turbo used in Boeing B-29, producing from 2200 hp to over 3700 hp. The apex of radial engine output during this period was the Pratt & Whitney R-4360 Wasp Major quad row (4x7 cylinder) produced over 4300hp on 115/145 fuel.

German aero-engine production of the period, was dominated by the BMW 801 radial of around 2000 hp and the Daimler Benz DB603 & DB605 engines. These were licensed to a number of axis powers and formed the basis of independent developments. Italy, Russia, and Japan all struggled during this period to do more than evolutionary development of existing engines and problem solving of immediate issues. This was primarily due to the pressures of war on resources, availability of materials and a reliance on licensed engines.

With the advance of gas turbines towards the end of World War II, the writing was on the wall for piston for higher power applications. Stretched to their limits, both the air-cooled radial and liquid-cooled vee large displacement aero-engines were complex, expensive and heavy compared with their gas turbine rivals. Improved reliability and durability of the gas turbine through the late 1940s and into the 1950s, combined with greater range, quietness and negligible vibration, saw the end of further serious development of large piston aero-engines. War surplus piston engines continued to be used, as they had after the First World War, for more than a decade, based mainly on low cost and availability. But eventually, only smaller piston engines continued to be developed for use in light aircraft, where their simple maintenance and low cost provided an advantage in propeller applications.

National and Corporate Trends in Aero-engines Developments

From this brief review of the development of aero-engines up until 1950, we can see the formation of some national and corporate characteristics. With two major periods of war between 1915 and 1950, as well as the emergence of commercial flying, companies were set up in response to military orders and the need for a range of engines that was competitive for both cost and performance. This led to designs coalescing around single, dominant, configurations within an organization, often championed by a technical leader within the business. This was a natural outcome from heavy investment in a particular technology and the result of developed knowledge. For larger organizations, particularly during times of stability, there was the opportunity to experiment with new configurations, usually prompted by the desire to resolve a particular issue, such as a packaging constraint or power density issue. In terms of our biological analogy, this is akin to mutation or rapid development in response to environmental stress.

For most corporations, this was not an option, as they had neither the resources nor know-how to experiment on this scale. For those companies, the usual route was to license a successful engine, learn from its operation and make incremental changes to improve performance over time. In particular, this was the route chosen by Russian and Japanese companies, much to the frustration of their own engineers, who were in all regards, as capable as those of Europe and the USA, but simply lacked the resources and political support to develop their own engines on the same scale as their allied opponents. Italy was a particular case were they were often class leading in the 1920s and 1930s, but lost this lead through the exigencies of war, where they were reduced to the manufacture of licensed engine from Germany or the continued production of outdated units. This approach of judicious replication and development can be thought of as progressive Darwinian evolution under our biological model.

A significant national difference between the US and Britain was the emphasis on simplification of designs to reduce costs and ease mass production in the US, whereas British aero-engines gained in complexity through the 1940s in the pursuit of performance. The US contributed much through the application of high volume automotive approaches to improvements in quality and output of aero-engines during World War II, whether of domestic radial designs or the Packard V-1650 versions of the Merlin engine.

It was expected that a biological model might show most rapid growth of engine types during the periods of highest stress, i.e. during war conditions, and that in the absence of such strong drivers, developments would be relatively static, such as during periods of peace. A review of the periods of most dynamic configuration assessment however, as characterised by variants in production, indicates that this is not the case. Indeed, during both World Wars, engine variants rapidly diminish to a relatively few types that are mass-produced in order to satisfy volume demands, whilst minimising technical risk. Developments come through rapid evolutionary change at a component and feature level, with hardly any configuration or arrangement experimentation. Conversely, periods of relative calm in commercial and political spheres, gave breathing room for more speculative experimentation, partially stimulated by a desire for glory through racing or in the approach of an expected conflict. The most creative periods were just before World War I, the interwar years, and right at the end of World War II.

