

# Source Data for NMUSAF\* Piston Engine Tour

*\*National Museum of the USAF, Dayton, OH*

**Initial Release**

**30 May, 2023**

**This is NOT a NMUSAF document, nor is it endorsed by the NMUSAF in any way.**

This is an informal training document for Docents giving the “History of Aviation Piston Engines” Tours. That tour was approved on May 8, 2023 by the NMUSAF and is currently presented by Bob Dana, Bob Recchiuti, and Jeff Robeson.

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# Source Data for NMUSAF Piston Engine Tour

This draft is intended as training material for tour guides for the “History and Evolution of Aircraft Piston Engines” to provide a factual and consistent foundation for the tour. It is divided into four sections as follows:

## 1- Primary Engines for Tour

These engines have been selected to be normally addressed in each tour and are listed in the order encountered as the tour progresses in the normal chronological path through the Early Years, WWII, and Korean War galleries. Each tour guide should familiarize himself/herself sufficiently to address each engine during the tour. He/she should draw from “Talking Points” provided for each engine to provide an overview, and may draw on additional information provided as appropriate for individual audiences or in response to questions.

## 2- Topics Related to Aircraft Piston Engines

Each tour guide should also familiarize himself/herself with this supplemental material. It is primarily intended to allow the guide to address questions that are not for a specific engine but more general in nature. The tour guide might also choose to include some of this material in his/her tour, regardless of questions.

## 3- Backup Engine Information

This section provides optional information on other engines not designated as primary engines but which may be encountered while following the tour path. The tour guide is not required to study this material, but it is offered as a resource for those interested.

## 4- Endnotes, Bibliography, and Appendices

This page provides sources used throughout this document and clarifies use of the endnotes.

This material has been extracted from numerous credible sources and the material has been arranged to flow like a narrative under each topic. A goal was to minimize redundant material from these diverse sources.

*Note that red italic font is only used for various editorial comments and often does not draw on material from the sources in the bibliography.*

# Table of Contents

<b>PRIMARY ENGINES FOR TOUR</b>	6
Wright Engine (On 1909 Flyer)	8
Curtiss OX-5	9
Tour Choice regarding Rotaries	12
Le Rhone C-9	12
Gnome N-9	14
Hispano-Suiza Model A	15
Packard Liberty 12A	17
Salmson Z-9	20
Wright J-5 Whirlwind Engine	22
Curtiss D-12	25
Wright R-2600 Cyclone 14	27
Wright R-1820 Cyclone	29
Allison V-1710	33
Packard V-1650 Merlin	34
Wright R-3350 Duplex Cyclone	36
Pratt & Whitney R-4360 Wasp Major	39
<b>TOPICS RELATED TO AIRCRAFT PISTON ENGINES</b>	49
History of the National Museum of the USAF51	49
Early Aircraft Propulsion - Through 1918	49
Piston Engines After 1918	51
Curtiss Engines After 1918	51
Rotary Engine Introduction	51
Introduction to the Radial Engine	52
Why Radial Engines Always Have an Odd Number of Cylinders	52

Hydraulic Lock and Prop Walking	53
Cam Rings Replace Camshafts in Radial Engines	54
Air vs. Liquid Cooling	54
The End of Separate-Cylinder Liquid-cooled Engines	55
Wright Engines up to Split Leading to P&W	55
Rentschler and the Formation of Pratt & Whitney	56
Improvements in AvGas	56
Ethylene Glycol	57
Drag Considerations	57
Carburetor Progress Between the Wars	58
A Brief Note on Fuel Injection Systems	58
Water injection	59
Brief Background on the Rolls-Royce Merlin Origins	59
Scaling	60
Propeller Technology	60
Reduction Gear Influence on Configuration	62
Ignition Systems	62
Magnetos	62
Supercharger	62
Glenn Curtiss	64
Two-stroke Engines	64
A Caution on Power Ratings	64
Piston Engines Today	65
Notes on Engine Manufacturers	65
<b>BACKUP ENGINE INFORMATION</b>	68
Fiat A-12	68
Anzani (On Bleriot Monoplane - removed Feb. 2023)	68

Roberts Model 4-X	69
Wright 6-60	69
Sturtevant 5A	70
Curtiss V2-3	70
Hall-Scott Engine	71
King-Bugatti U-16	71
Bentley B.R.2	72
Lorraine-Dietrich 8Be	72
R.A.F. 1A	73
Anzani 10	73
Benz BZ.IV	74
Renault 12-F	74
Curtiss K-12	75
Rausenberger (Rausie) E-6	76
Packard DR-980 Diesel	76
Liberty 12A Inverted	77
Curtiss V-1570 Conqueror	77
Almen A-4 Barrel Engine	78
Pratt & Whitney R-985 Wasp Jr.	78
Ranger L-440	78
Pratt & Whitney R-1830 Twin Wasp	79
Pratt & Whitney R-2800 Double Wasp	79
Pratt & Whitney R-1340 Wasp	81
Rotax 912 UL	82
Allison V-3420	82
<b>ENDNOTES, BIBLIOGRAPHY, &amp; APPENDICES</b>	84
Sources Used in this document:	84
Additional references (not used in this document)	86
Appendix A - Piston Engines in NMUSAF Aircraft	87

# PRIMARY ENGINES FOR TOUR

The table on the following two pages represents an inventory of aircraft piston engines that are on display in the NMUSAF as of December 2022. The engines highlighted in yellow are the engines chosen as the primary engines for the tour. Note all of these engines are uninstalled except for #3.

ABS SEQ	GAL	NAME	A/C NEARBY	LOC DETAILS	TYPE	CYL	COOLING
1	EY	FIAT A-12	CAPRONI Ca. 36	AT TAIL	I	6	L
2	EY	CURTISS FOUR CYLINDER	CURTISS 1911 MODEL D	BENEATH	I	4	L
3	EY	WRIGHT (INSTALLED)	1909 FLYER	INSTALLED	I	4	L
4	EY	WRIGHT 6-60	SPAD VII	CASE AT STBD WING	I	6	L
5	EY	ROBERTS MODEL 4-X	SPAD VII	CASE AT STBD WING	I	4	L
6	EY	KIRKHAM 4-CYL	SPAD VII	CASE AT STBD WING	I	4	L
7	EY	STURTEVANT 5A	SPAD VII	ON WALL OPP	V	8	L
8	EY	CURTISS V2-3	SPAD VII & AVRO 504K	BETWEEN	V	8	L
9	EY	CURTISS OX-5	SPAD VII & AVRO 504K	BETWEEN	V	8	L
10	EY	LeRHONE C-9	AVRO 504K	PORT WING	RO	9	A
11	EY	OBERURSEL UR2	NIEUPORT 28	WALL NEAR PORT WING	RO	9	A
12	EY	GNOME N-9	NIEUPORT 28	CASE NEAR PORT WING	RO	9	A
13	EY	HISPANO-SUIZA MODEL A	SPAD XIII	PORT WING	V	8	L
14	EY	KING-BUGATTI U-16	FOKKER D.VII	BENEATH	X	16	L
15	EY	LIBERTY L-8	LUSAC & DH-4	BETWEEN	V	8	L
16	EY	LIBERTY L-6	LUSAC & DH-4	BETWEEN	I	6	L
17	EY	LIBERTY L-4	LUSAC & DH-4	BETWEEN	I	4	L
18	EY	PACKARD LIBERTY 12A	LUSAC	PORT WING	V	12	L
19	EY	R.A.F. 1A	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	V	8	L
20	EY	ANZANI 10	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	RA	10	A
21	EY	BENZ BZ.IV	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	I	6	L
22	EY	CURTISS K-12	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	V	12	L
23	EY	LORRAINE-DIETRICH 8Be	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	V	8	L
24	EY	RENAULT 12-F	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	V	12	L
25	EY	BENTLEY B.R.2	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	RO	9	A
26	EY	BRITISH ABC WASP	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	RA	7	A
27	EY	SALMSON Z-9	CAPRONI Ca. 36	BETWEEN Ca. 36 & EY ENTRANCE	RAD	9	L
28	EY	WRIGHT J-5 WHIRLWIND	AMBULANCE	AT REAR	RAD	9	A
29	EY	RAUSSENBERGER (RAUSIE) E-6	THOMAS-MOORE S4C	BEHIND	I	6	L

ABS SEQ	GAL	NAME	A/C NEARBY	LOC DETAILS	TYPE	CYL	COOLING
30	EY	WRIGHT T-3 TORNADO	THOMAS-MOORE S4C	BEHIND	V	12	L
31	EY	CURTISS R-600 CHALLENGER	THOMAS-MOORE S4C	BEHIND	RA	6	A
32	EY	PACKARD DR-980	THOMAS-MOORE S4C	BEHIND	RA	9	A
33	EY	LIBERTY 12-A INVERTED	THOMAS-MOORE S4C	STBD WING ON WALL	V	12	L
34	EY	CURTISS D-12	P-6E HAWK	IN FRONT	V	12	L
35	EY	CURTISS V-1570 CONQUEROR	P-6E HAWK	IN FRONT	V	12	A
36	EY	LAWRANCE L-4S	ROMA DISPLAY	ON WALL BEHIND CABINETS	RA	3	A
37	EY	ANSALDO ENGINE	ROMA DISPLAY	ON WALL BEHIND CABINETS	V	12	L
38	EY	ALMEN A-4 BARREL ENGINE	B-10	BEHIND IN CORNER	B	18	L
39	EY	WRIGHT R-1820 CYCLONE	B-10	FRONT AT PORT WING	RA	9	A
40	EY	PACKARD 3A-2500	B-10	FRONT AT STBD WING	V	12	L
41	EY	RANGER L-440	A-17A	STBD WING	I	6	A
42	EY	WRIGHT GIPSY L-320	HURRICANE & BT-14	BETWEEN	I	4	A
43	WWII	WRIGHT R-2600 CYCLONE 14	B-25	STBD WING	RAD	14	A
44	WWII	ALLISON V-1710	P-39	AT WALL OFF STBD WING	V	12	L
45	WWII	PW R-985 WASP JUNIOR	AT-11 KANSAN	BENEATH AT REAR	RA	9	A
46	WWII	P&W R-1830 TWIN WASP	B-24	BENEATH STBD WING	RA	14	A
47	WWII	WRIGHT R-1820 CYCLONE	B-17F	FRONT OF STBD WING	RAD	9	A
48	WWII	ALLISON V-1710	P-38	AT PORT WING	V	12	L
49	WWII	PACKARD V-1650 MERLIN	P-51D	AT STBD WING	V	12	L
50	WWII	P&W R-2800 DOUBLE WASP	P-47D "GINGER"	AT NOSE	RA		A
51	WWII	WRIGHT R-2600-13	A-20G	PORT SIDE	RA	14	A
52	WWII	WRIGHT R-3350 DUPLEX CYCLONE	B-29	PORT SIDE	RAD	18	A
53	WWII	FRANKLIN O-405-9	KAWANISHI GEORGE	OFF STBD WING	O	6	A
54	KOR	P&W R-4360 "WASP MAJOR"	C-124	STBD SIDE	RA	28	A
55	CWG	CONTINENTAL O-470-13A	T-34A MENTOR	BENEATH	O	6	A
56	CWG	P&W R-4360 "WASP MAJOR"	B-36	UNDER PORT WING	RAD	28	A
57	CWG	ROTAX 912	MH-53	PORT SIDE OF TAIL ROTOR	O	4	A
58	R&D	ALLISON V-3420	FISHER P-75A	NEARBY	*	24	L
59	R&D	AFRL PDE	LONG-EZ BOREALIS	NEARBY, ON GROUND	*	8	L

## Wright Engine (On 1909 Flyer)

The Wright Brothers four-cylinder vertical water-cooled engine was rated 30/35 horsepower at 1200 RPM and was said to deliver 39 hp at 1600 RPM. Total displacement was 240.5 in.<sup>3</sup> and the weight was 180 pounds. Individual cast iron cylinders were jacketed only around the barrels with thin aluminum jackets and had no provision for head cooling. Interchangeable valves stood vertically in the cylinder heads; the inlets operated automatically, and the exhaust by pushrods and rockers from a camshaft in the crankcase. The crankshaft is fitted with a flywheel, and two sprockets which drove two propellers by chain at a 0.272 ratio. No carburetors are used; a small gear pump discharged the fuel into the open bell mouthed end of the inlet pipe through a small jet orifice which regulated the amount of fuel to each cylinder. Lubrication was force-fed by a gear pump driven from the camshaft. Cooling water was circulated by a centrifugal pump, and magnetos furnished ignition.<sup>4</sup>



*Wright engine on Wright 1909 Military Flyer, from front and rear (Robeson photos)*

The “Vertical Four” engine was developed primarily by Orville Wright in 1906 and became the primary powerplant for their aircraft for the next 10 years, including the 1908 Model A, the 1909 Military Flyer, and the 1911 Model B. Approximately 125 Model B’s were made in the US and Europe between 1910 and 1915. It was the final production engine design of the Wrights, although a later 6-cylinder version was developed.<sup>24</sup>

It had a compression ratio of 4.7:1, was liquid cooled, and had a splash-type lubrication system with circulation by pump and gravity.<sup>24</sup>

Greg Cone is the Wright Experience’s specialist in antique engines. He previously restored the Wright Vertical Four engine, Serial #20, making it the only original operating Wright engine in the world. (Note this source is undated so it is unknown how recently this old engine ran.) It was demonstrated at Oshkosh in 2000 and 2001.<sup>24</sup>

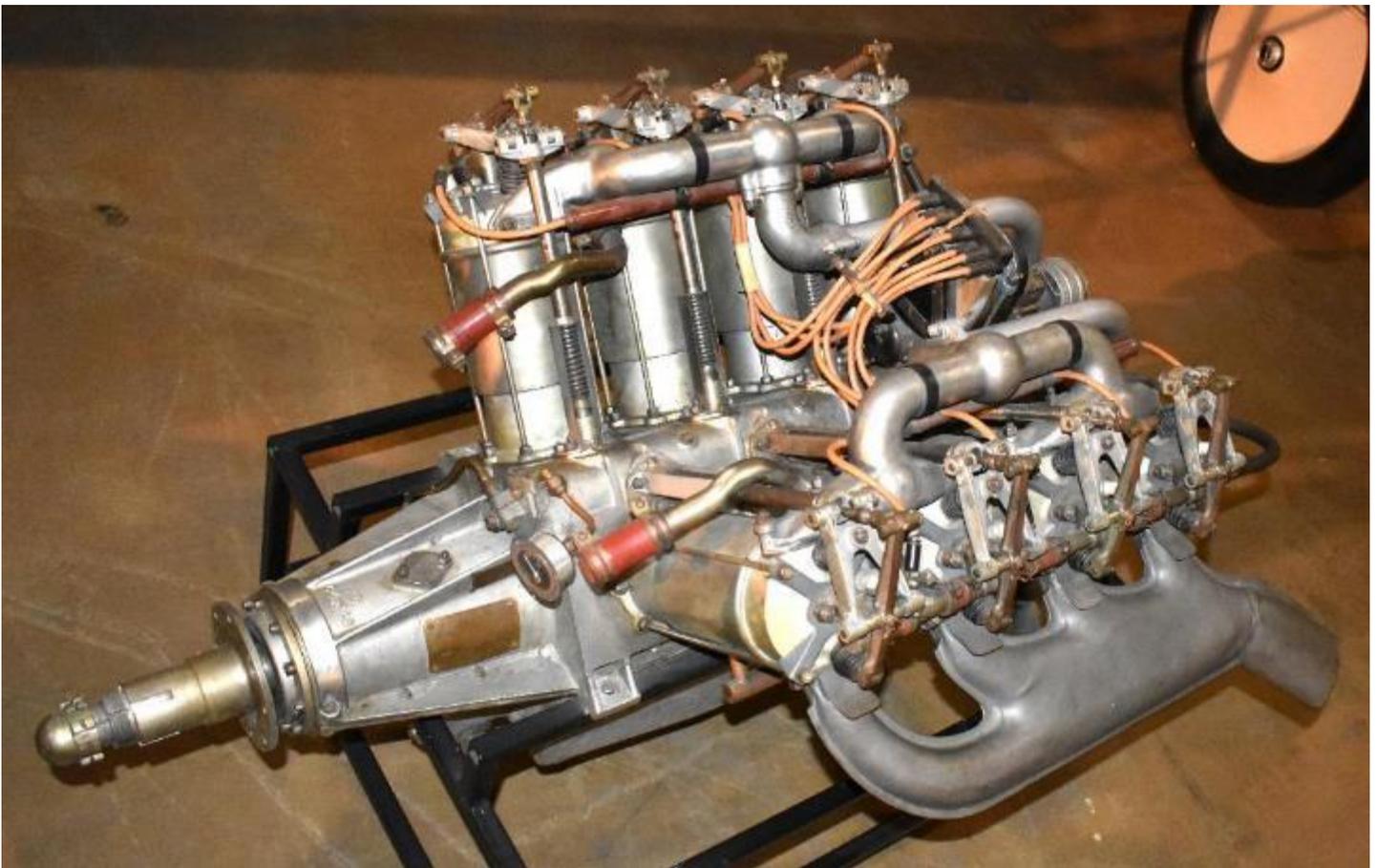
### Talking Points:

- Intro to the Wright Brothers – Per the Smithsonian Institute’s study on aircraft propulsion, the Wright engine of 1903 and the Langley engine of 1901 can be taken as the real beginning of the age of internal combustion engines in aeronautics. This four-cylinder, water-cooled engine was a Wright brothers design and the oldest engine in the Museum
- The Wrights donated this original engine, although this 1909 Military Flyer is a replica

- This engine type was used on over 100 Wright aircraft
- Used on 1908 Model A, the 1909 Military Flyer, and the 1911 Model B
- The chain and sprocket drive system drove the propellers at optimum speed – slower than the engine rpm.

## Curtiss OX-5

The Curtiss OX-5 has the distinction of being the first mass-produced aircraft engine in the United States. First available in 1915, it served in trainers through World War I, continued to be produced by Curtiss as well as other licensees until 1918 or 1919, and then powered a veritable explosion in general aviation after the end of the war and for a decade to follow. In 1929, 2,510 of 6,631 licensed airplanes (38%) were powered by OX-5s. Though in 1930 almost all aircraft engines were better, few could compete with the cost of war-surplus engines (some sold new in the crate for a mere \$20.00).<sup>6</sup> Over 10,000 were built and for years after the War barnstormers, sportsmen pilots and commercial flyers used them because they were cheap and plentiful.<sup>9</sup>



*Curtiss OX-5, between SPAD VII & Avro 504K (Robeson photo)*

Following the obsolescence of the rotary engine, the water-cooled vee-type engine became dominant. In the US, the Curtiss OX-5 lead the field until 1917, when the Liberty and Hispano-Suiza engines were introduced. Used by both the Army and Navy, it powered practically all United States and Canadian training airplanes and was probably responsible for training more pilots for World War I and any other engine.<sup>3</sup>

The Curtiss OX-5 was the most important and successful American engine of the First World War. While the Liberty engine was a high-tech engine, the OX-5 was a low-cost prewar design. At the time of Armistice, there were less than 200 Liberty-powered DH4's in service but more than 8000 OX-5-powered Jennies had been built.<sup>19</sup>

## History

Glenn Hammond Curtis was born May 21, 1878 in New York... he disliked formal schooling and dropped out of high school at the age of fourteen... became interested in racing bicycles... he was soon producing motorcycles with engines of his own design, and started the Curtiss Company in 1902. Development of motorcycles led to his January 1907 World Record of 136.36 mph in Ormond Beach, Florida, making him the fastest man on earth for the next seven years.<sup>6</sup>

By 1906, Curtiss had developed V-8 air-cooled engines used to power aircraft of the Aerial Experiment Association, led by Dr. Alexander Graham Bell.<sup>6</sup>

Curtiss made his first flight on his 30th birthday - May 21, 1908 - in White Wing, a design of the Aerial Experiment Association. White Wing was the first plane in America to be controlled by ailerons instead of the wing warping used by the Wrights. It was also the first plane on wheels this side of the Atlantic.<sup>6</sup>

Curtiss had big years from 1908 through 1910. He won the Scientific American magazine trophy, the Gordon Bennett Trophy plus a \$5,000 prize at the first international air meet at Rheims, France, and the \$10,000 New York Times prize for the first flight between Albany and New York City. These accomplishments were primarily due to Curtiss always having the engine edge in his aircraft.<sup>6</sup>

Curtiss deserves credit for pioneering the design of the floatplane, the amphibian, and the flying boat. It was a Curtiss plane flown by Eugene Ely, a company exhibition pilot that made the first successful takeoff from a Navy ship in 1910. Another Curtiss plane, the NC-4, made the first crossing of the Atlantic in 1919. He received the Collier Trophy... during 1911.<sup>6</sup>

The Curtiss Company merged with Wright in 1929 to become Curtiss-Wright. Glenn Curtiss died in July of 1930.<sup>6</sup>

## Design and Development

Early Curtiss aircraft engines were variants of his air-cooled V-twin motorcycle engine.<sup>6</sup>