A measure of development of aero-engines is linked to their absolute performance, the speed capability of the engines and the displacement required to achieve this output (hp/1000rpm/cu.in.). Using this metric for a range of representative military and commercial aero-engines from Europe, USA, Russia and Japan we can see some broad trends in aero-engine developments. Figure 5 shows us four broad phases of development:

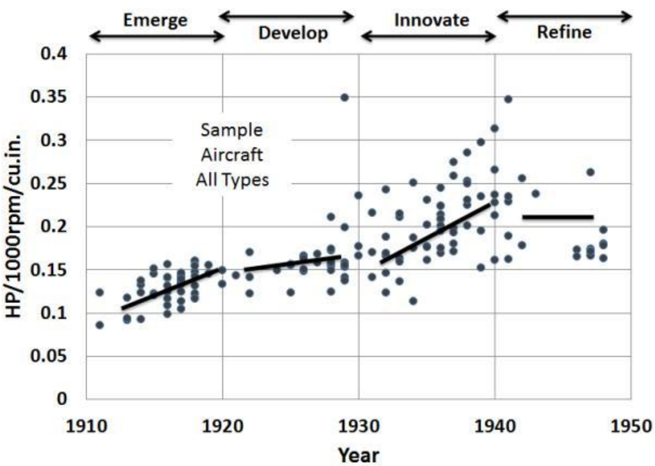

Figure 5. Phases of aero-engine development.

Emergence – From the initial developments of bespoke aero-engines, through to 1920, this phase is characterised by a rapid development of the technology based on rotary and radial engines. A few key designs were developed, as issues of reliable performance were resolved. The First World War provided an impetus for consolidation of designs, with engines produced in such large quantity that they provided a cheap stock of engines for commercial use immediately after the cessation of conflict.

Development – From 1920-30 developments of new configurations gathered pace, with the wider introduction of inline, liquid cooled and radial engines. These formed the basis of all major configurations that were to be exploited over the next 30 years, but none were produced in great numbers and apart from the exceptional development of the Schneider Trophy race engines, none had significant performance growth.

Innovation – The 1930s saw improvements through materials, fuels and detail design changes. Learning from racing and previous generations of engines was applied to a variety of configurations and types. Much experimentation occurred in this period, as manufacturers sought solutions to the challenges of ever higher specific output.

Refinement – From 1940 onwards, the aero piston engine developments concentrated once more on refinement of existing designs, with a premium placed on reliable operation, volume production and performance improvements brought by the relatively evolutionary development through fuels and supercharging.

This analysis provides an overview of aero-engine trends, but it can be nonetheless useful as a means of evaluating macro drivers for decisions made about engine configuration.

Conclusion

Biological analogy can provide a useful model for the evaluation of technological developments, however when applied to aero-engines, the model proves somewhat inadequate in replicating the modes of developmental progression, failing to fully explain how periods of maximum innovation occurred during periods of relatively low environmental stress. Indeed, the greatest performance improvements appear to have come through steady, evolutionary development of stable designs, rather than through innovative changes in engines configurations.

The important use of design knowledge and the underappreciated role of licensing and competitive benchmarking give us clues as to the transmission of engineering DNA through the design ecological landscape. This is worthy of more extensive study.

What is worth remarking on is how closely piston engine development has mimicked evolutionary trends in the animal world. One obvious analogy is the final period of the dinosaur era, when land animals rose to a gigantic size, but vanished almost overnight, despite their ferocity. Similarly the big piston engine really could not go much further and was waiting for the fall. Increased engine output could only be obtained by progressing to four row radial engines, or by creating “X” configuration engines by effectively adding together two vee type designs. The jet engine was to the big piston, was as the “asteroid collision” was to the dinosaurs.

Furthermore, just as with the evolutionary tree, branches prospered for a time, only to die off under the competition from a more adaptable species. One thinks of the Neanderthals and Homo Sapiens. For engines, the analogy has got to be the rotary and the radial. But one does end this paper with an "alternate history" thought about which form of piston engine would have won out if the jet engine had not come to fruition. Which was really the best, the big air-cooled radial or the big liquid-cooled engine? And as this conference never got to decide, would these engines have used poppet or sleeve valves?

Acknowledgements

The author is indebted to Dr Fred Starr for his comprehensive review of this paper and additional contributions, particularly in area of materials developments and poppet vale design evolution.

Bibliography

Use has been made of several seminal texts in the history of aero-engine developments throughout this paper.

E.W. Constant, "A model for Technological Change Applied to the Turbojet Revolution", *Technology and Culture* Vol. 14, No. 4 (October 1973), pp. 553-572.