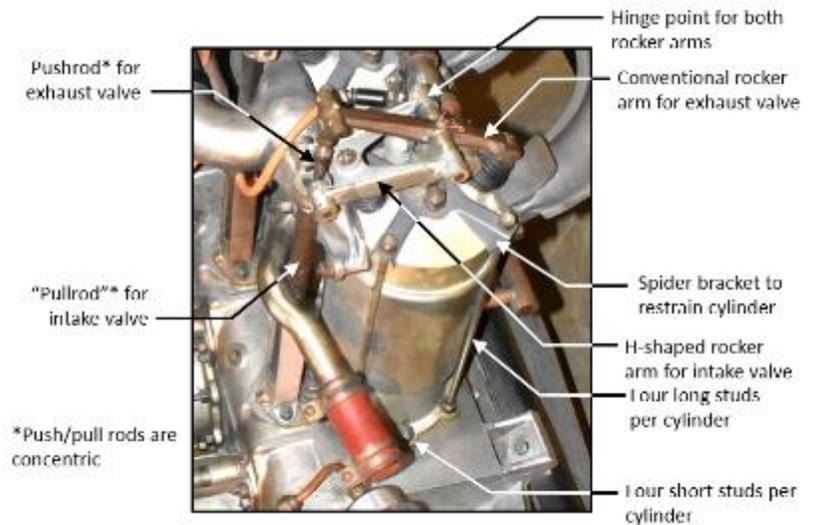
Curtiss was able to attract and afford some of the best engineering talent available at the time. This included Henry Kleckler, Charles Kirkham, and Charles Manly. Kleckler had come up through the ranks at Curtiss. Charles Kirkham, chief of engine design, had manufactured a line of both motorcycle and aircraft engines of his own before coming to Curtiss. Charles Manly was a former SAE president and had built the 1903 Manly-Balzer 5-cylinder radial to power the Langley Aerodrome. This team refined the OX-5 pistons, valve gear, intake manifold, magneto drive, and carburetor in 1915.<sup>6</sup>

The OX series with its characteristic push-pull valvegear arrived in 1913 and went through more or less identical 4 in bore and 5 in stroke variants.<sup>19</sup>

Rated at 90 HP at 1200 rpm and used extensively in Curtis JN training airplanes. Water cooled V-8. Cylinders cast from grey iron with Monel metal *water* jackets brazed in place. Crankshaft 4-throw 5-bearings. Pistons *and crankcase* were aluminum. Ignition by single spark 8-cylinder magneto. Duplex Zenith carburetor. Oil pressure from gear pump. Dry weight 390 lb. Despite relatively low power/weight, considered very reliable in its day.<sup>4</sup>

The cylinders were originally mounted to the crankcase by 8 short studs, but after experiencing cylinder cracking, 4 short studs were replaced with long studs that clamped the cylinder from the top by means of a spider bracket. The valvegear was very unique, using a conventional pushrod and rocker arm to open the exhaust valve, but a concentric “pull-rod” to open the intake valve.<sup>35</sup>

It was said the the OX-5 was the “engine most swore at and swore by”. Basic block, crankshaft, bearings, and cylinders were robust – most reliability issues were related to the accessories. A single camshaft was driven at half the speed of the crankshaft. The piston had a hemispherical convex head.<sup>35</sup>



**Unique features of OX-5 cylinders and valvegear (Robeson photo and labeling)**

It is interesting that these large, fairly heavy aircraft performed as well as they did with only 90 hp. Some authors have attributed this to the engine having great torque, which in their mind made up for horsepower. Horsepower, however, is nothing but torque times RPM. Two factors were responsible for its better-than-expected performance. First, its rating of 90 hp was at 1,400 RPM, though it was capable of running as fast as 1,800 RPM for short periods, and producing nearly 105 hp. This slow engine speed, especially when compared to modern direct-drive aircraft engines, allowed propellers to be much larger and more efficient, producing greater thrust.<sup>6</sup>

The OX-5 was easily adapted to pusher or tractor installations and left or right-hand rotation.<sup>19</sup>

### Service

Though the OX-5... typically having a time-between-overhaul (TBO) of a few hundred hours, the valve gear was both fragile and troublesome. It had no provisions for lubrication other than grease and oil applied by hand. The single ignition typically powered by a Dixie or Berling magneto did not stand up well in service. Other problems resulted from vibration-induced cooling leaks. The large volume of oil in conjunction with long intake manifolds made cold weather starting difficult. Pilots would often drain the oil from the engine and keep it warm overnight to aid cold starting. Since the engine had been widely licensed, Curtiss had no control over the quality. Though Curtiss-produced engines were of high quality, many of the licensed units exhibited appalling quality.<sup>6</sup>

The OX-5 was considered reliable for its day, but few pilots completed their training without at least one forced landing. Weaknesses included single ignition, flimsy valve-operating gear including “pull-rods” for the inlet valves, and a tendency to leak water from the water pump down onto the low-slung carburetor. In freezing weather, the latter defect accounted for many forced landings.<sup>3</sup> [Not the most reliable engine, one aviation writer described it as “A failure looking for somewhere to happen”.](#)<sup>19</sup>

Another concern was the single ignition system and poor reliability of its single Dixie magneto. Largely at the insistence of the USN, the OXX development of this engine used a dual ignition system with two magnetos. Significant advantages were low cost to buy and maintain, and the separate cylinder design allowed repair of piston or valve issues.<sup>19</sup>

### Specifics<sup>6</sup>

Configuration: 8-cylinder, water-cooled 90° Vee  
 Output: 90 hp @ 1,400 RPM

Weight:	390 lb.
Displacement:	503 in <sup>3</sup>
Compression Ratio:	4.9:1

### Talking Points:

- The first mass-produced aircraft engine in the United States
- Mostly used in over 8000 Jennies during World War I, but because they were cheap to obtain and maintain, in 1929 38% of all licensed aircraft were powered by the OX-5
- Glenn Curtiss, perhaps the greatest aviation pioneer after the Wright brothers, began in motorcycle racing and building motorcycle engines, but went on to invent the amphibian and the flying boat
- This water-cooled V-8 engine used unique, concentric push and pull rods to activate intake and exhaust valves through rocker arms
- A significant cause of problems was the single ignition system that had only one unreliable magneto
- One aviation writer described this as “A failure looking for somewhere to happen”
- Used on Curtiss JN-4 Jenny

## Tour Choice regarding Rotaries

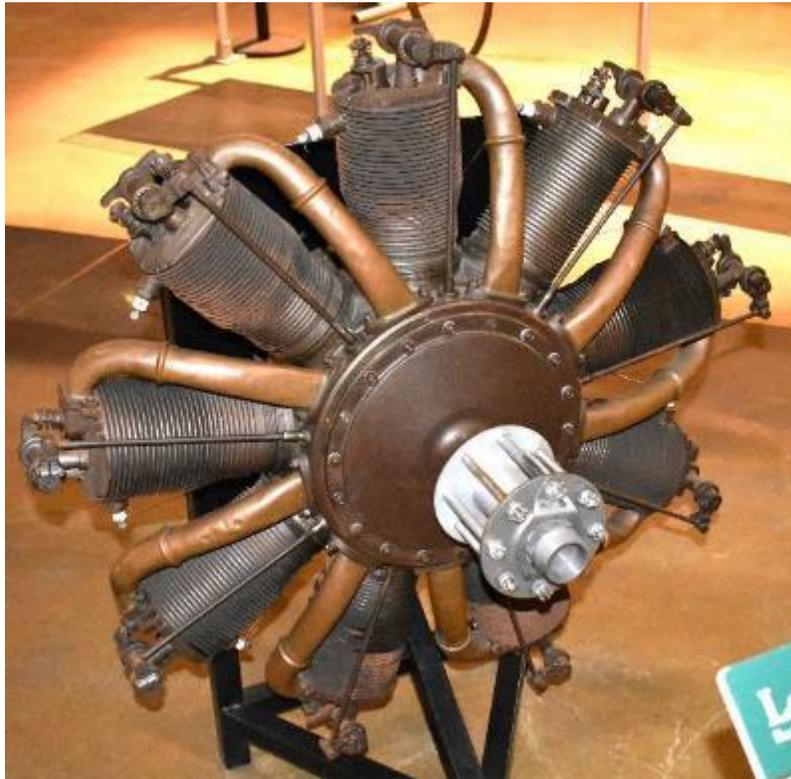
The tour guide should not present both the Le Rhone and the Gnome engines. They each offer unique opportunities and he/she may choose one, the other, or one in detail with brief comments on the other.

**Talking Points:** (These talking points are common for either the Le Rhone or the Gnome and should not be repeated for both engines)

- A nine-cylinder, air-cooled rotary engine in which the crankshaft is attached to the airplane, and the propeller and the entire engine rotate at the same speed
- Incentives for the rotary engine were self-cooling, and using the spinning engine to eliminate the need for a flywheel
- Many aircraft that used rotary engines had an opening at the bottom of the cowling to encourage exhaust to pass beneath the airplane (potentially combustible and a laxative)
- Control of the rotary engine for starting was typically a fuel valve and an air valve, but the engine was generally run at one power setting throughout flight. To reduce power for landing, an ignition switch was used to interrupt combustion
- Rotaries were obsolete at the end of WWI. They were limited to about 200 hp by centrifugal loads on the spinning cylinders and the hollow crankshaft diameter limited fuel/air intake.

## Le Rhone C-9

Used in the Sopwith Camel, the Sopwith Pup, the Thomas Morse Scout, and the Fokker DR.1 Triplane, the Le Rhône rotary engine was a very successful engine in spite of its complexity. Thousands of Le Rhône engines were built and they worked very well. Even today, one can turn one of these 90-odd-year-old engines over by hand and feel it moving as smooth as an old sewing machine.<sup>12</sup>



***Le Rhone C-9, at port wingtip of Avro 504. (Robeson photo)***

Le Rhone air-cooled rotaries were built by Societe des Moteurs Gnome et Rhone in Paris and in The Gnome and Le Rhone Engine Co. London. The Type C was also made in the US by Union Switch and Signal Co. in PA.<sup>4</sup>

The Gnome was built by a firm called Gnome-Rhone, which also made the somewhat different Le Rhone rotary. The Le Rhone had an induction system that was considerably more conventional than the Gnome but, had a remarkable method of connecting the link rods to the master link. In the Le Rhone, the fuel mixture went first to an annular chamber at the back of the crank case and then through attractive polished copper pipes, to conventional intake ports and cam-operated valves in the cylinder heads. The master rod had three concentric grooves to take slipper bearings from all the other cylinders (it was split to allow assembly). The remaining rods carried bronze shoes, shaped to fit in the grooves, at their inner ends. With the master rod as number 1, the shoes of numbers 2, 5 and 8 rode in the outer groove, those of 3, 6 and 9 in the middle groove, and 4 and 7 in the innermost groove.<sup>2</sup>

Cylinders are machined with integral cooling flanges from steel forgings and the inside lined with cast-iron liners. Pistons were usually from cast iron and had special tungsten steel ring. The gas mixture enters the crank compartment through the hollow fixed crankshaft from a carburetor at the rear, and is then led to the cylinders through copper inlet pipes by centrifugal force.<sup>4</sup>

A 9-cylinder rotary rated at 80 HP at 1200 rpm had a compression ratio of 4.8 and displacement of 664.3 cu in. Total weight was 253 lb. At rated power, consumption was approximately 7.5 gal/hr. for fuel and 1 gal/hr. for oil.<sup>4</sup>

The Le Rhone's employed an unusual method of valve actuation. A single rocker arm, pivoted near its center was made to operate both the *single* exhaust valve and the *single* intake valve. Pulled down, it opened the intake valve; pushed up, it opened the exhaust.<sup>2</sup> The system worked well enough that some makers used it up to the late twenties, but its use made overlap of valve openings impossible. In an engine designed for high power and speed, the intake valve begins to open before the exhaust valve is quite closed, but on the Le Rhône, the rocker arm must clear the exhaust before it can

contact the intake. While this puts a limit on power output, it is not necessarily a fault. As it was, most Le Rhône models produced all the power that their structural strength and cooling arrangements could cope with.<sup>12</sup>

Le Rhone 80 hp models were made under license in the United States by a Pennsylvania firm, Union Switch and Signal, and 110 hp models in Sweden by Thulin. In Germany, Oberursel made the 110 hp model, supposedly without authorization. Less ambitious than some, the largest wartime Le Rhone gave only 130 hp. They were dependable engines.<sup>2</sup>

The Le Rhone Model 9C was used on Nieuport, Ruchonnet, Hanriot, Bleriot-SPAD, Morane, Sopwith, Farman, Caudron, and Voisin I aircraft.<sup>18</sup>

The largest wartime Le Rhône gave only 130 hp. As rotaries went, they were dependable engines.<sup>12</sup>

### **Talking Points:**

- The air-gas mixture enters the crankcase through the hollow crankshaft from a carburetor in the airplane, and by centrifugal force through the copper pipes into the cylinders
- A single push-pull rod activated both the intake and exhaust valves
- Used on Nieuports (not the 28), Thomas-Morse S4C Scout, Sopwith Camel & many others

## Gnome N-9

Rotary engines had been built for automobiles in the United States before 1900, but it was first adapted to flying in the Gnome. The design of the Gnome was by Laurent Seguin, and was made entirely from steel forgings machined all over, with integrally machined cooling fins and a modern master-rod system. The Rotary design eliminated the need for a separate flywheel, which had previously been thought to be essential, and also assisted significantly in cooling. Typical cowlings used with the Gnome had an opening for outlet air at the bottom probably to encourage discharge of exhaust gases and oil under the airplane, away from the pilot.<sup>3</sup>



*Gnome N-9 (motion activated, near Nieuport 28) (Robeson photo)*

The real father of the rotary engine for aircraft was a French engineer named Laurent Seguin. His first engine, called the Gnome, started at five cylinders in 1908 and soon led to a production version of seven cylinders. Next was a nine-cylinder version that soon grew from 80 to 110 hp and served in the early Nieuports in the middle war years. A double-row, 14-cylinder 160 hp Gnome held the world speed record before the war and the later 160 hp nine-cylinder version powered the effective Newport 28 in 1918.<sup>2</sup>

The Gnome used a peculiar but effective method of getting fuel into its cylinders. Fuel and air flowed through a hollow crankshaft and then through automatic intake valves in the piston heads to the combustion chambers. Centrifugal force helped the outward flow with the mixture and, by acting on small counterweights on the valve stems, closed the valves. Unlike the intake valves on stationary engines, those on the Gnome needed no springs to close them. There was no exhaust manifold; the gasses were simply allowed to shoot out from the rapidly revolving cylinders. A cowling typically confined the fireworks display that was emitted from the exhaust. On pusher airplanes these cowlings were typically omitted because the fuselage was then out of the line of fire.<sup>2</sup>

The Gnome was also made in “Monosoupape” (single-valve) form.<sup>2</sup>

Type N was 9-cylinder rotary normally rated at 165 HP at 1350 rpm and 970.4 cu in. Compression ratio of 5.45. Consumption per hour at rated power 26 gal fuel & 2.7 gal oil. Weighed 290 lb.<sup>4</sup>

The Gnome was also manufactured in England and America.<sup>9</sup>

**Talking Points:**

- Use the motion-activated display to explain the principle of the rotary engine
- One pushrod actuated the exhaust valve. Instead of an intake valve, the piston admitted fuel/air from the crankshaft through holes in the cylinder wall at the bottom of its stroke
- Used on Nieuport 28, some Sopwith Camels

## Hispano-Suiza Model A

From a technical standpoint, the Hispano-Suiza V-8 was indisputably the outstanding airplane engine during World War I. It was first built in Barcelona by a Swiss engineer, Marc Birkigt, and soon adopted for French fighters in 1915, including perhaps the best fighters of World War II – the Spad VII and XIII. The two primary contributions of Birkigt was the ‘en bloc’ cylinder construction with a cast-aluminum water jacket containing steel cylinder barrels and with enclosed and lubricated valves and valve gear.<sup>3</sup> **Prior to this enclosure, the valve mechanism had to be greased at regular intervals - often after every flight. The cylinders were cast aluminum blocks with steel sleeves instead of being cast individually - resulting in considerable weight savings.**<sup>9</sup> The success of this engine started a revolution in liquid-cooled engine design which culminated in the Rolls-Royce Kestrel and Merlin via the Curtiss K-12, C-12, and D-12 engines.<sup>3</sup>



*Hispano-Suiza Model A (“Hisso”, near port wing of SPAD XIII) (Robeson photo)*

Marc Birkigt invented the sports car, built cars that could go 100 mph, made 12-cylinder cars that were better than any from Rolls-Royce, and designed the first good aircraft cannon (*20 mm HS.404, used from the 1930's through WWII, Korea, and later Israeli Wars*). He also turned out, in 1915 a 150 hp V-8 aircraft engine that showed the world how a water-cooled engine ought to be built. His new firm was called Hispano-Suiza, meaning Spanish-Swiss - in recognition of the nationalities of its principal backers and of himself. The original factory was in Barcelona, but a Paris branch soon outgrew the Spanish plant. Its name was commonly shortened to Hisso.<sup>2</sup>

Societe Hispano-Suiza first airplane engine in 1916. France quickly adopted for Spads and shown to do well in combat at the front. Other French firms and Wolseley Motors Ltd. in England and Simplex Automobile Co. in America had manufacturing rights. Adapted to US manufacturing methods they were produced in quantities by the Wright-Martin Aircraft Corporation in New Brunswick, NJ. After the war this became Wright Aeronautical Corp. and moved to Paterson, NJ.<sup>4</sup>

The Hisso differed in two ways from all existing aero engines of the day: integral cast aluminum cylinder block (with steel liners) and all moving parts enclosed in oil- and dust-tight covers and lubricated by pump-fed oil.<sup>2</sup> *The valves, two per cylinder and mounted vertically in the cylinder head, were actuated by a single overhead camshaft which operated the valve stems directly, without the interposition of either pushrods or rockers.*<sup>56</sup> It was rigid, light, durable, and dependable. The original Hisso was eventually developed to give 220 hp; a later enlarged version gave 300. It powered the SPADs, the SE-5, and a few lesser aircraft, and it was eventually built, not without difficulties, in England and America as well as in France.<sup>2</sup>

Cylinders formed from an aluminum block casting with cored water passages into which are screwed 4 forged steel barrels that are threaded on the outside. The assembly is coated with baked enamel inside and out.<sup>4</sup>

Pistons from aluminum castings. Connecting rods forked type. Valve mechanisms at top enclosed by an oil tight cover. Cooling water circulated by centrifugal pump and gear pumps used for lube oil. Dual ignition from magnetos and duplex carburetors located in the vee.<sup>4</sup>

Water-cooled V-8 with cylinders off 90 deg. Rated 150 HP at 1450 rpm. Displacement 718.9 & compression ratio 4.72.<sup>4</sup>

The only weakness in the early Hispano-Suiza engines, was a tendency toward exhaust-valve burning. This was due to the fact that the steel cylinder heads were "dry", that is they did not come directly into contact with cooling water. The flat steel head had a tendency to warp and lose contact with the aluminum jacket, which reduced valve cooling and also distorted the valve seats, causing exhaust valves to leak and burn.<sup>3</sup>

A Hispano-built Hisso was a fine engine, but a licensed builder's Hisso was very apt to be a bad one. The American licensee was Wright-Martin, and it took American rights as early as 1916, even before real production got started in France. Wright-Martin had significant problems getting started but partly solved its problems by derating the Hisso back to its original 150 hp (the production models in France developed 180 hp almost from the start). By late 1917 Wright-Martin was producing good engines of too little power for combat use (some went into JN-4D's) while European makers were building 180 to 200 hp engines of too poor quality for that same wartime use.<sup>2</sup>

In the course of turning Birkigt's design into a somewhat lesser engine that it could build successfully, Wright-Martin made one modification that held considerable significance for the future. The original design employed closed-end cylinder sleeves. This meant that the valves could seat directly in openings in the top of the sleeve, but it also meant that the heat of combustion had to travel through the steel, past the joint, and travel through the aluminum of the head before it was carried away by the cooling water. Wright went to open-ended sleeves and seated the valves against inserts in the head, a change that improved both cooling and ease of manufacture.<sup>2</sup>

### **Talking Points:**

- This was the most outstanding airplane engine during World War I
- The aircraft engine company, Hispano-Suiza, meant “Spanish-Swiss”. This was typically shortened to “Hisso”
- Two outstanding features were a integral cast aluminum block with steel cylinder liners and enclosed and lubricated valves and valve gear. Previously, valve mechanisms had to be manually greased at regular intervals.
- Dual ignition system using two magnetos improved reliability
- Used on SPAD VII and XIII and SE-5E in NMUSAF & many others

## Packard Liberty 12A

The Liberty was the most important American separate-cylinder engine. The principal designers were Jesse G Vincent of Packard and E J Hall of Hall-Scott, the two Americans with most experience in the type of engine the government wanted. These two men settled in a Washington hotel suite and had drafting materials and draftsman sent in and designed the engine between May 30 and midnight June 4, and the first engine (*the V-8 version*) was completed and running by July 3.<sup>2</sup> They started design of the engine in the Willard Hotel, Washington DC, after a decision to proceed by the War Production Board only seven weeks after the US had entered the War.<sup>3</sup>