J.F. Hanieski,, "The Aeroplane as an Economic Variable: Aspects of Technological Change in Aeronautics 1903-1955", *Technology and Culture* Vol. 14 No. 4 (October 1973), pp. 535-552.

F.W. Geels, "Co-evolutionary and Multi-level Dynamics in Transitions: The Transformation of Aviation Systems and the Shift from Propeller to Turbojet (1930-1970)", *Technovation* 26 (2006), pp. 999-1016.

W.G. Vincenti, *What Engineers Know and How They Know It* (John Hopkins University Press, Baltimore, 1992), pp. 200-256.

H. Smith, *A History of Aircraft Piston Engines* (Sunflower University Press, Manhattan, 1981).

K. Frenken and L. Leydesdorff, "Scaling Trajectories in Civil Aircraft 1913-1997", *Research Policy* 29 (October 1985), pp. 331-348.

K. Macksey, *Technology in War Engines* (Guild Publishing, London, 1986), p. 106.

Y. Gordon and Y. Rigmant, *Tupolev Tu-4* (Midland Publishing, Hinckley, 2002).

R. Mikesh, *Zero* (MBI Publishing, Osceola, Wisconsin, 1994).

T. Suzuki, *The Romance of Engines* (Society of Automotive Engineers, Warrendale, USA, 1997).

J. Liston, *Aircraft Engine Design* (Maple Press Company, York, Pennsylvania, 1942).

A.P. Fraas, *Aircraft Power Plants* (McGraw-Hill, New York, 1943).

W. Green, *Famous Fighters of the Second World War* (Doubleday, New York, 1975).

P. Jarrett, *Biplane to Monoplane: Aircraft Developments 1919-39* (Putnam Aeronautical Books, London, 1997).

E. Angelucci, *The Rand McNally Encyclopedia of Military Aircraft* (Rand McNally & Company, Chicago, 1981).

C.H. Chatfield,., C. Fayette Taylor, C.H.,Shatswell Ober, *The Airplane and its Engine*, (McGraw-Hill, New York, 1949)

G.W. Gray, *Frontiers of Flight: The Story of NACA Research* (Alfred A. Knopf, New York, 1948).

G.A. Burls, *Aero Engines* (Griffin Publishing, London, 1915).

A. Nahum, "Two Stroke or Turbine? The Aeronautical Research Committee and British Aero Engine Development in

World War 2", *Technology and Culture* Vol. 38, No. 2 (April 1997), pp. 312-354.
D. Mondey, *International Encyclopaedia of Aviation* (Hamlyn, London, 1988), pp. 33-49.
H-H. Stapfer, *Strangers in a Strange Land* (Squadron/Signal Publishing, Carrollton, Texas, 1988).
J.R. Smith, E.J. Creek and P. Petrick, *On Special Missions: The Luftwaffe's Research and Experimental Squadrons 1923-1945* (Classic Publications, Hersham, 2003).
W. Gunston, *The Development of Piston Aero Engines* (Haynes Publishing, Yeovil, 1999).
V. Kotelnikov, *Russian Piston Aero Engines* (Crowood Press, Marlborough, 2005).
V. Bingham, *Major Piston Aero Engines of World War II* (Airlife Publishing, Shrewsbury, 1998).
E. Weibel, C.R. Taylor, and L. Bolis, *Principles of Animal Design* (Cambridge University Press, Cambridge, 1998), pp. 312-354.
G.J. Vermeij, *Nature: An Economic History* (Princeton University Press, Princeton, 2004), pp. 70-1.

Notes on Contributor

Brian Price is an academic based at Aston University in the UK, teaching engineering and product design. Active research areas include ultra low carbon vehicles, charging/fueling networks and engine/transmission design. With over 25 years experience in industry, working worldwide on engine design consultancy, he brings a pragmatic approach to new product development. Previously chief engineer or technical director at Lotus Engineering, Cosworth Technology, Mercury Marine, Harley-Davidson and Ricardo, he is also a visiting professor at Loughborough University, UK, University of Wisconsin-Madison, USA and Hanyang University, South Korea. Correspondence can be addressed to b.j.price@aston.ac.uk