*Packard Liberty 12A with turbosupercharger, at port wing of LUSAC. (Robeson photo)*

Liberty engines were developed to provide standard units that could be produced in large quantities in the US. The original idea was in May 1917 and led to an initial 8-cylinder engine that was judged obsolete already. The 12-cylinder version was well tested by Aug. 1917.<sup>4</sup> [The first production engine was delivered on Thanksgiving, 1917, only six months after the first design sketches at the Willard.](#)<sup>3</sup> Not a new invention, it was based on several US and European designs then in service. The success of the program was because some of the best engineers, facilities, and production experts were at the USG's disposal. Due to the pooling of interests and consultations it is not possible to assign credit for individual design features.<sup>4</sup>

The government had done nothing to encourage industry or individuals to enter the aircraft or aircraft-engine production field. The government incentives that characterized the development of our early technology were not applied to the furtherance of the aviation industry in the nation that invented the first heavier-than-air machine to lift a man from the ground in sustained, controlled, powered flight. The aircraft developmental work the Wright Brothers carried out almost in secrecy on the Huffman Plain near Dayton, Ohio, was accepted and continued with great energy and enthusiasm in Europe. It was treated as a curiosity, a passing fancy in the armed services of the country of its birth. At the beginning of 1917 the United States ranked 14th among the nations of the world in aviation. The Liberty Engine was an apology for our nation's lack of foresight and for its failure to develop the aircraft born at Kitty Hawk.<sup>55</sup>

The engine that emerged had only two features that departed from accepted European practice. Instead of magnetos, it used coil ignition, like an automobile, and the angle between the cylinder banks was 45° instead of the normal 60°. Coil ignition was adopted out of the well-founded distrust in the ability to make good magnetos in quantity in America, and the narrow angle was adopted to reduce frontal area. In its basic 12-cylinder form, it had the best weight-to-power ratio of any engine to date. It displaced 1649 cubic inches.<sup>2</sup> [It was rated at 421 HP at 1700 rpm and a max HP of 449 at 1940 rpm. It weighed 844 lbs. Water added 45 lb. and battery, switch, voltage regulator added another 13 lb.](#)<sup>4</sup> For the first time, the Manly engine ([from Langley Aerodromes](#)) had been surpassed in lightness for power.<sup>2</sup>

Large quantities of the Liberty-12 engine were produced by automobile companies, including Packard, Ford, Lincoln, and some General Motors divisions. It was used by the British in their military airplanes as well as by the US Army and Navy. After the war, many were sold at low prices to "rum runners" who installed them on boats and were very successful in running liquor through Coast Guard blockades during Prohibition.<sup>3</sup>

The name was not always "Liberty." It was originally the "U.S.A. Standardized Aircraft Engine", but, when the name "Liberty" was suggested in the early part of the period of production, it immediately caught on. The name "Liberty," as associated with the engine, was given the distinction of being registered as the trademark of the U.S.A. Standardized engines by the United States Government on 17 June 1919. This is the first instance of the United States Government registering a trademark under its own laws or the laws of any other country.<sup>55</sup>

The reliability of the Liberty has been much debated, but the fact seems to have been that Liberty quality and reliability varied considerably from maker to maker. Carefully selected Liberties flew nonstop across the continent, made the first Atlantic crossing, stayed up 36 hours in the first inflight refueling experiment, and flew American Douglasses around the world; but run-of-the-mill Liberties in airmail service were somewhat troublesome. The worst Liberties came from Packard, the best were built by Lincoln, and those from Ford fell in between these extremes. Henry Martyn Leland founded Cadillac and in his 70s sold his shares in Cadillac to start Lincoln. Lincoln Liberties were not only the best, they were also the cheapest.<sup>2</sup>

The original plan was to build the Liberty in a four, a six, an eight, and a 12. The first Liberty completed was an eight. It ran well but vibrated too much for use in an aircraft and no more were made. The six was a good enough engine but only 52 were made. While two fours were built and forgotten, no less than 20,478 12's were made, 2543 of them after the Armistice. The Liberty 12 was the only American-built engine to see combat service. It powered the British-designed, American-built DH-4's that were America's sole contribution of material to the Allied Air Forces.<sup>2</sup>

The cylinders were made from separate steel forgings and have pressed-steel water jackets welded on. The cylinder barrel and combustion chamber are forged integral; the swaging process developed by the Ford Motor Company being virtually the closing of the end of a tube. Valve ports were made from steel forgings and welded to the cylinder head. The coolant passages were arranged to bring the water first to the hottest part of the cylinder and there were perforations to relieve steam pockets. A single inlet and exhaust valve are on each cylinder.<sup>4</sup>

The lube system is dry-sump pressure-feed type, oil delivered to bearing by a gear pump. A centrifugal pump circulates cooling water. Two duplex carburetors are located in the vee. Ignition of the Delco Battery type consists of a low voltage generator, and 8-volt storage battery, and a double distributor system. The distributors are located at the driving ends of the camshaft housing, and two spark plugs are almost vertical in each cylinder head.<sup>4</sup>

The design was largely based on the welded – cylinder construction pioneered by Mercedes. It had no radical features, but was an excellent synthesis of the state of the art of its time. Principal weaknesses were cracking of the cylinder-head water jackets, burning of exhaust valves, and breaking of accessory gears. These faults were gradually reduced as time went on. Later modifications included a bar welded between the ports to reduce cylinder distortion and jacket cracking, and heavier teeth in the gears.<sup>3</sup>

This 12-cylinder, liquid-cooled 449-hp Liberty 12A is configured with a General Electric F-1A Turbosupercharger. In 1923 engineers at McCook and Wright Fields equipped a Liberty 12A engine with the Form F turbine-driven supercharger to test operations at altitudes. This version of the turbosupercharger included a variable nozzle area, removable turbine and impeller, and a split turbine wheel. Even at 30,000 ft. altitude, the engine was able to deliver the same amount of power as when flying at sea level. Engine weight was 844 lb.<sup>34</sup> *Note the NMUSAF sign does not indicate if 844 lb. weight includes supercharger or not.*

The British apparently used all their Liberties in multi-engine planes, such as Vickers-Vimy bombers and various large flying boats. Four of them powered the NC-4 across the Atlantic, and two were used in the Martins that formed the Army's first real bombing force.<sup>2</sup>

Liberties were expensive to operate. It took a lot of skilled maintenance labor hours to keep them running. As a result, there were only three civilian applications of any significance. The Liberty was put back into production in England in 1938 as an engine for tanks, and the "Cruiser" and the "Cavalier" actually saw service in World War II with Liberty power.<sup>2</sup>

The Liberty engine remained important in US Army and Navy aviation well into the 1930s. This engine was used in the NC-4, the first aircraft to cross the Atlantic in 1919.<sup>3</sup> [The Liberty-12 was also used in the first circumnavigation of the world by Douglas World Cruisers in 1924.](#)<sup>9</sup> A turbo-supercharged version established world altitude records in 1920, 1921, in 1922.<sup>3</sup>

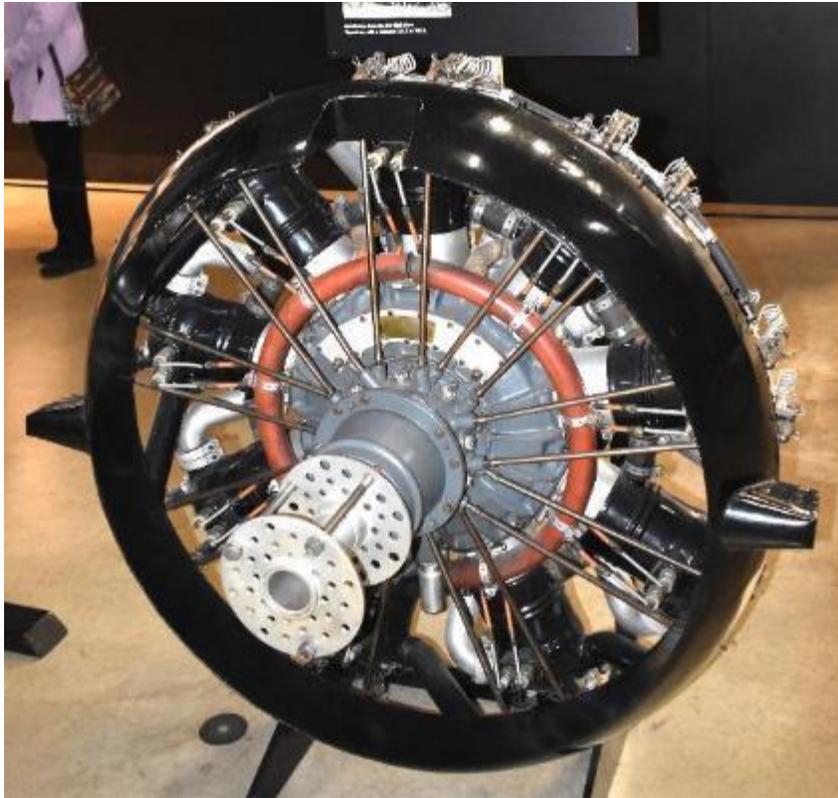
### **Talking Points:**

- In 1917, a new aircraft engine design optimized for mass production was initiated. Designers from Packard and Hall-Scott began design of the first Liberty engine only weeks after the US entered the war, and the first engine ran only five weeks later
- The Liberty family included designs of 4, 6, 8, and 12-cylinder versions, but ultimately the 400 hp 12-cylinder version went into production, with over 20,000 built
- This was the only American-built engine to see combat service, powering British-designed, American-built DH-4's and various British bombers
- This example is equipped with a turbosupercharger, which enabled it to establish altitude records for several years.

- ☹ Briefly describe how mechanical superchargers enabled power recovery at higher altitudes, and the turbosupercharger used piston exhaust to drive the compressor through a turbine (*NMUSAF website shows/describes version w/ reduc gear – no longer applicable*)
- The 12-cylinder Liberty engine was used in the Navy NC-4, the first aircraft to cross the Atlantic in 1919. It was also used in the Douglas World Cruisers, which accomplished the first circumnavigation of the world in 1924
- Used on DH.4, MB-2 and LUSAC 11 in NMUSAF

## Salmson Z-9

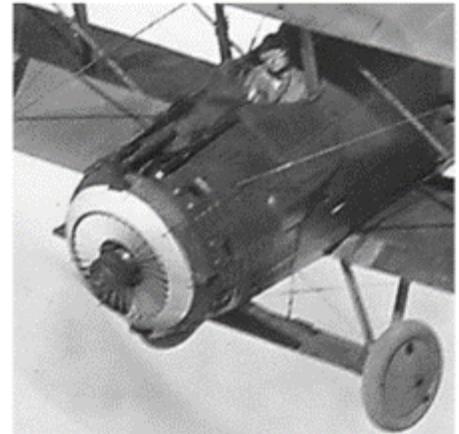
The French Salmson Z-9 water-cooled radial popular from 1908 to 1920 and licensed to both Britain and Russia.<sup>10</sup>



*Salmson Z-9, in row of engines between EY entrance and Caproni (Robeson photo)*

The Salmson Z-9 was a 270 hp engine that was obsolete by 1920. The Z-9 normally came complete with radiator and cowl, making a compact “power egg”. It was also efficient, having a specific consumption of .495 pounds. The cowls in the power egg included radiator flaps for good temperature control; no doubt this made its contribution to fuel consumption.<sup>2</sup> [The Salmson Z-9 was the earliest “stationary” design of radials produced for WWI combat aircraft.](#)<sup>42</sup>

The Salmson engines were built in France by the Societe Anonyme des Moteurs Salmson of Billancourt France, and in Great Britain by the Dudbridge Iron Works, Ltd., of Stroud, Gloucester. “No other water-cooled radial engine has been more thoroughly developed than the Salmson designs” (as of 1926). Salmson airplanes equipped with Salmson engines were successfully used in large numbers by the French and American armies during the war.<sup>4</sup> The Salmson 2 A.2 was a reliable reconnaissance biplane – over 3000 served in WWI in French units and 700 with American units.



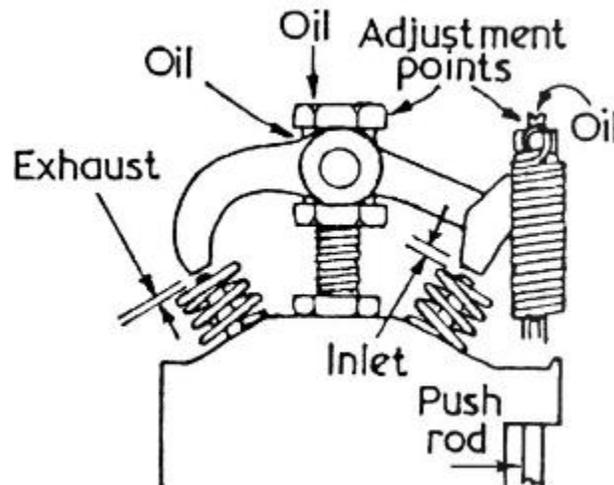
**Salmson Z-9 installed in Salmson 2 WWI aircraft. Note louvered radiator in front of exhaust manifold. (Wikipedia photo)**

[The Z-9 model was developed during the war and had nine cylinders and total displacement of 1146.4 in.<sup>3</sup>](#) Compression ratio is 5.4, 230 hp was produced at 1500 RPM and 280 hp at 1650 RPM. Engine weight was 473 pounds.<sup>4</sup>

Pistons were made of aluminum. Steel cylinders had welded-on sheet steel water jackets. Wedging rings on the exterior were used to pull the cylinder up tightly against the crankcase. Inlet and exhaust valves were operated through pushrods and rockers by three inlet and three exhaust cams turning in the direction of the crankshaft at one fourth its speed.<sup>4</sup>

Dual ignition was supplied by two 9-cylinder magnetos. Duplex carburetors furnish the mixture and oil was circulated by two oscillating plunger pumps; the small plunger forced oil to the bearings under pressure and the large one was used for scavenging.<sup>4</sup>

The idea of a water-cooled radial seems strange today, but such engines were quite common in the early days of aviation. The first US aircraft engine, the Balzer-Manly that powered Samuel Pierpont Langley’s ill-fated Aerodrome, was a water-cooled 5-cylinder radial. By 1939, others had been built by Albatross, Anzani, Clement-Bayard, Fiat, Garuffa, Rumpler and Salmson. During the Second World War, Wright Aeronautical tested a 42-cylinder liquid-cooled radial, Lycoming tested a 7,755 cu in, 36-cylinder liquid-cooled radial, and BMW built a 28-cylinder liquid-cooled radial.<sup>28</sup>



***Salmson 1921 single pushrod. The drawback of these single cam per cylinder systems is that it cannot provide valve overlap (only important years later when higher performance demanded it.)<sup>19</sup>***

### Talking Points:

- As the first example of a radial engine, explain the difference between a radial and rotary
- This French-designed radial engine was used in large numbers during World War I, and was unique in that it was water-cooled
- Used on Salmson aircraft and nine other types, including the Vickers Vimy prototype
- Note unusual exhaust manifold molded as leading edge of cowling

## Wright J-5 Whirlwind Engine (also known as Wright R-790)

*NMUSAF signage and website identify this as the Wright R-790 and note that the “civilian version of the R-790, the Wright J-5 Whirlwind, powered Mr. Charles A. Lindbergh’s Spirit of St. Louis”. Actually, they have it backwards. The data plate on this engine (front, under shaft) identifies it as “WHIRLWIND J-5-C” with a contract date of 1927 and 200 HP at 1800 rpm and manufactured at Wright Aeronautical Co. in Paterson, NJ.*

Around 1916 Charles L Lawrance began developing air-cooled engines with aluminum cylinders having steel liners. In 1921, Lawrance developed a nine-cylinder 200 hp radial known as the J-1, which was supported by an order for 200 engines from the US Navy.<sup>3</sup> With aluminum cylinders with steel liners, the J-1 could run for 300 hours vs. 50 hours for typical engines of the day. With the encouragement of the USN, Wright Aeronautical bought Lawrances’ firm and soon produced the J-5 Whirlwind, which by 1925 was widely claimed as “the first truly reliable aircraft engine”, giving USN pilots confidence for long missions over the ocean (and Lindbergh to use in his Ryan NYP).<sup>10</sup> The nine-cylinder engine was developed in improved models known as the Wright J-3, J-4, and J-4b, still incorporating the Lawrance cylinder design.<sup>3</sup>



**Wright J-5 Whirlwind, at rear of Ford WWI Ambulance (Robeson photo)**

Around this time S D Heron left England and was employed by the US Army Air Service at McCook Field in Dayton Ohio to assist in development of large radial engines. By 1921 he had successfully demonstrated air-cooled cylinders of nearly 6 inch bore. The Lawrance and Heron developments were brought together when in 1926 Heron joined Wright Aeronautical Corporation, of which Lawrance was president. The first result, the Wright J-5, was essentially a Lawrance-type engine with Heron-type cylinders. This was a successful engine in the 200 hp class, as evidenced by its use in Lindbergh's New York to Paris flight of 1927, in many other pioneering flights, and in a number of early transport planes.<sup>3</sup>

In 1928 The Collier Trophy for 1927 was awarded by the National Aeronautic Association to Charles L. Lawrance of the Wright Aeronautical Corporation for his outstanding work in the development of the air-cooled engine which figured so prominently in the 1927 transoceanic flights.<sup>31</sup>

Heron designed the cylinder head for the new J-5 model and horsepower went to 220 and the yielded the highest reliability of any aircraft engine to date. The valves are very widely angled, allowing them to be larger and permitting very generous finning and ample airflow between the ports. For the first time, a radial had all the air it needed.<sup>2</sup>

The development of the J-5 type of engine was undertaken in an effort to place the air-cooled engine fully on a par with the water-cooled type as regards fuel consumption. The cylinder is characterized by a hemispherical combustion-chamber employing two valves with axes inclined at 70 deg. The valve-seats are of aluminum-bronze shrunk into the cast-aluminum head. The cylinder-barrel with integral cooling-fins and hold-down flange is screwed and shrunk into the

aluminum-head casting. Among the advantages claimed for this cylinder over the Lawrence type of cylinder are superior head-cooling due to the larger fin-area provided by the hemispherical combustion-chamber and the relatively large space between the valve-ports; the superior barrel-cooling due to the integral steel-fins, which avoids the necessity of conducting the heat across a thermal gap between the aluminum barrel and the steel liner; the high fuel-economy presumably due to the excellent combustion-chamber shape and to the efficiency of the valve cooling; greater strength and ability to withstand abuse due to the hemispherical shape of the combustion-chamber and the superior cooling; and remarkable freedom from detonation presumably due to the combustion-chamber shape, valve cooling and spark-plug position. The shape of the combustion-chamber is also said to offer the further advantage that relatively large valves can be employed without unduly crowding the valve-seats together at the center of the head.<sup>14</sup>

The author (*of a 1926 SAE paper*) believes that the results of these endurance tests place the air-cooled engine definitely on an equal footing with the best water-cooled engines and that the air-cooled engine will become the standard of comparison.<sup>14</sup>

It displaced 778 inches with 9 cylinders; was light at 510 lbs.; had no water-cooling appurtenances. It was simple and easily maintained; its cooling was so efficient that it could be operated with a lean air/fuel mixture, almost unheard of then, since rich mixtures were usually necessary to help cooling. The Whirlwind developed 220 HP at 1800 rpm, a low speed that contributed to its reliability.<sup>15</sup>

The Whirlwind developed the same 220 hp that its predecessor, the J-4 had, but had greatly improved valve gear and cylinder head designs which resulted in an increase in durability and reliability. S. D. Heron was responsible for these improvements. The Whirlwind put Wright Aeronautical on the map.<sup>9</sup>

It had one fault, which was not important or even recognized at the time - its large frontal area would produce excessive drag, but airplanes were slow then, and engine drag was not an important factor. Wright Aeronautical now had a first-class product and looked for a way to advertise the engine and show it to the world.<sup>15</sup>

Giuseppe Bellanca was a Sicilian immigrant living with his brother in Brooklyn. He was an engineer whose passion was aerodynamics. Over several years he designed and built a line of airplanes, paying close attention to every detail of aerodynamics and streamlining. Wright contracted with Bellanca to build an airplane tailored to the J-5C. The resulting machine, the Wright-Bellanca WB-2, is considered to be a benchmark airplane of American aviation. It soon set new endurance records. Charles A. Lindbergh tried to buy the Bellanca but was considered to be an unreliable barnstormer. Instead, the plane was sold to a New York businessman who planned to make the Paris flight. The plane was then named Columbia. The Columbia was temporarily grounded over a legal hassle and lost the chance to be first. It made the transatlantic flight shortly after Lindbergh, outdistancing Lindbergh by about 300 miles.<sup>15</sup>

Lindbergh's Spirit of St. Louis was designed around the J-5 but his Whirlwind modified the rocker arm lubrication to allow for longer-than-normal periods of continuous operation.<sup>2</sup>

The J-5C Whirlwind was the progenitor of all the great radials that came afterwards.<sup>15</sup>

### **Talking Points:**

- In 1923, Wright Aeronautical acquired Charles Lawrence and his engine company, which was doing pioneering work in radial air-cooled engines that used aluminum cylinders.
- In 1926, S D Heron left McCook Field in Dayton Ohio to join Wright Aeronautical Corporation. His first contribution was to the cylinder design of the new J-5 Whirlwind engine
- The Whirlwind was considered "the first truly reliable aircraft engine", lasting six times as long as competing engines of the day
- This engine was quickly selected by Charles Lindbergh for his Spirit of St. Louis, and also won the Collier trophy

- Most experts agree that the Whirlwind was the prototype of all the great radial engines that came afterwards
- Used on Fokker Tri-Motor, Spirit of St. Louis, Lockheed Vega & about 40 other types

## Curtiss D-12

The Curtiss D-12 was considered America's best water-cooled engine from 1921 to 1928. <sup>13</sup>



*Curtiss D-12. (Robeson photo)*

Kirkham left Curtiss over disagreements over how much redesign the K-12 needed. Extensively redesigned by Arthur Nutt, the K-12 morphed into the direct-drive D-12 of 350 hp. <sup>2</sup>

The D-12 now used seven main bearings and separate blocks and crankcase, and gave 425 hp at 2250 RPM in racing versions. In 1922 in a Curtiss racer, the D-12 became the first engine ever to power a plane to 200 mph, and during the first half of the 1920s D-12-powered Curtiss racers swapped the unlimited record back and forth with Hisso-powered SPADs and Nieuports in France. It won two Schneider Cups and was a threat at the National Air Races as late as the mid-30s. <sup>2</sup>

The D-12 was a 443 hp (330 kW) 12-cylinder Vee, liquid-cooled engine with seven main bearings using separate cast blocks for the cylinders and crankcase. The lubrication system drew oil from a separate oil reservoir through an oil cooler, otherwise known as a dry-sump system. The cylinders used wet-sleeves which allowed water to contact almost the entire length of the cylinder. This was a development of the Curtiss AB, later to become the K-12 engine. It used an old-style closed end cylinder sleeve. There were four valves per cylinder which were seated directly into the head. There were no valve seat inserts in the head. The valves were operated by two camshafts, one for the exhaust and one for the intake valves. This allowed all of the exhaust valves to be located on the outside of the cylinder to 12 separate stacks, one for each exhaust port. The engine had a dual ignition system using Splitdorf SS-12 magnetos. <sup>2</sup> Both spark plugs were

located on the inside of the Vee to prevent fouling. Stromberg NA-Y5 carburetors became standard for all D-12 engines.<sup>13</sup>

The D-12 replaced the propeller reduction gears with a more reliable direct-drive connection and resulted in the designation "D" for direct-drive. The engine was matched with a new propeller designed by Dr. S.A. Reed. It was a high-speed aluminum propeller that allowed the engine to use its full power. This combination, along with the Stromberg carburetors, increased the engine to 2,500 rpm and allowed the Curtiss R-6 to achieve 244.9 mph in 1923.<sup>13</sup>

The D-12 was as effective as a workhorse as a racer. Its durability and reliability enabled Curtiss to sell it to the Army on the legitimate grounds that the newly purchased D-12 was cheaper in the long run than a Liberty obtained free from surplus stock. It powered all the Army's fighters until the coming of the Pratt & Whitney Wasp. It was the world's outstanding engine in its class until at least 1927.<sup>2</sup>

In 1923, a Curtiss PW-8 powered by a D-12 broke the dawn-to-dusk continental crossing record by covering the USA in 21 hours and 48 minutes. The flight began from Mitchel Field, Long Island at 3:00 a.m. EST and finished in San Francisco 9:48 p.m. Pacific Time. Allowing for refueling stops in along the 2,645 mile route, the actual flying time was 10 hours, 20 minutes.<sup>13</sup>

The D-12 was a lighter and smaller than the other two other 400 hp class engines at the time, the Rolls-Royce Eagle and the Napier Lion. It was so advanced that in 1924, the Fairey Aviation Company Limited took out a license to produce the D-12. They designed a light bomber around the D-12 engine called the Fairey Fox which was a very advanced plane for the time and subsequently purchased by the RAF.<sup>13</sup>

The Curtiss D-12 was the effort of Dr. Arthur Nutt, who was Chief Engineer of Curtiss. It won the Schneider trophy (for racing seaplanes) and was so good that the British Government bought some and gave one to Rolls-Royce with instructions to "do better". Therefore, the engine inspired a series of Rolls-Royce engines starting with the Kestrel and culminating in the Merlin.<sup>9</sup>

After 1925 the Curtiss Company stopped development on the D-12 after achieving a virtual monopoly on fighter power plants. The D-12 was used on the Curtiss Falcon observation plane which replaced the De Havilland D.H. 4 and served well into the 1930s. It was a durable and reliable engine and powered all of the US Army's fighters until the emergence of the lighter and simpler air-cooled Pratt & Whitney Wasp in 1925. The D-12 was enlarged to the V-1400 and then eventually to the V-1570 which became known as the Curtiss Conqueror.<sup>13</sup>

Specifications for Curtiss D-12:<sup>13</sup>

Date:	1922
Configuration:	V-12, liquid-cooled
HP:	443
RPM:	2250
Displacement:	1145 in <sup>3</sup>
Weight:	704 lb.

### **Talking Points:**

- This engine was considered America's best water-cooled engine in the 1920s, and led directly to the development of the famous Rolls-Royce Merlin engine
- The British Government was so impressed that they bought some D-12's and gave one to Rolls-Royce with the challenge to "do better". That challenge led to the development of the Merlin engine

- This V-12, 350 hp engine was the first to power an aircraft 200 mph, and was an important engine in national and international speed competitions
- Recent developments in high-speed aluminum propellers enabled this engine to operate at high speed without reduction gear (hence, the “D” for direct drive).
- The world’s outstanding engine in its horsepower class until 1927, it proved to be cheaper for the Army to operate than a Liberty engine obtained free from surplus stock

## Wright R-2600 Cyclone 14

The R-2600, designed and produced by the Wright Aeronautical Corporation, originated from the company's specification #439, September 23, 1936. The Air Corps bought one experimental engine in October 1936. The Air Corps Materiel Division tested the engine March 10 to May 24 of 1936. The Chief of the Experimental Engineering Section at Wright Field then recommended the R-2600 as an approved engine type.<sup>8</sup>

When the contract was placed, the R-2600 was not fully developed and occasioned much trouble before becoming an outstanding engine. There were, as late as October 1943, accessory drive gear failures, cylinder failures (caused by corroded or rusting barrels), supercharger clutch failures, and excessive oil consumption.<sup>8</sup>

The R-2600 was Wright’s first two-row engine with more displacement than the single-row R-1820. The R-2600 initially used the same cylinder design (two valve hemispherical combustion chamber) and diameter (6.125") as the R-1820 Cyclone, but with a reduced stroke of 6.312". Seven cylinders were used in each row. It passed its type test on June 10, 1937 and was in production by the end of the year. It initially produced 1,500 take-off horsepower at 2,300 rpm. By the end of WWII, the R-2600 was producing 1,900 hp. The R-2600 was used in North American B-25s, Boeing Model 314 Clippers, Navy TBF Avengers, and Douglas A-20 Havocs.<sup>7</sup>



***Wright R-2600 (left, sectioned under starboard wing of B-25, right, between A-20 and P-47 “Ginger”) (Robeson photos)***

Wright had expanded to six plants in the Paterson, New Jersey area, and had built a new plant in Ohio exclusively for production of R-2600s.<sup>7</sup>

### Carburetion

One of the earliest problems was that of carburetor failure. The calibration of a model test engine in May 1939 engine test found the Stromberg PD carburetor to be too small. A Holley carburetor fitted to the Model -9 series engines finally solved the problem. Wright Aeronautical believed that the Holley carburetor (type unspecified) would aid "in curing the... faulty carburetor distribution and overheating" problems. Overheating was not so cured.<sup>8</sup>

Carburetor problems caused R-2600-29 engine failures in A-20K airplanes, making them unfit for ferrying, reported the British Air Commission October 1944. Holley HA carburetors replaced Holley HB units, allowing ferrying. The Air Transport Command would not ferry B-25s to Hawaii for the same reason. Installation of Holley HA carburetors permitted ferrying. The carburetors were returned after each trip for reuse!<sup>8</sup>

### **Cylinders and Oil Consumption**

Other hard-to-solve problems were piston and piston ring wear and excessive oil consumption.<sup>8</sup>

Thirteen of thirty-three A-20B airplanes (for delivery to Oran, Africa) landed elsewhere in December 1942 because of broken and stuck piston rings and high oil consumption.<sup>8</sup>

Similar failures happened to other aircraft using the R-2600 engine (B-17, A-31, and A-35). Reports from Brazil in January 1943 stated that A-31s delivered to Army Air Force bases were mostly "out of commission" from fouled spark plugs and excessive oil consumption. High engine temperature may have accelerated piston ring wear.<sup>8</sup>

During Army maneuvers in Louisiana seven of twenty-six engines in A-20A airplanes were changed because of high oil consumption. The RAF in June 1943 reported Middle East delivery delays of R-2600-powered airplanes because of a "prohibitive rate of oil consumption." The RAF proposed that oil consumption could be minimized by restricting power during the first ten hours of engine life.<sup>8</sup>

### **Cylinder Rust and Corrosion**

The most vexing problem was rust and corrosion in the cylinders. The Corrosion Committee, established May 17, 1943, wrote, "We do not know the answer but are beginning to suspect Gremlins." The "epidemic" of December 1942 to March 1943 was corrosion, and that of June-July 1943, rust.<sup>8</sup>

The problem became more serious and the FBI was asked in August 1943 to investigate. The FBI reported September 22, 1943 no sabotage. Meanwhile Wright Field's Engineering Division announced August 3, 1943 that a mixture of 75% new oil and 25% rust preventive compound solved the problem. On September 7, 1943 a Memorandum Report specified a modified Bakelite varnish be sprayed and baked on all steel parts.<sup>8</sup>

### **Other Engine Problems**

The R-2600-31 engine passed its 150-hour model test November 1943. Some parts showed "scratching, pitting, or picking out." These weren't considered serious and on January 26, 1944 Wright Field's Power Plant Laboratory recommended the R-2600-31 for satisfactory completion of the 150-hour model test, except for unsatisfactory wear of piston pins and intermediate impeller shaft bushings.<sup>8</sup>

By November 1944 failures of reduction gear pinion bushings and piston pin retainers in R-2600-B engines were so serious that Wright Aeronautical was holding all engines. All engines shipped after October 25, 1944 were returned to Wright's Lockland plant for no-cost replacement of unsatisfactory parts. An approved change of design was expected to fix these failures.<sup>8</sup>

### **R-2600 Engine Production**

Production of R-2600 engines at the Wright Corporations' Lockland plant (Lockland, Ohio) dropped from 1,000 engines a month to only 21% of that by June 1943. This decline was caused by, it was claimed, more rigid inspections imposed after the Truman Committee and Air Force investigations.<sup>8</sup>

Production schedules for R-2600 engines changed several times in 1944. Each change brought serious operating problems to Wright Lockland management, the Company becoming confused, making a production commitment impossible for the R-2600 and R-3350 engines.<sup>8</sup>

Lockland production of R-2600 engines declined in 1944 partly because Wright Aeronautical failed to acquire enough master rods.<sup>8</sup>

June 1945 began a plan for gradual reduction of R-2600 engine production at Lockland, to accommodate production of R-3350 engines (rising to 1,000 engines a month by December 1945). Later the Special Advisory Group, Material, Maintenance and Distribution raised the R-3350 production target to 1,200 engines a month by October 1945.<sup>8</sup>

#### **Production of R-2600 engines<sup>8</sup> *total Lockland (Cincinnati) & Paterson, NJ***

- 1941 - 7,425
- 1942 - 18,096
- 1943 - 22,918
- 1944 - 29,581
- 1945 - 9,559 on contract (completion by January 1946)

#### **Talking Points:**

- This engine was an early two-row radial engine, which could double the power output without increasing frontal area (and aircraft drag)
- It started production in 1937 at 1500 hp, and by the end of World War II was producing 1900 hp.
- Wright plants included six in Paterson, New Jersey and the newest, largest plant in Lockland, Ohio
- Over 95,000 were built, and significant quality problems at the Lockland Ohio plant resulted in FBI investigation of sabotage, which was not confirmed
- Used on A-20G and B-25B in NMUSAF. Also Boeing 314 & various USN aircraft

## Wright R-1820 Cyclone

### **History**

The R-1820 traces its history to the Wright P-1, the first "Cyclone". Development began in 1923 under a Navy experimental contract for two engines given to Wright largely out of respect for the air-cooled design talents of Charles L. Lawrance. Wright had recently acquired the Lawrance Company, and C. L. Lawrance was a Wright vice-president. The P-1, displacing 1,654 in<sup>3</sup>, was reported to produce 406 hp at 1,650 rpm with a dry weight of 812 lb. It was hoped that the P-1 could produce twice the power of the Whirlwind with the same diameter. This was not to be. The engine was not a success. Wright quickly moved on to design the second engine, and cure the problems with P-1.<sup>5</sup>



***Wright R-1820 Cyclone, near nose of Memphis Belle (Robeson photo)***

The P-2, begun in 1924, used the same bore and stroke as the P-1 but used more conventional cylinders with enclosed lateral valve placement based on cylinders designed by Sam Heron of the Army Power Plant Laboratory at McCook Field, Dayton, Ohio. Opinion was changing as to the importance of small frontal area, allowing a larger diameter and more orthodox cylinders. The P-2 was the first Wright engine to incorporate a gear-driven centrifugal supercharger. During the development of the P-2, Frederick Rentschler, President of Wright, had a falling out with the board of directors and departed. C. L. Lawrance replaced Rentschler as president. Wright's top engineering, design, and production talent soon followed Rentschler, hurting the P-2 project. The engine was eventually type- and flight-tested in 1926, producing 435 hp at 1,800 rpm and 500 hp at 1,900 rpm and weight of 851 lb. The P-2 was never produced.<sup>5</sup>

In 1926, E. T. Jones, head of the powerplant section at McCook Field, and Sam Heron came to lead Wright's engineering team in the development of the R-1750. This 9-cylinder engine with a 6.000" bore and 6.875" stroke incorporated Heron's new type M cylinder with enclosed grease-lubricated valve gear and sodium-cooled exhaust valves. It was type-tested in 1927 with an output of 525 hp at 1,900 rpm and a weight of 760 lb. It was available with or without propeller reduction gears. About 100 R-1750s were sold to power a number of Navy twin-engine flying boats.<sup>5</sup>

In 1929, Wright merged with Curtiss, bringing the engine design talents of Arthur Nutt (of Curtiss D-12 fame) on board.<sup>5</sup>

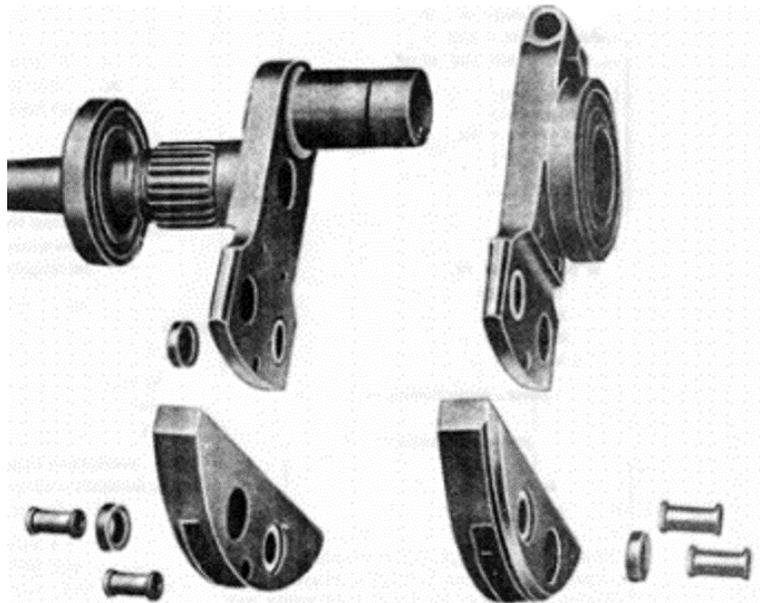
## Design and Development

In the early 1930s, Wright found itself developing no less than six engines... it was decided to throw all development effort into the Cyclone. The bore of the R-1750 was increased to 6.125" in 1932, and gave rise to the R-1820E. Air deflectors and individual spark plug coolers were provided, marking Wright's first example of attention to engine cooling in its final installation. The R-1820E introduced (for Wright) the first use of cast-in rocker arm housings. The R-1820E was rated at 575 hp at 1,900 rpm.<sup>5</sup>

The R-1820F Cyclone introduced several new features for Wright, including forged aluminum crankcases and actual supercharging via increases in the gear ratio of the supercharger impeller, a down-draft carburetor with automatic mixture control, cylinders with closer, deeper fins and tighter baffles for improved cooling, and improved valve gear lubrication. As better gasoline became available, compression ratios, top rpm and power ratings were increased. Provisions were also made for controllable-pitch propellers using engine oil as a hydraulic actuating medium.<sup>5</sup>

*Following paragraph retained verbatim because it finally gave insight to the mysterious "dynamic counterweights"... more comments after paragraph.*

"In 1934, geared R-1820s with controllable-pitch propellers began breaking propeller shafts. Orval Cook and Turner A. Aims of the Wright Field Propeller Branch traced the root of this difficulty to the increased weight of the new controllable-pitch propellers, which increased the effective propeller inertia to the point that crankshaft torsional periods fell into the engine operating range. E. S. Taylor of MIT proposed the use of pendulum dampers (*per note below in red, "vibration absorber" is preferred and "damper" misleading*). Roland Chilton of Wright designed a mechanism consisting of a large counterweight suspended like a pendulum from the crankshaft in a manner that allowed movement in the direction of rotation. Counterweight mass and pendulum length were calculated to vibrate at 4.5 (the number of power pulses per revolution) times the rate of crankshaft revolution, but out of phase with the crankshaft. This tended to remove crankshaft torsional vibration, reduce wear and tear on magnetos, supercharger drives, and propeller components. Chilton received a patent for this innovation, which has been used in almost every high-powered aircraft engine since."<sup>5</sup>



*reference figure below from this source... it is not clear from the illustration that once assembled there are any moving parts, but the key is that the two pins for each counterweight are smaller than the holes through the counterweights, thus allowing the counterweight (the pendulum) to swing a small distance circumferentially according to minor speed changes in the crankshaft. it is important to note that these are "absorbers" and not dampers (that work by changing motion into friction and thus heat). this basic design is called the bifilar type of CPVA (Centrifugal Pendulum Vibration Absorber)*

The F model crankcase was split along the cylinder centerline to form two sections. The cylinders were a further improvement of Sam Heron's type M cylinder, incorporating a steel barrel with machined cooling fins, screwed and shrunk into an aluminum head. Two valves were provided in the hemispherical head, with the exhaust valve being sodium-cooled. Valve lubrication was accomplished by periodically supplying pressurized lubricating oil via a manually operated valve to the rocker arm shafts. No provisions were made for returning this oil to the engine. A one-piece master rod necessitated the use of a two-piece crankshaft that was supported by massive roller bearings. The master rod bearing was steel-backed lead-indium-silver.<sup>5</sup>

Multi-pinion planetary reduction gearing was contained in a magnesium nose case that also housed the cam ring and roller cam followers. The supercharger was of General Electric design. Carburetion was via a two-barrel downdraft Holley. Scintilla magnetos mounted on the rear accessory housing provided ignition. Performance was from 575 to 890 hp and weight was typically around 1,000 lb.<sup>5</sup>

The G model Cyclone provided a forged steel crankcase and still more cooling area. It also was the first Wright engine to use a supercharger developed in-house. After realizing that the GE-designed supercharger was inefficient and hampering the overall power output of the engine, Wright engineer Kenneth Campbell developed a single-speed single-stage supercharger with an efficiency of 65% and a pressure ratio of 1.5. By the end of production, efficiencies of over 75% had been achieved. The Cyclone G also incorporated automatic valve gear lubrication for the first time at Wright. This was accomplished by forcing engine oil through the valve push rods and rocker arms. Excess oil was returned to the sump via the push rod housings.<sup>5</sup>

Numerous other small changes were made to the pistons, cylinder heads, induction system, and dynamic counterweight. The final series of the Cyclone line produced 1,525 take-off hp at 2,800 rpm with antidetonation injection and weighed 1,469 lb.<sup>5</sup> *someone recently told me that water injection systems were sometimes called antidetonation injection or ADI*

### **Service**

Wright had a number of significant design wins with the R-1820. It was chosen by Douglas to power the DC-2, DC-3 and SBD Dauntless; by Boeing to power the B-17; and by Grumman to power the FM (General Motors-built) Wildcat. It was even used to power the Army T-1 heavy tank. The majority of World War II engines were manufactured under license by Studebaker in facilities at South Bend and Fort Wayne, Indiana. After the war, Lycoming built R-1820s under license.<sup>5</sup>

Competition for the R-1820 came in the form of the Pratt & Whitney R-1830. Where the R-1820 was a single-row 9-cylinder engine, the R-1830 was a two-row 14-cylinder. Each company touted their respective advantages: The R-1820 was lighter and simpler, the R-1830 was smoother and smaller in diameter. Both were fine engines, but the (PW) R-1830 was built in far larger numbers than the R-1820.<sup>5</sup>

The R-1820 was copied by engineers of the former Soviet Bloc and continued to be manufactured in Poland and powered a number of passenger and agricultural aircraft including the Antonov AN-2.<sup>5</sup>

### **Specifics (R-1820-82)**<sup>5</sup>

Configuration:	9-cylinder, air-cooled single row fixed radial
Output:	1,525 hp @ 2,800 rpm and 56.5 in Hg @ S. L.
Weight:	1,469 lb.
Displacement:	1,823 in <sup>3</sup>
Compression Ratio:	6.8:1

### **Talking Points:**

- the The Cyclone encountered a significant problem that was solved with an innovative solution. The use of heavier constant-speed propellers resulted in crankshaft failures due to torsional resonance. The solution, developed by MIT, was the use of dynamic counterweights, which became standard features on subsequent large radial engines
- To improve exhaust valve cooling, Wright used hollow valve stems filled with sodium. Developed in an earlier Wright engine, the sodium melts and provides significantly better heat transfer than the ferrous-based valve stems

- It was also the first Wright engine to use automatic valvegear lubrication, forcing oil through the valve push rods and rocker arms
- Used on B-10, B-17, B-18, O-47B, OA-12, HU-16B, T-28B & A-24 in NMUSAF. Also DC-3, DC-5, S-2 Tracker, Helldiver, and Wildcat

## Allison V-1710

The only American liquid-cooled engine to see service in World War II was the Allison V-1710. Allison was in Indianapolis and had done well with Liberty modifications and reduction gears for others' engines.<sup>2</sup>



*Allison V-1710, currently next to P-38 Lightning. (Robeson photo)*

Around the time the Army was washing its hands of the Curtiss Conqueror, Allison began to develop its own engine, at the request of Allison General manager Norm Gilman. The target was 1,000 hp, and Allison intended that the engine should be large enough to deliver this power easily. A successful V-1710-A was test run in 1931 and delivered 650 hp at 2,400 RPM on 80-octane fuel. Development proceeded slowly until the Navy entered the picture. The Navy, while not losing its attachment to air-cooled power plants for airplanes, it still needed liquid cooling for dirigibles. The Navy requested eliminating the supercharger (rotary induction blower) in favor of two carburetors placed in the Vee of the engine. A significant redesign was undertaken by R.M. Hazen in 1936. This "C"-model passed its acceptance test in 1937, establishing a rating of 1,000 hp at 2,600 rpm at sea level<sup>11</sup>, and became the first American engine to qualify at 1000 hp for the new 150-hour military type test.<sup>23</sup>

The V-1710-C was the first in the "long nose" series that provided a basis for later improved and higher-powered versions. Allison designers created the long nose by extending the propeller shaft about 12 inches to maximize streamlining.<sup>23</sup> A number of incremental improvements were made during the life of the "C"-model, eventually leading to "C"-models with takeoff ratings of 1,150 hp at 2,950 rpm and supporting 3,500 rpm for overspeed during dives.<sup>11</sup>

After the loss of the dirigible Macon in 1935, the USN lost interest in dirigibles and the V-1710, but GM remained committed, enlarged the Indianapolis plant and provided the capital to get the V-1710 to production.<sup>2</sup>

It was one of the most important large USA aero engines, with over 70,000 engines produced from the time of the first in 1931 to the last in 1948. The engine was produced for several important fighters of WWII, including the P-38 Lightning, P-39 Airacobra, P-40 Warhawk, P-51A Mustang, P-63 Kingcobra, P-82 Twin Mustang and the Consolidated XA-11A, an experimental attack version of the Consolidated P-25.<sup>11</sup>

The production engines turned out to be sturdy and reliable but its real shortcoming was its inability to deliver power at sufficiently high altitudes. This resulted from an early Army decision to rely on turbosupercharging to obtain adequate power at combat heights. During World War II the shortage of alloying materials, especially tungsten, made it impossible to make turbosuperchargers for any but a small proportion of the Allison. Bomber engines got the priority. The few turbosupercharged Allison engines that were made were allocated to P-38's making the high-altitude performance of that plane its best feature. All 14,000 P-40s got gear-driven superchargers and, as a result, were never first-rate fighter planes. There is no doubt that the deletion of the turbosupercharger ruined the P-39 making it only useful as a ground-attack plane.<sup>2</sup>

Had Allison's engineers been able to put the effort into gear-driven superchargers that Pratt and Whitney and Rolls-Royce did, it might have been a different story. As it was, there can be little doubt that the V-1710 had more potential than was actually exploited.<sup>11</sup>

The Allison V-1710 powered most U.S. Army fighters in World War II including the Lockheed P-38, Bell P-39, P-63, Curtiss P-40, and early North American P-51s.<sup>23</sup>

**Specifications: Allison V-1710-G6<sup>11</sup>**

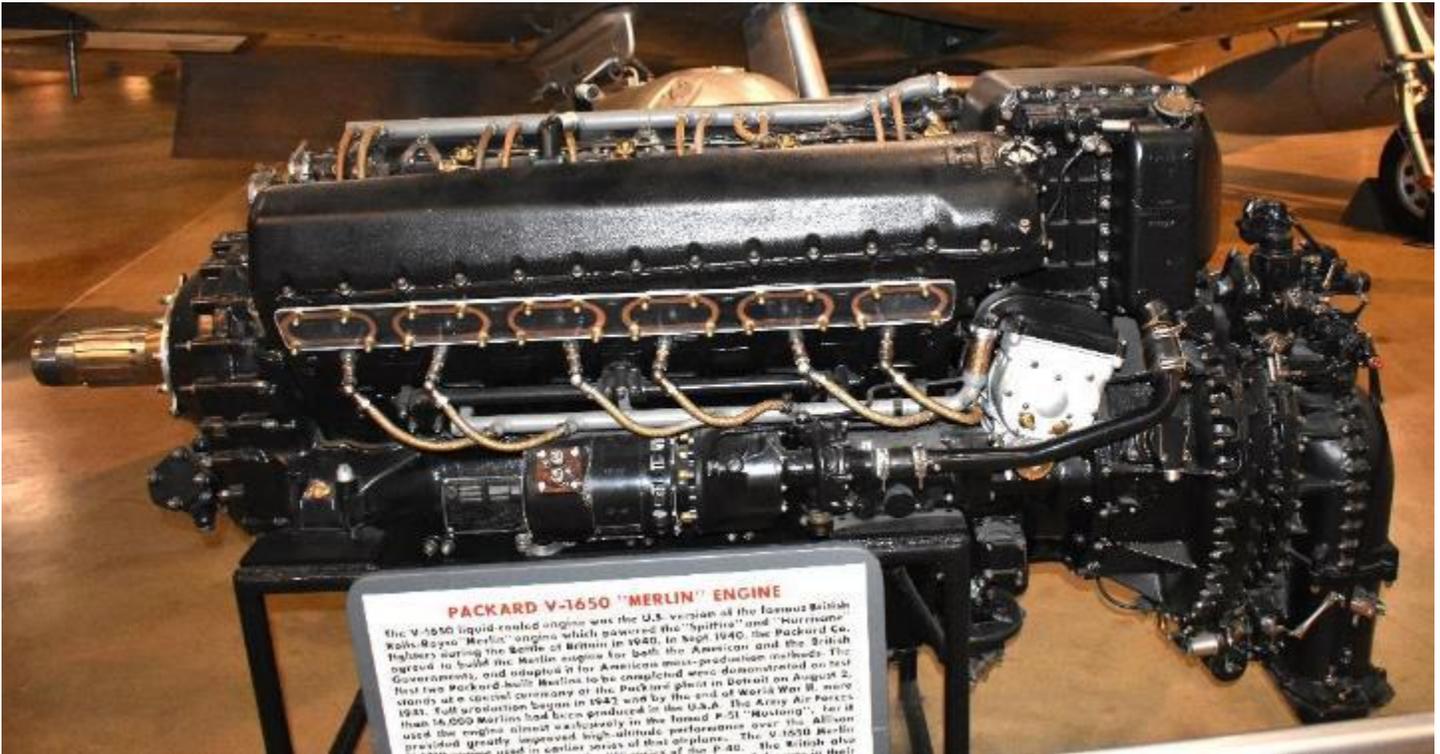
Cylinders:	12
Configuration:	V type, Liquid cooled
Horsepower:	1,250 hp
R.P.M.:	3,200
Displacement:	1,710 cu. in.
Weight:	1,595 lbs.

**Talking Points:**

- The only American liquid-cooled engine to see service in World War II
- Although the US Navy specified air-cooled engines for its aircraft in 1921, it helped fund Allison for the development of this new 1000 hp liquid-cooled engine for use on its dirigibles
- Over 70,000 engines were produced between 1931 in 1948, and were used in the P-38 Lightning, P-39 Airacobra, P-40 Warhawk, P-51A Mustang, P-63 Kingcobra, and P-82 Twin Mustang
- The V-1710's shortcoming was its inability to deliver power at higher altitudes. The V-1710 was designed for turbosupercharging, but war priorities favored the bombers over the fighters. Thus, the P-38 excelled at high altitudes with its turbosupercharger, but many other fighter applications were relegated to ground attack
- Used on P-39Q, P-40E, P-38L, A-36A, and P-82G in NMUSAF. Also early P-51's and P-63

## Packard V-1650 Merlin

In the US, Packard built Merlins with detachable heads, a modification soon adopted, to the benefit of the engine by Rolls-Royce itself. The Packard Merlins were the engines that transformed the P-51 from a mediocre fighter with the Allison engine into what may have been the best all-of round fighter of the war.<sup>2</sup>



**Packard V-1650 Merlin, between P-38 and P-51D. (Robeson photo)**

The Packard/Rolls-Royce relationship goes back a long way. They came into existence as car companies in 1899 and 1904 respectively. The first production Merlin I appeared in 1936 and the Merlin II the next year. Engineering refinements meant that by the end of the war, the Merlin 66, an intercooled variant of the engine sporting a two-stage, two-speed supercharger, was making 2,050 hp (increased from 1,030 hp in the Merlin II)—and these improved engines were allowing aircraft to operate at significantly higher altitudes, as well.<sup>16</sup>

Packard investigated building Merlin's under license as early as 1938, but it was the outbreak of WWII in September 1939 that got things moving. Before Packard got involved, Henry Ford committed to building Merlins in 1940 but controversially backed out when he learned some of the Merlins were for use by England and not the US. Packard quickly got the blueprints already delivered to Ford and went to work. All drawings had to be redone for American conventions and creating tolerances applicable to mass production. Merlins at Rolls-Royce often involved parts being reworked to fit where mass production methods demanded tolerances such that any part fit without rework. The engine also had to be modified so that it could be fitted with American fittings and accessories [for example, carburetors, fuel pumps, generators and so on] or British accessories and fittings, depending upon which government the engine was intended for.<sup>16</sup>

The first Packard Merlin ran in August 1941, and in total delivered 55,523 engines. Rolls-Royce produced 82,117 Merlins at three plants, switching over to mass-production tolerancing, and another 30,428 were built by Ford of Britain.<sup>16</sup>

Some other improvements made by Packard, such as a two-piece cylinder block, had actually been planned by Rolls-Royce but not yet implemented.<sup>16</sup>

**Talking Points:**

- The first Merlin appeared in 1936, and Packard investigated licensed production in 1938.
- Henry Ford committed to building Merlin's in 1940 but reneged on the deal and soon Packard was starting work
- Packard delivered over 55,000 Merlin's, Rolls-Royce built over 82,000, and Ford of Britain built another 30,000

- In NMUSAF, Packard Merlin on P-51D, F-82B; Rolls-Royce Merlin on, Spitfire PR.XI and Mk. Vc, Hurricane Mk.IIa, and DH 98 Mosquito. Packard Merlins also used Lancaster, other Marks of Spitfire, Hurricane, Mosquito, and P-40F/L. RR Merlins also used on Lancaster, Halifax, Lincoln, Beaufighter, Mosquito, Wellingtons and British Mustangs

## Wright R-3350 Duplex Cyclone

On September 29, 1946, a Navy P2V1 Neptune named the “Truculent Turtle” left Perth, Australia and flew 11,236 miles unrefueled to Columbus, Ohio, a record that stood until the Voyager flight around the world during the fall of 1986. The P2V1 was powered by two Wright R-3350 Cyclones.<sup>7</sup>



*Wright R-3350 Duplex Cyclone, port side of Bockscar (Robeson photo)*

### History

Work began on the R-3350 in January of 1936, nearly 18 months before the engine upon which it was based, the R-2600, passed its type test. The R-2600 was Wright’s first successful two-row radial. By 1930, it had become clear that single-row radials had reached a displacement limit of around 1,860 in<sup>3</sup> and that cylinders of more than 207 in<sup>3</sup> were impractical. Both Pratt & Whitney and Wright had experimented with multi-row engines during the 1930s.<sup>7</sup>

When the Army requested proposals for a bomber capable of striking targets in Japan, all five bidders proposed the R-3350. The Army ultimately selected the Boeing XB-29 Superfortress and the Consolidated XB-32 Dominator for production. Only seven engines had been delivered to the Air Force for the XB-19 project prior to the B-29 order of April 15, 1941. These early R-3350s had performed acceptably, but they had not flown very many hours and all accumulated time had been at low power settings and low altitudes. When they got to the XB-29 and XB-32 bomber programs, quite a different picture would emerge.<sup>7</sup>

March of 1944 was set as the target date for B-29s to be operational in China.<sup>7</sup>

Wright was meanwhile gearing up with new plants and subcontractors for the R-3350. Plant #7 was constructed in Woodridge, NJ. Chrysler Dodge built a new plant in Chicago to manufacture the engines under license. B-29s were in the

meantime rolling off the Wichita, Kansas assembly line without engines. These engines were later installed outside under abysmal wintertime conditions.<sup>7</sup>

## **Design and Development**

### **ORIGINAL DESIGN**

The R-3350 used 9 cylinders per row (18 total) with the same bore and stroke as the R-2600, which used 7 (14 total). Cylinders employed forged steel barrels screwed and shrunk into cast aluminum heads with two valves and a hemispherical combustion chamber. Exhaust valves were sodium cooled. Departing from the traditional machined steel cooling fins on the cylinder barrels, Wright applied their patented “W” finning, which used very thin aluminum sheet metal fin segments that were swaged into grooves in the steel cylinder barrel. This increased cooling area (3,900 in<sup>2</sup> per cylinder) and the ability to repair battle damage via fin replacement.<sup>7</sup>

A three-piece crankcase split along cylinder row centers was utilized. Initial cases were aluminum, later ones forged steel. The crankcase supported a three-piece two-throw split-clamp-type crankshaft on three large roller bearings (front, center, rear). One-piece master rods with silver-lead-indium bearings were used. Each crankshaft throw was fitted with a dynamic counterweight. Dual dynamic counterweights had been sufficient to damp torsional vibration on previous double row engines, all of which had been less than nine cylinders per row. Once nine cylinders per row were introduced, a nasty second-order (twice the frequency of crankshaft rotation) vibration appeared which resulted in propeller shaft fatigue failures.<sup>7</sup>

Radial engines employing the master/articulating rod system exhibit a secondary unbalance due to the different motion of each piston. In single row engines, this tends to whirl the engine in a circle eccentric to the crankshaft. This tendency becomes worse as the number of cylinders per row increases. Two-row engines have this same motion in each row, but the two whirling circles are out of phase with one another and tend to wobble the engine about its center main bearing. As a result, the propeller constantly tries to change its plane of rotation, bending the propeller shaft until it eventually breaks. The cure is one or more secondary balance weights for each row rotating at twice crankshaft speed. These rotating weights oppose the inherent wobble.<sup>7</sup>

Wright used a supercharger developed in-house for the R-3350, considerably improving on the ones previously designed by General Electric.<sup>7</sup>

### **INITIAL FLIGHT TEST PROGRAM**

By September of 1942, Wright had shipped 65 engines to the XB-29, XB-32, and Lockheed Ventilation (a twin-engine test aircraft) test programs. All three aircraft flew for the first time in September. Problems were immediate and widespread.<sup>7</sup>

One change that was not approved would cost dearly in service. Wright wanted to use forged cylinder heads in place of the cast ones. These would have allowed better cooling and higher outputs. Nevertheless, U.S. forging capacity was insufficient at the time, and many aircraft and crew were sacrificed as a result.<sup>7</sup>

All involved wanted to replace carburetors with direct fuel injection. Large, highly supercharged engines with giant induction systems full of compressed explosive vapor are prone to severe damage from backfires. Although the backfires were typically caused by careless operation by inexperienced crews, everyone knew that proper training would take too long and delay the program. The obvious solution was to mix fuel with air at the latest possible moment, preferably in the cylinder. Unfortunately, manufacturing tolerances of direct injection fuel pumps were too stringent for the U.S. at the time, and a number of other solutions were tried. The one that worked first was to adapt existing Bendix-Stromberg pressure carburetors to serve as control units, metering fuel to two nine-cylinder injection pumps. Two pumps were

used to allow engineers to tweak the fuel-air mixture between front and rear cylinder rows and compensate for differences in the amount of air delivered to each by the imperfect induction system.<sup>7</sup>

Improvements resulting from the XB-29 No. 2 post-crash investigation, coupled with other changes identified when the R-3350 finally entered service, forced an almost unbelievable 48,500 engineering and tooling changes upon engine builders and subcontractors.<sup>7</sup>

#### RENEWED FLIGHT TEST PROGRAM AND TRAINING

The March 1944 deployment date stayed firm. Although everyone knew that the R-3350 suffered cooling problems, these were to some extent worked around by changes in operation, power limits, ground run-time limits, and cowl flap usage.<sup>7</sup>

#### Service

The first two B-29s, each with a spare R-3350 slung in its bomb bay, landed in China on April 24, 1944. ...caused many engine failures and aircraft losses. B-29s were flying twelve-hour missions with six of those hours with power settings of 80% or better. Efforts eventually produced acceptable fixes for the overheating in the form of revised operational techniques, tighter-fitting baffles, better front exhaust collectors, careful cylinder head temperature indicator calibration, and performance sacrifices. Perhaps the most important was a change in strategy from high-altitude formation to low altitude raids. Since the engines did not have to endure the long climb to altitude, they fared better.<sup>7</sup>

It was fitted with variable spark advance and three exhaust turbines whose output shafts were geared to the crankshaft through fluid couplings. This added about 600 hp to the take-off power rating. At the start of service, R-3350s averaged about 100 hours before overhaul. This number rose to 400 by the end of the war. In airline service, it became reliable (in some cases with a time-between-overhaul of 3,000 hours) and produced more power than any other with a final take-off rating of 3,700 horsepower. These high powers were achieved with the best specific fuel consumption of any gasoline aircraft engine - about 0.38 lb./hp/hr. An old joke among airline pilots who flew both was: "A DC-6 is a four-engine airplane with three-bladed props, while a DC-7 is a three-engine airplane with four-bladed props!"<sup>7</sup>

The R-3350 powered the B-29, and after the war Wright put turbo-compounding on this engine. It had three blow-down turbines that gave the engine 20% more efficiency and enabled the Lockheed Constellation and the Douglas DC-7 to fly nonstop across the US. Turbocompounding differs from turbocharging in that it does not put an excess burden on the cylinders, but simply takes the waste exhaust gases and converts them into power at the crankshaft by means of shafts and fluid drive couplings.<sup>9</sup>

The PRT (Power Recovery Turbine) was an exhaust turbine drive mechanical device that was coupled directly to the engine crankshaft. Three PRTs were inserted into the exhaust piping of each group of six cylinders and were geared to the engine crankshaft by fluid couplings. PRTs recovered about 20 percent of the exhaust energy equaling about 550 horsepower at take-off power and 240 horsepower at cruise settings over a similar non-turbo-compounded R-3350. Operation of the PRTs is fully automatic the increased power was achieved with a weight penalty of about 500 pounds.<sup>37</sup>

Allison, Pratt & Whitney and Napier all carried out developmental work with the turbo-compounding concept, but Wright was the only aircraft engine manufacturer to put a turbo-compound engine into production. The first production turbo-compound R-3350s were delivered in March 1950. Initially, all Turbo Compound R-3350s were for the US military and commercial turbo-compounds were not produced until January 1952.<sup>37</sup>

#### Specifics (981TC18EA Turbo Cyclone)<sup>7</sup>

Configuration:	18-cylinder air-cooled two-row fixed radial with 3 exhaust-driven blow-down turbines
Output:	3,700 hp @ 2,900 rpm and 59.5 in Hg @ S. L.

Weight: 3,670 lb.  
Displacement: 3,350 in<sup>3</sup>  
Compression Ratio: 6.7:1

**Talking Points:**

- The Duplex Cyclone was selected by the Army to power the new B-29 Superfortress. Development was painful, delaying the appearance of the B-29
- The first B-29's delivered to China each had a spare R-3350 in its bomb bay, and overheating problems led to many engine failures and aircraft losses
- Operational changes in Japan requiring lower altitude firebombing improved reliability because long times climbing to altitude were eliminated
- After the war, Wright added turbo-compounding, with three turbines driven by exhaust gases, adding shaft horsepower to the crankshaft. These versions were used in the Lockheed Constellation and the Douglas DC-7
- Used on B-29, A-1E, A-1H, C-119J, VC-121E & EC-121D in NMUSAF. Also DC-7, Martin Mars, USN Neptune and Sea Fury

## Pratt & Whitney R-4360 Wasp Major

Pratt & Whitney's 28-cylinder, four-row radial, the R-4360, was the largest and most complex aircraft piston engine to enter production in the West. After cancellation of P & W's liquid cooled sleeve valve efforts, the R-4360 was rushed into development with an initial rating of over 3000 hp. Although too late for WWII, it played a significant part in postwar military aviation and to a lesser degree, in commercial aviation.<sup>1</sup>



*PW R-4360 Wasp Major (motion activated, starboard side of C-124) (Robeson photo)*

## Introduction

As the gas turbine became prominent, more engineering talent was siphoned off for this new form of motive power, leaving the R-4360 program short of engineering talent at critical times during its development.<sup>1</sup>

Pratt & Whitney's brilliant engine designer, Luke Hobbs, chose to follow the path they were familiar with; an air-cooled radial. Wisely, Pratt & Whitney chose to use the same cylinder dimensions used on the successful R-2800.<sup>1</sup> He initially evaluated configurations of 3 rows of 9 cylinders, 4 rows of 7 cylinders, and 6 rows of 5 cylinders before settling on the 4 row, 28 cylinder configuration.<sup>50</sup> Twenty-eight R-2800 sized cylinders resulted, in a displacement of 4,363 cubic inches.<sup>1</sup>

Serious design efforts were initiated on 11 November 1940 with the first proof of concept engine running on 28 April 1941. The unusual fore-and-aft valve positions had evolved, though the first attempts placed the exhaust port on top of the cylinder and the intake off to the side. In retrospect, this may have been the better arrangement than the one finally chosen.<sup>1</sup>

The first flight with the R-4360's was on 25 April 1942, powering a modified Vultee Vengeance dive-bomber and designated V-85.<sup>1</sup> The first production engine was shipped in January, 1945.<sup>50</sup>

## R-4360 Main Production Design Features

Unlike the R-2800, for instance, which went through major redesigns, the R-4360 only went through incremental improvements during its production life span.<sup>1</sup>

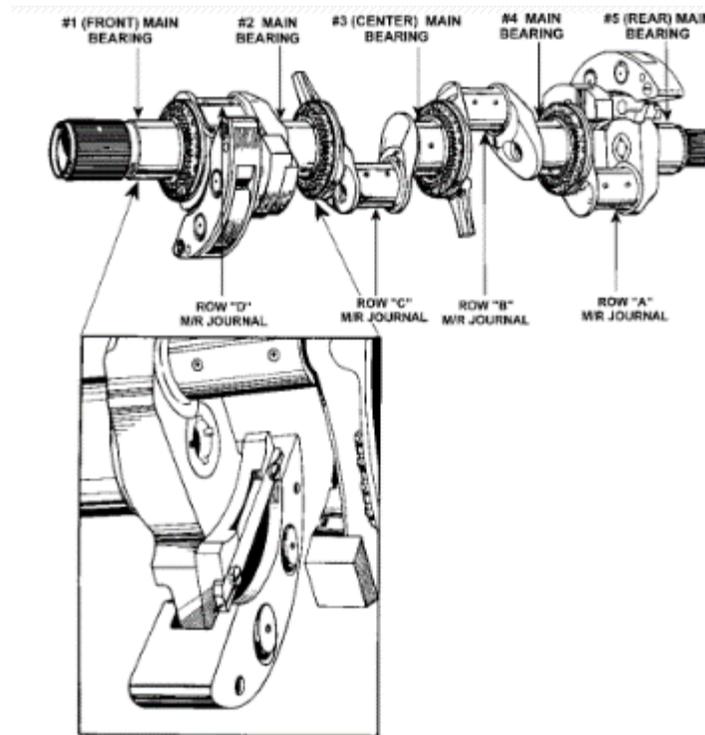
Not only did this concept give perfectly even firing but it also had the additional advantage that in the event of a magneto failure, only one bank, i.e., four cylinders, would be lost, which reduces vibration due to uneven firing. For smoothness and reduced engine stress, even firing is always advantageous.<sup>1</sup>

### Crankshaft Design

For the R-4360, Pratt & Whitney chose to take the more prudent route of a one-piece crankshaft with split master rods.<sup>1</sup>

During its early development, the R-4360 was top secret and to make sure it stayed this way some innovative red herrings were implemented. One of these red herrings was to call out five throws on the crankshaft drawings and this is how the first few crankshaft forgings were manufactured by one of Pratt & Whitney's vendors. Of course, as soon as the crank was received at Pratt & Whitney, the extra master rod and main bearing journals were machined off!<sup>1</sup>

### Vibration



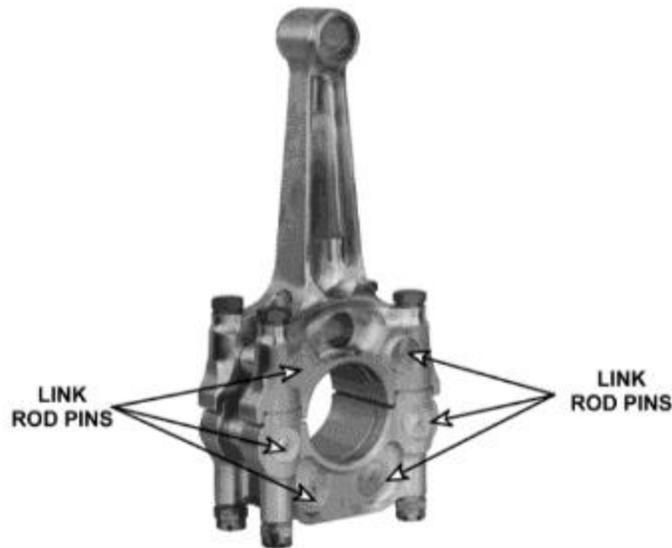
*Figure 6. Engineering elegance at its finest – the R-4360 crankshaft. This view also shows to advantage the bifilar dynamic counterweight, the master rod journals and main bearing journals.<sup>1</sup>*

The pairs of crank throws A, B and C, D each produce additive rocking couples which tend to rotate the crankshaft in a counter clockwise direction. However, these couples and any other unbalanced primary force of significance may be balanced simply by a pair of dynamic counterweights located at extreme ends of the crank at the number one and number five main bearing crank webs. They are of the "bifilar" type, in other words, a floating dynamic counter weight is supported on two floating bushings and rollers (Figure 6).<sup>1</sup>

To further assist in attenuating vibration, fixed, bolt-on counterweights are attached at the ends of the crank, inboard of the D and A crank throws. Pratt & Whitney called in the cavalry in the form of J.P. Den Hartog, the world's most respected vibration expert. Early crankshafts were breaking at the crank cheek. In a counterintuitive move, Den Hartog recommended removing material in order to make the crankshaft less rigid. Once again, Den Hartog worked his magic.<sup>1</sup>

## Master and Link Rods

Pratt & Whitney had extensive experience in the design of two-piece master rods. Split along the centerline of the master rod bearing, the upper half contained the master rod and a link rod on both sides (Figure 7). The bearing cap contained the four remaining link rods. Bronze bearings are pressed into both ends of each link rod, which ride on hardened steel pins. Four precision bolts attach the cap to its master rod. Each pair of bolts straddles the link rods. Holes drilled through the link-rod pins closest to the bearing parting line allow the bolts to pass through.<sup>1</sup>



*Figure 7. Pratt & Whitney chose to use a conventional design for this highly stressed component. R-1535, R-1830 and R-2000 influence is apparent. These engines also used two-piece master rods.<sup>1</sup>*

One inevitable by-product of running a high-performance engine is debris entering the oil system. This debris can take the form of carbon from combustion or wear particles from other engine components. Bearings need to have “embeddibility”, in other words, the capability to absorb small particles of debris within the bearing material, without compromising bearing performance.<sup>1</sup>

Based on Pratt & Whitney’s pioneering work in the 1930s a lead/indium silver bearing is employed, not only for the master rod, but other key load bearing components such as the crankshaft main bearings and reduction gear pinion bearings.<sup>1</sup>

## Crankcase Design

Pratt & Whitney found out from its very first engine, the R-1340 Wasp, an aluminum forging offered the best material and mechanical properties for radial engine crankcase construction. Pratt & Whitney’s solution was to use a five-piece construction with the five sections stacked in line so as to form the basic crankcase. The center line through each cylinder row represented the parting line between sections. In this way, the middle of each crankcase section of the three center sections supports a crankshaft main bearing.<sup>1</sup>

With a one-piece crankshaft, a hole was required in the three center sections of the crankcase that would accommodate the main bearing carrier. In this way, the crankcase sections could be slipped over the one-piece crankshaft. The three center main bearing carriers are manufactured from magnesium and are located in a steel ring pressed into the forged aluminum crankcase section. Under operating conditions, the magnesium carrier expands more than the steel ring thus ensuring an interference fit and the requisite rigidity.<sup>1</sup>

## Engine Cooling

At the time of its early design, 1941, Pratt & Whitney were getting into full stride developing a forged cylinder head for the "C" series R-2800. With the capability of unlimited depth and any number of cooling fins, it became a no-brainer to use forged heads. Commensurate with the requirement to keep head temperatures at something below a value that would not cause undue stress to the engine, i.e., less than 500°F (260°C), cooling drag had to be kept to a minimum.<sup>1</sup>

Contrary to popular belief, the drag of a radial engine is not so much related to frontal area but rather the momentum of cooling flow into the engine cowl. In other words, a large pressure drop would indicate a large mass airflow throughout the cowl, which was not good for low drag. It had been determined, via exhaustive testing, that the required cooling air flow requirements get into gas turbine territory. Testing had indicated that a mass air flow of 6,250 pounds per hour per cylinder was required to cool the R-4360 at take-off power. This amounts to a staggering rate 48.6 pounds of cooling air per second.<sup>1</sup>

Normal radial engine cooling, whether it is for a single row or two-row, requires the cooling air follow a straight-through path. The R-4360 concept was quite different. Instead, seven plenums (extended chambers) are created between rows of cylinders. Air enters the plenum and is forced through the cylinders (Figure 9).<sup>1</sup>

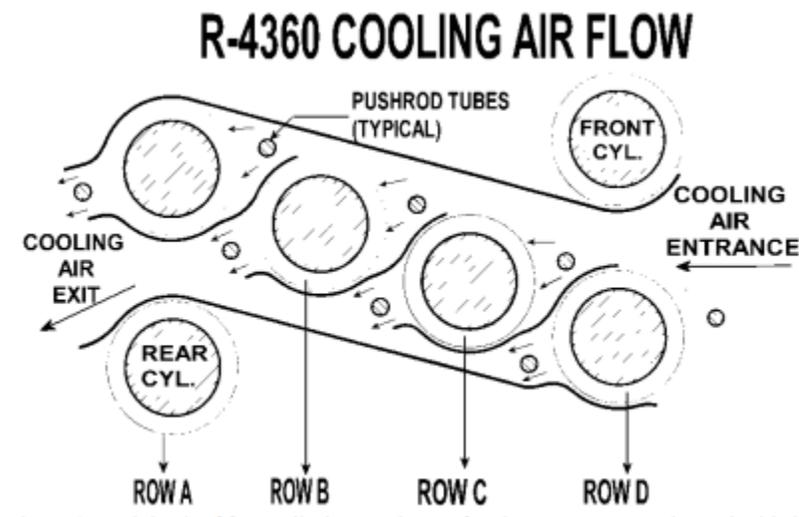


Figure 9. Each bank of four cylinders made up of a plenum system as shown in this line drawing.<sup>1</sup> (note row A is at rear, D is at front)

Cooling airflow is helped with extensive baffling of the cylinders so every ounce of mass airflow is put to good use. Furthermore, it was imperative that any R-4360 application sealed the cooling air to avoid leakage.<sup>1</sup>

As an example, at take-off power on a 100°F day, over 50 pounds per second is required to keep things cool. Of course, at the start of the take-off roll, this kind of mass air flow is not possible; instead, the engine relies on its 3,500 pounds of mass to absorb heat until sufficient air speed has built up to generate the required air flow through the cooling fins.<sup>1</sup>

## Cylinder Design

Following the successful design of the R-2800 combustion chamber, the R-4360 followed suit with a two-valve hemispherical design. When Pratt & Whitney developed the R-2180, often described as half a R-4360, the top exhaust and side inlet was, once again, employed.<sup>1</sup>

All cylinders were interchangeable, unlike most other multi-row radial which require different cylinders for the front and rear rows. Even more remarkable was the fact cylinders could be rotated 180 degrees to accommodate a pusher or

tractor installation. However, a different cam rings would be required depending on whether it was a pusher or tractor. Even so, this clearly helped with spare parts inventories for the military which operated R-4360s in both configurations.<sup>1</sup>

Construction of the R-4360 cylinder followed advanced air-cooled radial practice, i.e., the forged head is screwed and shrunk onto a steel barrel. Interestingly, all cooling fins on the barrel as well as the cylinder head are in the horizontal axis. Not only does this improve cooling, it makes for an easier manufacturing job in not having to worry about machining fins in two (horizontal and vertical) axes.<sup>1</sup>

### **To Scavenge or Not to Scavenge**

A dry sump lubrication system was employed. Two main lines connect the tank to the engine: “oil in” and “oil out”. As their names suggest, the oil-in line supplies oil to the suction side of the main engine pressure pump. After performing its lubrication duties, the oil is sucked out of the engine via scavenge pumps through the “oil-out” line. Scavenge oil (oil out) is pumped through a cooler(s) and then back to the oil tank. Pratt & Whitney learned this valuable lesson when developing the R2800. Early “A” series R-2800s were rated at 1850 horsepower. Follow-on “B” series R-2800s were rated at 2000 horsepower. The additional 150 horsepower came by simply improving the scavenging efficiency of the oil system. And this improvement was obtained through the ridiculously simple expedient of opening up drain holes in the crankcase sections. As an added bonus, the “B” series engine imparted less heat in the oil so a smaller oil-cooler could be used.<sup>1</sup>

In another departure from previous practice, the R-4360 used a gerotor type scavenge pump in each crankcase section. These four pumps were driven off the cam drive gears. It is unclear when the gerotor type pump was first developed but the R-4360 must have been one of the first applications of this type.<sup>1</sup>

### **Ignition**

Two basic types of ignition systems were employed by the R-4360: high tension and low tension. The better of the two was demonstrably low tension; however, this superior system was still under development during the R-4360’s embryonic years. A significant problem when operating an ignition system at high altitude was that of cross fire (a type of short-circuiting) due to the low dielectric strength of the upper atmosphere. With the reduced insulation value of the upper atmosphere, it was possible for the 20,000 volt high tension intended for the spark plug to take the path of least resistance. This resulted in cross firing inside the magneto. Low-tension ignition solved these and other ignition related woes. Instead of generating 20,000, or greater, voltage, the magneto generates 100 to 150 volts. High tension is generated at the cylinder head via step-up transformer or coil – one for each of the 56 spark plugs. Early B-36s fitted with high-tension ignition suffered greatly with ignition problems because of the high-altitude capability of this remarkable aircraft. Over 50,000 ft was attained with the lightly loaded reconnaissance versions of this aircraft.<sup>1</sup>

#### **High-Tension**

All early R-4360s used high-tension ignition in the form of seven Bendix D-4RN-2 magnetos. Arranged radial fashion around the periphery of the magneto drive case, the magnetos each fired eight spark plugs in the four cylinders making up a bank. Unlike many ignition systems, both magneto and distributor requirements are assembled in one unit. In the event of a magneto failing, four cylinders would drop out leaving the remaining 24 cylinders to pick up the slack.<sup>16</sup> With the high-altitude capability of the R-4360, it was inevitable that high altitude flashover would occur. The usual answer to in this scenario is to pressurize the magnetos. A pressurization pump ensured that a sea-level atmosphere was maintained within the magneto regardless of altitude. Even this arrangement had its problems. It was critical that pressurized air was allowed to bleed off, otherwise dangerous amounts of nitric acid would build up in the distributor (the nitric oxide presumably coming from electrical discharges).<sup>1</sup>

#### **Low-Tension**

Once the clear advantage of low-tension ignition had been proved with some models of the “C” series R-2800, the R-4360 followed suit. For highflying aircraft such as the B-36 low-tension ignition solved many operating and maintenance woes. Still arranged radial fashion around the front accessory case, the number of magnetos was reduced to four. Each magneto fired the seven cylinders making up a row. Unlike other engines employing low-tension ignition, the R4360 used a boost coil for each spark plug, 56 in all. Normal practice was to use a single boost coil per cylinder with two outputs, one for the front plug and one for the rear.<sup>1</sup>

### **Front Section**

Following a similar concept to the “C” series R-2800, the front section was made up of two major assemblies; the “propeller shaft case” and the “magneto drive case”.<sup>1</sup>

A multi-pinion epicyclical reduction gearing is also housed in the propeller shaft case. A bevel gear, attached to the pinion shaft support, drives the propeller governor and the front section scavenge pump which mounts at the bottom of the propeller shaft case. This scavenge pump is made up of three chambers; the top one scavenges oil from the propeller shaft case and magneto drive housing, the middle chamber scavenges the rocker box front sump and the bottom chamber scavenges the front cam compartment.<sup>1</sup>

The magneto drive housing, sandwiched between the propeller shaft section and the front of the crankcase, is packed full of components. These include the magneto drive requirements, seven magnetos, spark advance mechanism and the torquemeter.<sup>1</sup>

Not all R-4360s were equipped with a torquemeter.<sup>1</sup>

### **Dual/Contra-Rotating Nose Cases**

A 3,000 to 4,000 horsepower engine sounds very attractive to the airframe manufacturers, which is why all the major aircraft companies designed at least one aircraft around the R-4360. However, that prodigious power comes with liabilities, mainly in the form of torque reaction. One solution was contra-rotating propellers. The drawback is added weight from the increased gearing and the weight and complexity of an additional propeller. A good example of the propeller issue was the ill-fated Hughes XF-11 which featured a Hamilton Standard “Super” Hydromatic propeller. Failure of one of the propellers almost cost Hughes his life. But apart from the XF-11, a number of aircraft were powered by R-4360s driving contra-rotating propellers. These included the Northrop XB-35, Boeing XF8B-1 and Douglas XTB2D-1 Skypirate. None of these aircraft entered full scale production.<sup>1</sup>

The B-36 was one of the few completely successful shaft-drive airplanes. The engines were buried in the thickest part of the wing and drove the pusher propellers through long rearward extension shafts. Probably the main reason for its success was the large number of cylinders. A four-cycle engine with 28 cylinders has 14 power impulses per revolution reducing the torque variation to a negligible factor in comparison with the six impulses that a 12-cylinder engine would produce.<sup>2</sup>

### **Rear Section**

The rear section can be considered everything behind the crankcase. This means the supercharger, accessory drive housing, intake ducting from the carburetor and auxiliary drive housing.<sup>1</sup>

### **Supercharger**

With the exception of the VDT engines, all R-4360s used some form of gear driven supercharger. *Curious that VDT is not defined in this source! It stands for Variable Discharge Turbine, and on the R-4360 it refers to a configuration using power recover turbines. Like turbochargers, they draw power from the exhaust, but instead of driving a compressor they return extracted power directly to the crankshaft through fluid couplings.* Right from the initial design studies, flexibility

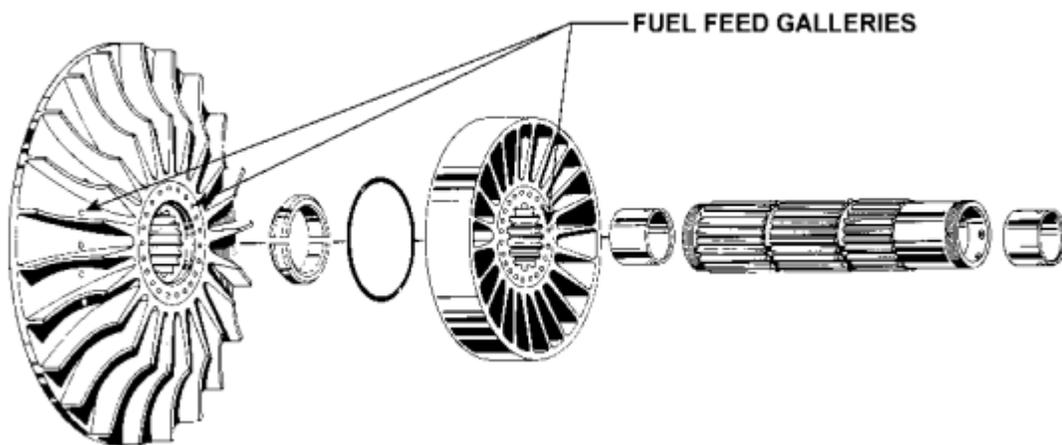
was designed into the R-4360. Depending on mission profile, R-4360s could have the following supercharger configurations; (i) relatively simple and basic single stage, single speed supercharger, (ii) single stage, two speed, (iii) single stage - variable speed, (iv) single stage with an auxiliary intercooled gear driven supercharger and (v) single stage augmented by turbosupercharging. The foregoing does not include the VDT which utilized turbosupercharging for all its boost requirements.<sup>1</sup>

The supercharger casing is made from a complex and intricate magnesium casting bolted to the crankcase. With the simple single stage, single speed blower, a two-stage step-up gear is used to obtain the appropriate ratio. All the engines augmented with turbo-supercharging used this set-up.<sup>1</sup>

### **Supercharger Impeller Assembly**

Although typical of its type, the centrifugal supercharger employed by the R-4360 benefited from years of prior experience using this method of boosting manifold pressure. Although ostensibly a centrifugal supercharger, the impeller employed a significant axial flow component.<sup>1</sup>

In 1942 Pratt & Whitney patented their “slinger ring” concept of fuel distribution. Wright Aeronautical copied this unique method of getting fuel accurately distributed for its radials such as the later R-1820s and R-3350s (Figure 22). Fuel enters the supercharger via the fuel feed valve, essentially a low-pressure pintle-type valve. Fuel is injected into an annular groove machined into the impeller shaft. To avoid fuel leaking into the blower section, sealing rings are employed. Therefore, fuel injected into the annular groove can only go to one place; into the impeller throat. A ring, the so-called slinger ring, picks up fuel from the annular groove. With multiple small holes drilled into its periphery, fuel is centrifuged into the eye of the impeller where it gets slung out under the powerful influence of centrifugal force. Further assisting fuel distribution are galleries drilled between each vane of the supercharger impeller, thus some fuel enters these galleries to be slung out through exit holes positioned at about half the diameter of the impeller.<sup>1</sup>



*Figure 22. Supercharger shaft and impeller assembly showing unique fuel feed system.*

### **Accessory Drive Case**

As related above, the R-4360 was designed to be as flexible as possible. This means that with relatively minor modifications, it could power everything from a single-engine fighter to multi engine strategic bombers. For example, a R-4360-35 which would normally power a Boeing B-50 bomber. The 3,800hp is achieved with the aid of ADI and 61.5in. Hg manifold pressure and 2,800rpm. Power ranged from 3,000hp for early production models to 4,300hp for the VDT variants.<sup>1</sup>

Part of this flexibility was the use of auxiliary superchargers and pusher installations with fan-assisted cooling. Typical radial engine design locates accessories such as starters and generators at the rear and mounted in the same longitudinal axis as the engine. Not only did this increase the length of the engine, it also negated the possibility of easily mounting a cooling fan or a bolt-on auxiliary supercharger on the rear face of the engine.<sup>1</sup>

In contrast Pratt & Whitney engineers thought laterally. A large ring gear, integral with the accessory drive shaft driven off the rear of the crankshaft was essentially a “one stop shop” for all accessory drive requirements. Somewhat reminiscent of the ring gear in the rear axle of a truck, numerous gears engaged this central ring gear. Disposed radially around the periphery of the rear accessory case, pads were supplied for essentials such as the starter, fuel pump, hydraulic pump(s), tachometer generator, etc.<sup>1</sup>

In some cases, the speed output would not have been correct if the drive gear engaging the accessory drive gear simply drove the requisite accessory. To overcome this, intermediate jackshafts were interspersed so the correct output speed was obtained via appropriate intermediate gearing. Another key requirement of the accessory drive case was that of providing a mounting surface for the truly massive carburetor. Following prior Pratt & Whitney practice, the carburetor is mounted on a rectangular pad set at an angle. This pad opens up into the inlet throat of the supercharger. The fuel feed valve is installed behind the carburetor and intersects the annular groove for the slinger-ring which is integral with the supercharger impeller.<sup>1</sup>

### **Power Control Unit**

Almost from the dawn of aviation the Eclipse Corporation supplied many aircraft accessories such as starters and generators. With this wealth of aviation experience, they delved into the design and manufacture of automatic controls. One aspect of many US-built aircraft engines that created some problems was the lack of an automatic boost control. In other words, a pilot could, and often did, over-boost an engine. Situations such as a high gross-weight take-off and combat situations often saw manifold pressures soar to astronomical values. If the engine did not suffer severe damage, it often needed intensive maintenance after over-boosting. However, airlines in particular, did not embrace the concept of automation. Their argument seems to have been “That’s what we pay flight engineers and pilots for!”. And unlike military aircraft, commercial aircraft are supposed to fly under well regulated conditions, in which panic-stricken, full-throttle operation, regardless of altitude, is a not a requirement. Another negative consideration was that automatic systems often proved to be a maintenance headache, adding to passenger costs. The military, because of experience during the first few years of WWII, in which American designed engines had been wrecked, got Eclipse to develop an automatic boost control for the R-4360.<sup>1</sup>

The Eclipse power control unit is attached to a pad on the left side of the accessory drive case. It performs the task of automatic boost control, in other words, even if the throttle was pushed all the way forward, particularly at low altitude, there would be no danger of over-boosting the engine. With this control unit, one cockpit control is required which operates and coordinates the carburetor throttle and supercharger fluid drive coupling selector valves. As an automatic power manifold pressure regulator, it maintains a constant manifold pressure regardless of change in altitude. At reduced power, the supercharger impeller is driven at the lowest speed which will maintain the desired manifold pressure.<sup>22</sup> This latter point is key when it is understood that the drive requirements of an R-4360 supercharger can run into the hundreds of horsepower, which has to be taken from the engine. Because of its complexity, only a relative few R-4360s were fitted with the power control unit.<sup>1</sup>

### **Auxiliary Cooling Fan**

Several R-4360 applications demanded an auxiliary cooling fan. These applications included the Convair B-36, and Northrop’s B-35. Both of these aircraft were pusher installations with the engines buried in the wing. This type of installation demanded a forced airflow over the engine to augment cooling, particularly on the ground. Pratt & Whitney used a very similar design to drive the fan as that used on the variable speed supercharger.<sup>1</sup>

The fan, mounted on the rear accessory case, has two ratios, high and low with fluid couplings being employed. Of course, the extra cooling comes at a price of over 200 horsepower under some conditions. Depending on the installation, some of that 200 horsepower could be recovered through optimizing cooling airflow to augment thrust. <sup>1</sup>

### **Auxiliary Supercharger**

If mission profiles demanded it, due to the flexibility designed into the R-4360, it was easy to install an auxiliary supercharger stage onto the rear accessory case. <sup>1</sup>

### **Conclusion**

Notwithstanding its challenging history, the R-4360 was the right engine at the right time. It filled the gap between early gas turbines and the last of the big piston engines. It soldiered on for the military into the 1970s powering KC-97s and C-124s. <sup>1</sup>

The R-4360 Wasp Major pushed radial technology to the limit, with 3000 hp initially and 4300 hp with dual turbos and supercharger. It also had cooling problems but not to the extent of inflight fires. Maintenance was difficult and expensive. They were used in B-36, B-29D's, and B-50's but as the biggest and most powerful radial of US production soon gave way to the jets. The Boeing Stratocruiser was unprofitable without government subsidy and dropped quickly once the jets were available. In all, 18,697 Wasp Major's were built between 1944 and 1955. <sup>10</sup>

### **Talking Points:**

- The R-4360 was the largest and most complex to aircraft piston engine to enter production in the West
- Every American aircraft company designed one or more new aircraft for this incredible engine
- The 28-cylinder engine was arranged in four rows of cylinders, each row rotated slightly to improve cooling from row to row by providing an air channel between cylinders.
- Earlier versions used seven magnetos, each firing four cylinders. Later versions went from a high-tension system to a low-tension system and only for magnetos were used, each firing seven cylinders
- All versions utilized some form of mechanical supercharger and the later versions added turbosupercharging
- Pratt & Whitney patented a "slinger ring" for fuel distribution, where the fuel is introduced in the supercharger impeller instead of the carburetor
- In the B-36 installation, cooling was a significant challenge because the engine had to be oriented backwards for pusher propellers. Additional cooling by means of separate fans could extract over 200 hp per engine at some conditions
- The Wasp Major started at 3000 hp and eventually reached 4300 hp.
- Used on WB-50D, KC-97L, B-36J, and C-124 in NMUSAF. Also C-74, some C-119, Howard Hughes XF-11 and H-4 Hercules, Boeing 377, Pregnant Guppy, and Martin Mars

# TOPICS RELATED TO AIRCRAFT PISTON ENGINES

## History of the National Museum of the USAF<sup>51</sup>

This brief overview of museum history is only intended to address the earliest years when only piston engines and biplanes populated the collection.

McCook Field was established in 1917 following the entrance of the U.S. into WWI to develop aeronautical technology to meet its wartime aircraft needs. In 1922 a museum was established with airplanes and engines to “encourage aeronautical engineers and other scientists to build on past aircraft developments”. The museum opened its doors to the public in 1923. By 1924, the holdings included 139 engines, 62 airplanes, and one helicopter. Exhibits of particular interest then were the Wright brother’s six-cylinder engine, the Le Pere Lusac 11’s original supercharger used by Schroedre and Macready to set world altitude records, and the Ansaldo engine originally on the airship Roma when it was purchased from Italy in 1920.

The Army Air Corps’ Engineering Division began moving to the new Wright Field, which was named in 1925, had ground breaking ceremonies in 1926, and was dedicated in 1927. Much of the museum collection was lost during this time with many aircraft destroyed. It was not until 1931 that the Army Aeronautical Museum was officially established, which was opened to the public in Bldg. 16 in July 1932. A new location for the Museum, Bldg. 12, was completed in 1934 and opened to the public in 1935. The Museum was closed in 1939 in anticipation of hostilities, briefly reopened for a few weeks in 1940, then closed to the public again until 1954.

## Early Aircraft Propulsion – Through 1918

A dirigible airship with a 3 hp steam plant weighing 351 pounds was flown by Henri Giffard in Paris in 1852. Steam ceased to be of importance for aircraft after flights by the Wright brothers and others demonstrated the superior qualities of the internal combustion engine.<sup>3</sup>

The earliest successful aeronautical application of the internal combustion engine appears to be in a dirigible-balloon flight in Germany in 1872. A four-cylinder 5 hp Lenoir engine using coal gas fuel was used. The Lenoir was the first commercial internal combustion engine.<sup>3</sup>

The relatively lightweight and relatively efficient “Otto-cycle” gasoline engine began development in Europe in the 1880s, stimulated by automobile development. The first flight with this type of engine was apparently that of a dirigible airship in Germany in 1897. The first successful heavier-than-air flight powered by gasoline engine was that of Langley’s quarter size model, which flew 350 feet on 18 June 1901, and 1000 feet on 8 August 1903. The engine was a five-cylinder air cooled radial, designed and built by Stephen Balzer and redesigned and rebuilt by Charles M Manly. It produced 3.2 hp at 1800 RPM with a weight of 7 pounds.<sup>3</sup>

The Langley engine used in the Aerodrome A, was originally designed by Balzer as a rotary engine. Manly redesigned it as a stationary radial, basically doubling the horsepower, attributable to better valve action in the absence of centrifugal force. The specific weight, 2.58 pounds per horsepower, remained as a low record until the Liberty engine of 1918. The 0.196 pound per cubic inch displacement has never been closely approached. This engine somewhat anticipated modern large aircraft engines in its use of the radial arrangement with a master connecting rod, its cam and valve-gear arrangement, and its use of crankcase, cylinders, and other parts machined to carefully controlled dimensions.<sup>3</sup>

Not until 9 November 1907, did anyone but the Wright brothers stay in the air for as long as a minute or fly a distance of over 1000 feet.<sup>3</sup> [On that date Henri Farman flew 1 minute and 14 seconds, covering 3368 ft in a Voisin biplane. The next year Glenn Curtiss flew shortly over a minute in NY using an air-cooled V-8 of his own design. Curtiss soon switched to](#)

water-cooled designs, first of a 4-cylinder engine of 25 hp and then a V-8 of 50 hp. He continued after 1908 with 4, 6, and 8 cylinders, and his model L V-8 evolved into the model OX which became available in 1914.<sup>40</sup>

Hall-Scott Motor Car Co. in San Francisco began making water-cooled aircraft engines in 1910, starting with a 4-cylinder model. In 1911 they followed with a V-8 of 60 hp called the A-2. Another V-8, known as the A-4, came out in 1914 with 120 hp. In 1915 their 6-cylinder A-5 model became the first Hall-Scott aircraft engine to see extensive use and developed 125 hp. Their next engine with significant service was the A-7 model, which was developed from the earlier A-5 model, but was reduced to 4 cylinders and produced 100 hp. The A-5 and A-7 engines were improved as the A-5a (6 cyl) and A-7a (4 cyl) and included a slight increase in cylinder bore – both were procured in quantity by the US Services. Hall-Scott's last development before WWI was a V-8 known as the A-8 model, which claimed 300 hp but was only experimental.<sup>40</sup>

Stationary air-cooled designs (inline or radial) reached a power limit around 150 hp because of the cylinder cooling limits imposed by iron or steel. An example is the R.A.F. 1A V-8 which produced 110 hp from 440 lb., and its development the R.A.F. 4A, V-1 which produced 150 hp from 680 lb. – both were air-cooled. It was not until the finned aluminum cylinder was perfected in the 1920's that stationary radial engines progressed to higher power levels. Although the rotaries were not limited by cooling limitations like the stationary versions, other limitations such as stresses from centrifugal forces also limited them typically to the 150 hp range.<sup>40</sup>

Before WWI US water-cooled engines were typically under 200 hp, but in Europe the impetus of war since 1914 produced significant improvements over the US. The best example of these superior advantages was the Hispano-Suiza V-8 with "monobloc" construction in which the two-cylinder banks and their cooling jackets are cast in a single aluminum block and joined to an aluminum two-piece crankcase. Steel cylinder barrels are screwed into the block to carry cast aluminum pistons. With no change in displacement but increases in compression ratio and speed power was increased from 180 hp to 200 hp and then 220 hp. In some cases with the higher speeds, reduction gears were fitted to keep propellers in an efficient speed range. With larger displacements up to 1127 in<sup>3</sup>, hp ratings up to 325 were achieved.<sup>40</sup>

In Britain in 1917 there were about 40 different aircraft engines being made and it was realized that a significant reduction in types was necessary to facilitate mass production as well as field logistics. Unfortunately, two engines were chosen of the new monobloc design: the Sunbeam 200 hp V-8 known as the "Arab" and a B.H.P. (Beardmore-Halford-Pullinger) 6-cyl design, the "Puma". Both of these engines had significant problems such that neither came close to approaching expected production quantities. Hispano-Suiza engines were built in quantity in France and soon Wolseley was contracted to produce versions of the H-S V-8 known as the "Viper" and the "Adder".<sup>40</sup>

An engine design starting from 1911 in Germany was by Daimler Co. and known as the Mercedes engines, which used machined forged steel cylinders with valve ports welded on at an angle to produce a hemispherical combustion chamber. Sheet metal water jackets were then welded on. With cylinders bolted to an aluminum crankcase and overhead valves driven by rocker arms, this design became a standard 6-cyl design in 1915, proved extremely reliable in several aircraft through the war, and influenced other significant designs. Renault built their own version of the 6-cyl Mercedes and in 1916 produced a V-12 known as the model 12 Fe, which produced 300 hp. Another French engine company, Lorraine-Dietrich, also took lessons from the Mercedes design, as well as Fiat with its A-12 6-cyl engine.<sup>40</sup>

The Mercedes design also had a significant impact on Rolls-Royce. They had never built an aero engine before the war started and had only been involved with luxury cars. The main problem with R-R aero engines was that they were nearly hand-built resulting in continual production shortfalls and requiring engines needing repair in the field to be sent back to the R-R factory. The British government made a 1914 Mercedes Grand Prix car available to R-R since the engine was the same design as the current Mercedes aero engines. After tear-down analysis, R-R built a few of these 6-cyl engines but soon developed the 240 hp V-12 Eagle engine of 1240.6 in<sup>3</sup> with overhead cams and valves (2 per cylinder). The first Eagle I was delivered in 1915 and later versions progressed to the Eagle VIII by 1917, putting out 360 hp. A slightly

smaller size of this V-12 was also produced as the Falcon. The Falcon III went into production in 1917 with a great power-to-weight ratio of 2.5 hp/lb., and remained in production until 1927.<sup>40</sup>

## Piston Engines After 1918

Many new engine types appeared. From the technical point of view, the period is marked by the following significant developments:<sup>3</sup>

- Further development of the liquid-cooled engine of the all-cast type, chiefly for military purposes
- The development of the air-cooled radial engine to a place of dominance in all but fighter-type military and small civilian aircraft
- The advent of four-cylinder vertical in-line, and later, opposed-cylinder, horizontal, air cooled engines for light aircraft

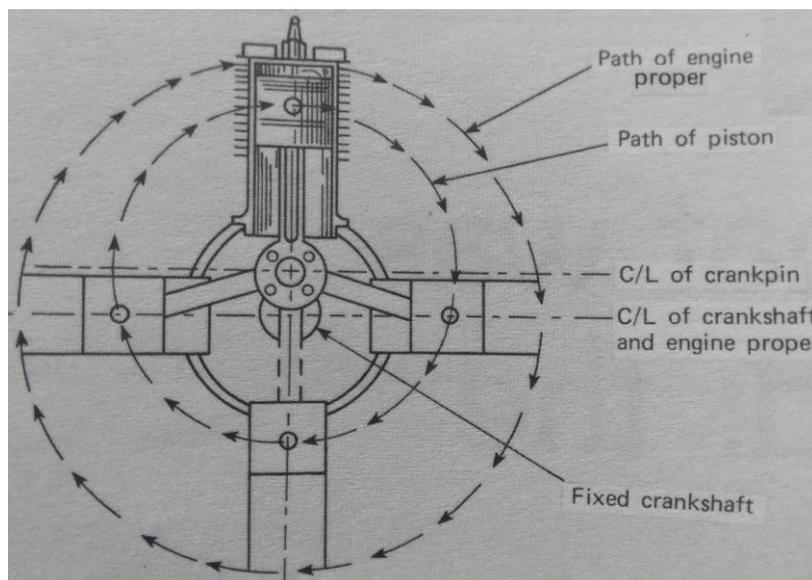
## Curtiss Engines After 1918

The Curtiss company took up the cast-aluminum engine, generally based on the Hispano-Suiza, with successive 12-cylinder designs known as the K-12, C-12, D-12, and V-1400 models. All had 4 valves per cylinder, instead of two as in the Hispano-Suiza<sup>3</sup>.

## Rotary Engine Introduction

The engine built to rotate around a stationary crankcase is called a rotary, and such power plants were a major type between 1909 and 1918. During that period, rotaries were unmatched in the medium horsepower class for lightness in relation to power. The first effective gasoline rotaries were built in the late 1800s by a Hungarian-born New York machine-shop proprietor named Stephen Balzer. His design objectives were good cooling and the elimination of the flywheel. Some of his early engines worked well despite a total absence of cooling fins.<sup>2</sup>

In a rotary, vibration is reduced by the fact that the pistons of a rotary engine do not actually reciprocate. Instead of coming to a stop at the beginning and end of each stroke, they orbit around the stationary crank pin.<sup>2</sup> *Great illustration below is from same reference.*



The rotary was beautifully built. The entire engine is made of polished steel. The Le Rhone is enhanced by polished copper intake pipes, and the Bentley has aluminum cylinders. In order to keep the engine as light as possible, everything

was kept to the minimum possible dimensions. The result was a very limited life; time between overhaul was 50 hours or less.<sup>2</sup>

Fuel consumption was high to the point where no aircraft intended for long-distance missions was ever powered by rotaries, since the weight penalty of water-cooled engines was more than made up on long flights by their smaller fuel consumption. Performance fell off rapidly as altitude increased, especially for the Gnoms with automatic intake valves.<sup>2</sup>

Rotaries had no carburetor or throttle as such. The carburetor wasn't required to mix the air in the gasoline because of the turbulence to which the mixture was subjected as it passed through the engine's interior. All that was necessary was to provide a needle valve for fuel control and a flap for the air. The engine was first started in a nearly flooded condition. It frequently caught fire from the spilled excess fuel and standard procedure was to shut off the gas until the fire burned itself out. As soon as the engine was warmed up, the air flap was opened wide and the fuel was cut back until the engine started to miss, and then the fuel valve was opened until the engine ran smoothly again; that was all there was to it. The engine was in general left wide open for takeoff, climbout, and subsequent flight. Reducing power for landing, however, was more challenging, and the solution called for intermittently cutting the ignition. The simplest, as normally used on the Gnome was a "blip switch", a button on the control stick which grounded the magneto. Since the entire engine weight was revolving, it would continue to turn for some time after the ignition was cut and would pick up again when the blip switch was released. The Clerget and Bentley rotaries had a different way for reducing power. They were equipped with a selector switch by means of which the engine could be made to run on seven, five, or three cylinders instead of the full nine. Whether the engine had a blip switch or a selector switch, the flow of fuel continued undiminished when the engine coasted and therefore the unburned fuel would usually catch fire either from releasing the blip switch or from the hot exhaust of the still-operating cylinders on Clergets and Bentleys.<sup>2</sup>

The Rotaries were considered obsolescent by 1918, due to limitations on speed due to centrifugal stress, considerable windage losses, design limitations imposed by rotation of all parts of the crankshaft, and a rather strong gyroscopic effect on the airplane during turns.<sup>3</sup> [Another limitation to rotary power was the limited volume of air/fuel that could be admitted through the center crankcase.](#)<sup>10</sup>

The most powerful rotary to go into mass production during World War I was the Bentley BR-2 rotary which was designed by W. O. Bentley; he also designed the Bentley automobiles made my Rolls-Royce.<sup>9</sup>

## Introduction to the Radial Engine

The radial configuration offers many advantages over the in-line type, especially when it is used in connection with air cooling. The short crankshaft gives compactness in the fore and aft dimension and rigidity without weight. It is well suited for air cooling. Because all cylinders act on the same crank throw, a major source of vibration in in-line engines, called "rocking couple" does not exist. Accessibility for servicing is excellent, and the absence of the radiator minimizes the susceptibility to battle damage.<sup>2</sup>

Gasoline in the early years was extremely volatile and so simple intake systems sufficed to assure adequate mixture distribution, but something better was needed for the gasoline in the 30s. Uneven distribution of the fuel-air mixture from the carburetor was often improved through the intake manifold arrangements. Until fuel injection became available, the best way to improve this situation was at least a mild degree of supercharging. This improved mixture distribution in two ways. First, the blower thoroughly agitated the mixture, completing the mixing job begun by the carburetor. Second the supercharger slightly pressurized the whole manifold, guaranteeing equal pressure at each intake port during the time the intake valve was open.<sup>2</sup>

## Why Radial Engines Always Have an Odd Number of Cylinders

Any four-stroke engine, regardless of construction, must fire all of the cylinders in two revolutions of the crankshaft.

Unlike an inline engine, a radial engine has only one crankshaft throw for all the cylinders in a bank. Therefore, each piston reaches top dead center (TDC) in succession, once for every revolution of the crankshaft.

For four-stroke engines, TDC must be the beginning of either the power stroke or the intake stroke.

If each cylinder repeated the same sequence, say power stroke at successive TDC, all cylinders would fire or provide power during the first revolution, and NONE would fire or provide power on the second revolution. Instead, radial engines use an odd number of cylinders and fire every other cylinder on the first revolution and on the second revolution fire the remaining cylinders that were skipped. Thus for a seven-cylinder engine (or 7-cyl bank of a multi-row radial), the cylinders fire in this order:

1 – 3 – 5 – 7 – 2 – 4 – 6

This convention distributes the power strokes to the crankshaft evenly per revolution and considerably simplifies implementation of cams necessary to open and close the intake and exhaust valves.

Although rare, some examples of even cylinders on a radial engine exist, but they are two-cycle engines and not four-cycle.

## Hydraulic Lock and Prop Walking

Radial engines incorporate a 'dry-sump' oil system. In addition, the cylinder skirts extend into the crankcase inside diameter. This keeps the oil from easily entering the cylinder bore. The oil is directed from the crankcase into the oil sump between the two lower cylinders and returned to the tank. With these provisions, the two lower cylinders still require constant attention. When allowed to stand, without running, the oil can accumulate in the combustion chambers. When the piston reaches top dead center (TDC) there is no place for the oil to go. This is known as hydraulic lock. If steps are not taken to drain the oil, severe engine damage can result.<sup>39</sup>



The typical protection against hydraulic lock is "walking the props" as illustrated above. This is generally done whenever a radial engine has been shut down for even a short period such as a half hour. If such a lock is detected, the remedy is to remove the spark plugs from the lower two cylinders and let the oil drain out. If a hydraulic lock occurs but is not addressed properly, it usually results in a piston rod being bent significantly or even cracking the cylinder wall – in either case a very serious and costly failure.

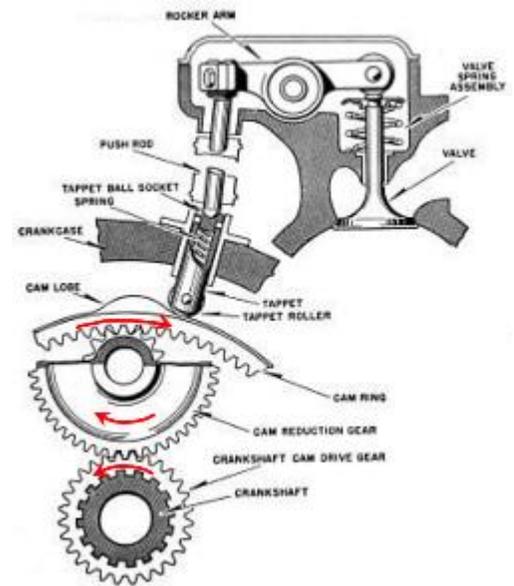
Radial engines are well known for leaking oil out of the breather due to the cylinder and sump arrangement, open clearances, and the force of gravity. Tee-shirt seen at the Oshkosh Air Show: "My radial isn't leaking oil... it's marking its territory!"

## Cam Rings Replace Camshafts in Radial Engines

Consider a nine-cylinder radial as an example. In a 9 cylinder, there are 40 degrees between the cylinders. Referring to the firing order explanation above, the crank progresses two cylinders between firings, or 80 degrees<sup>39</sup>

The cam drive gears are designed to run the cam one eighth the speed and in the opposite direction to the crankshaft. This is accomplished with two-stage gear reduction. A single jackshaft using a spur gear set makes a 2 to 1 reduction. On the other end of the jackshaft, a second stage reduction of 4 to 1 is made using an internal tooth ring gear mounted along the inside diameter of the cam ring. Other gearing combinations are possible, but are difficult to package in the limited space available in the crankcase.<sup>39</sup>

While the crankshaft is turning counter-clockwise through 80 degrees, as seen from the front, at the same time the cam ring is turning 10 degrees in the opposite direction. The combination is 80 + 10 degrees. So there are four lobes, each at 90 degrees on both the intake and exhaust cam rows<sup>39</sup>



## Air vs. Liquid Cooling

Arguments (often emotionally charged) over the benefits of liquid versus air cooling started in the early days of flying and continued to the end of World War II, when the advent of jet engines diverted attention elsewhere. Water cooling was dominant through World War I except for the rotaries, which at its close was obsolescent<sup>3</sup>

European military aviation generally committed to water cooling through World War II, although some air-cooled engines were used in bombers and transports, and there was one excellent air-cooled European fighter, the Focke-Wulf with the BMW 2-row radial, developed from a Pratt & Whitney license. Japanese fighter aircraft also used air-cooled radials copied from Wright and Pratt & Whitney designs. Their other military aircraft used these and copies of the German Daimler-Benz liquid-cooled engine.<sup>3</sup>

In the US, the Navy made a commitment to air cooling in 1921 which has held for reciprocating engines to this day. It was chiefly Navy support that underwrote early Pratt & Whitney and Wright air-cooling developments. The reason lay in the limitations of the aircraft carrier, which imposed design criteria such as short takeoff, compact size, and minimum maintenance<sup>3</sup> **While air-cooled radials do not need the plumbing and radiators for liquid cooling, it was pointed out that another drawback of the liquid-cooled systems was the jolts and bangs of heavy landings, especially in carrier ops, causing brazed structures to crack and leak.**<sup>10</sup>

The drag of air-cooled engines was greatly reduced by the advent of the very effective cowling and cylinder baffling developed at Langley Field by NACA starting in 1929. Further reductions in cooling drag were achieved by increased cooling-fin area, which reduced the air velocity required for cooling. These developments put the air-cooled radial virtually on a par with the water-cooled engines with regard to cooling drag, until the advent of high temperature liquid cooling with glycol-water mixtures<sup>3</sup>

The use of high-boiling liquids for engines formerly water-cooled was an important step in reducing the heat-transfer area, and therefore the drag of radiators for liquid-cooled engines. Early testing of the mixture of water and ethylene glycol took place at McCook Field in 1923. This method of cooling was adopted for Curtiss liquid-cooled engines by 1932, and used soon afterward by Allison and Rolls-Royce. This improvement, together with better radiator design and radiator cowling brought the drag of liquid-cooled engines well below that of air-cooled radials of equal power. Their installed weight, which had been greater than that of air-cooled radials, also came down to more comparable figures.<sup>3</sup>

Pratt & Whitney believed in the superiority of air-cooled radials over liquid-cooled engines from the forming of the company in 1925. In 1940, it was only after P&W President Rentschler convinced Gen. Hap Arnold that Pratt could drop its liquid-cooled engine programs that it began development of their greatest air-cooled radial, the R-4360.<sup>50</sup>

The fact that the Battle of Britain was won by liquid-cooled engines (the Merlin) gave a great impetus to the Army prejudice in favor of water-cooled fighters. Actually, both types were used, and it was found that the air-cooled fighter was better at low altitude both because of its lighter specific weight and its lesser vulnerability to small-arms fire<sup>3</sup>

For commercial uses, however, the elimination of the weight, complication, and maintenance requirements that characterize liquid-cooling has been a chief reason for the popularity of air-cooling for air-transport purposes since about 1932; and with few exceptions, commercial air transports all over the world have used air-cooled engines, mostly of American manufacture, from the early beginnings in the late 1920s up to the present.<sup>3</sup>

## The End of Separate-Cylinder Liquid-cooled Engines

After about 1918 the Hisso concept of aluminum blocks and steel sleeves led to better engines than the separate-cylinder concept. The Hisso and the D-12 had demonstrated this conclusively by 1923. Thus the persistence of the separate-cylinder engine needs explaining. There were probably two principal reasons for this persistence. One was the NIH syndrome, and the other was the challenge of making good aluminum castings of the size needed. Some nations seemed to learn the art better than others. It may be then, that the continued use of separate welded-steel cylinders was not necessarily due to technical backwardness or to mere stubbornness. It may have been because of a realistic assessment of available capabilities. In the end, the aluminum-block scheme won out everywhere but its total victory was a long time coming.<sup>2</sup>

## Wright Engines up to Split Leading to P&W

When Wright Aeronautical was incorporated in 1919, its charter was the design and manufacture of aero engines. During the war, as Wright-Martin, they had done an outstanding job with the Hispano-Suiza, greatly improving its design, mastering its very difficult manufacture and even expanding the engine to a V-12.<sup>15</sup>

The Wright brothers were no longer involved with the company. Wilbur had died, and Orville had other interests, but it can be said that Wright Aeronautical engine tradition began with the first Wright brothers' engine in 1903. In the early 1920's they were still building the Hisso in small quantities for military planes, a large 6-cylinder for Navy dirigibles and a 500 HP successor to the Liberty. Wright also made a tentative entry into the marine engine field. Manufacturing had moved to more modest facilities in Paterson, New Jersey.<sup>15</sup>

The aero engine business was not good then; the market was glutted with Curtiss Jennys which the Army sold for about \$400, engine and all. Further, the preferred military engine was Curtiss' remarkable D-12. Wright even built a few racers that competed unsuccessfully with Curtiss machines. These were the last Wright airplanes. Wright Aeronautical was moving in many directions and needed a specific "work package".<sup>15</sup>

Most engines of the period were water-cooled and suffered frequent cooling system failures. Radiators came apart; porous engine castings, lines, hoses and gaskets leaked. Failure rates were of great concern, particularly to the Navy where over-water flying was more hazardous. Wright did some work with air-cooled engines for the Army, but little came of this.<sup>15</sup>

The Lawrance Aero Engine Corporation bore the name of its owner, Charles J. Lawrance, an engineer devoted to the development of air-cooled radial engines. He had started the development of a series of promising engine designs and demonstrated a working model to the Navy. The Navy quickly promoted a union between Lawrance and Wright, he providing technical leadership and Wright its formidable financial, engineering and manufacturing resources.<sup>15</sup>

Wright bought his company and installed him as Chief Engineer, starting what would be their principal business for the next 40 years.<sup>15</sup>

Lawrance's most advanced design was his model J-5, an engine that Wright undertook to fully develop.<sup>15</sup>

Lawrance had the mechanical design of the J-5 right--but not cylinder head cooling. Radials had been built in England for some time, and air-cooled types and some viable designs were produced.<sup>15</sup>

Fortuitously, an Englishman, Samuel D. Heron, an engineer with wide experience in cooling English radials, was consulting at Wright Field at the time and was asked to help with the J-5. His redesign of cylinder head fin configuration made the engine a jewel.<sup>15</sup>

Wrights' board of directors was content to rest on its laurels and bank the profits from burgeoning J-5 sales, but their engineers were already anxious to build the next radial in the 400 HP range. Reluctant to spend additional investment funds, Wright lost key engineering people who signed up with a machine shop in Hartford, CT, Pratt & Whitney, and put them in the engine business. Their first engine was another jewel, forcing Wright to compete, a competition that lasted until the introduction of the jet engine.<sup>15</sup>

## Rentschler and the Formation of Pratt & Whitney

Frederick Rentschler's family had made automobile engines, and was a 1<sup>st</sup> Lt. in the aviation section of the US Army Signal Corps. During 1917 he inspected Hisso V-8 engines built by Wright-Martin. He became president of Wright Aeronautical where he became convinced that air-cooled radials were the engine of the future for aircraft. After his Board decided the emphasis for Wright-Aero should be liquid-cooled radials he left to start his own engine company with his Chief Engineer George Mead and several other leading employees. Pratt & Whitney Aircraft was formed with half being owned by Rentschler & Mead and the other half by Pratt & Whitney, a machine tool company.<sup>10</sup>

P&W built almost half the engines used by the Allies in WWII, with production reaching 50,000 a year by war's end.<sup>10</sup>

## Improvements in AvGas

By the 1930's the quest for higher power density lead to higher octane fuels to permit higher compression ratios without detonation occurring, which at best robbed power by premature ignition but more significantly caused premature wear of cylinder components or outright failures. Jimmy Doolittle was hired in 1930 by Shell Oil in his aviation department and was a strong advocate of developing higher octane fuel and set many speed records while using early developments of Shell avgas. Shell was able to produce 100/130 octane, but it cost about 100 times normal automotive gas. (The first number is the octane rating at a lean mixture, and the second number is the octane rating at a rich mixture.)<sup>43</sup>

In the late 1930's a much more economic process of refining 100/130 octane avgas was developed and reached production quantities just in time to be leveraged in WWII. For example, the Spitfire of 1939 could do 340 mph but had reached 425 mph by 1944. The Germans mostly used 91/100 gas and had smaller quantities of 95/120 starting in 1943. Further developments in Germany came later and were by then offset by Allied destruction of refining capacity. Japan's avgas peaked out at 87/91 during the war.<sup>43</sup>

In the early days of avgas development, other factors besides the octane level needed to be solved for powering aircraft engines at high altitudes. The fuel had to have a low vapor point to prevent vapor lock. A low vapor point means you can climb to higher altitudes (low pressure) before the avgas turns to a vapor. The viscosity also needs to be fairly constant and not gel at the low temperatures in higher altitudes (the ISO temp at 25,000 feet = -30 degrees F).<sup>43</sup>

Leaded gas (addition of Tetraethyl Lead LL) was the primary means of improving octane, but because of the toxicity it was eliminated from automotive gasoline years ago and is only used today in avgas. Today avgas known as 100LL has

about ½ the TEL of earlier automotive gas, and unleaded avgas is in development and should totally replace leaded avgas in the near future. To date 91/96UL and 94UL are FAA approved and available in some locations for low compression piston engines. G100UL produced by GAMI has recently been approved by the FAA for use in hundreds of low and high compression piston engines. GAMI is working to ramp up production and distribution for broad use at General Aviation airports.<sup>43</sup>

Octane rating does not relate directly to the power output or the energy content of the fuel per unit mass or volume, but higher octane fuels allow higher compression engine designs, therefore the ability to produce more power and thus thrust. The octane rating of aviation gasoline was extremely important in determining aero engine performance in the aircraft of World War II and was a significant advantage for allied fighters. The octane rating alone did not only determine the performance of the gasoline, but also the versatility of the fuel in handling a range of lean to rich operating conditions.<sup>44</sup>

## Ethylene Glycol

Gains from reduced engine frontal area were largely negated by the continuing problem of radiator drag until the introduction of ethylene glycol (Prestone) in the late 20s, allowed smaller radiators to be used.<sup>2</sup>

Since water boils at 212°F, its use requires a radiator large enough to bring this circulating coolant down to a temperature well below this figure. Adding ethylene glycol to the coolant raises the boiling point in proportion to the amount added. Since the coolant can be run hotter, a smaller radiator can be used, and the engine can be operated at what is actually a more efficient temperature.<sup>2</sup>

Prestone® was the anti-freeze trademarked in 1927 as “the first nonflammable Ethylene Glycol” by Eveready.<sup>25</sup> [Ethylene Glycol both has a lower specific heat capacity than water and thus the mixture has lower heat capacity than pure water. Additional benefits of ethylene glycol is corrosion prevention and inhibiting growth of most microbes and fungi.](#)<sup>26</sup>

## Drag Considerations

Spitfires and Messerschmitt’s used in the desert heat had to be “tropicalized” with larger radiators, and performance fell off to the point where the P-40s could fight Messerschmitts with some chance of survival.<sup>2</sup>

Prestone cooling might have led to complete replacement of the bulky radials in applications calling for high performance except for the Townend Ring, a British invention, which was a narrow cowling of airfoil section that was placed around radial engines. Often called a “drag ring” in the United States, it did not reduce frontal area but did confine the turbulence of the cooling air to the engine’s diameter. It was also said to generate a forward thrust component from the expansion of the air as it was warmed in passing over the cylinders. The American NACA cowl was named after the organization that gave the world most of its significant aerodynamic advances during the 1925 to 1940 period. It was a more sophisticated device than the Townend Ring, being longer and internally contoured to slightly pressurize the cooling air. Not as adaptable to existing aircraft as the Townend Ring because it required a bulkier fuselage to blend with its lines, it probably raised speeds 20 to 25 mph. A beneficial side effect was that its confined airflow allowed internal baffling to be provided, leading to better cooling for 2-row radial engines.<sup>2</sup>

The final American development in cowls for radials came in 1934 with the introduction of small adjustable flaps (which the British called “gills”) at the rear to control the area of the cooling-air outlet. Besides further reducing drag, cowl flaps allowed the flow of cooling air to be restricted during cruising conditions, when less was needed. Previously, without adjustable flow, an engine that was adequately cooled during takeoff and climb was over-cooled during cruise. Water-cooled engines had never had this problem because radiator flaps for temperature control had been in use since before 1914.<sup>2</sup>

## Carburetor Progress Between the Wars

Zenith was only important US carburetor at end of WWII, used on Liberty and Hissos built in US. Zenith disappeared after WWI. Stromberg (previously making automobile carburetors) became involved in aircraft carburetors after the war, primarily funded by Army & Navy. The Stromberg aircraft carburetor was put in production about 1922-1923.<sup>41</sup>

Early aviation carburetors used floats to maintain a constant fuel level in the carburetor and thus a constant fuel pressure, but climbs/dives, and inverted or negative-g flight made the float system problematic, but use continued through the 1920's, providing reasonable performance since prolonged negative-g flight was not required. Fuel systems were developed that provided a constant rate of fuel when the float was at the top of its chamber, making inverted flight feasible, but new challenges were encountered during rapid push-overs and the steep dive angles encountered during dive bombing.<sup>41</sup>

Air density changes due to altitude and temperature were typically accommodated by manual adjustment by the pilot when he sensed power losses until 1934. In 1934 the constant-speed propeller was introduced and automatic compensation for density by the carb became a necessity.<sup>41</sup>

The first successful floatless carburetor after M. E. Chandler, VP of Bendix-Stromberg Carburetor Co. teamed with Holley Carburetor Co. and in 1935 started the new Chandler-Groves Co. Part of his motivation had been that Wright engines had become so dissatisfied with carburetor problems that they were considering their own development and manufacture of carburetors. The new Chandler-Groves carburetor replaced the traditional butterfly throttle valve with a variable area venturi that was less sensitive to icing problems, and the float was replaced by a control valve that would maintain constant fuel pressure (without a constant gravitational field!). The Navy was very encouraged and chose the new Chandler-Groves carburetor on some applications and it was also put into service by TWA in 1937. The Army, however, was distrustful of the design, preferred the older float-type carburetor and declared that future single-engine tactical planes would soon be equipped with fuel injection.<sup>41</sup>

Stromberg began its own development of a floatless carburetor and it was an immediate success with production starting in 1938. While it was less sensitive to icing, P&W some years later developed the system of injecting the fuel at the supercharger instead of immediately after the carburetor, completely eliminating refrigeration icing. Although the Chandler-Groves carburetor made some improvements, the Stromberg carb remained the preferred design and Chandler-Groves basically came to an end after Chandler left the company in 1938.<sup>41</sup>

Shortly afterward, Chandler then formed the Chandler-Evans Co. (later known as CECO) and began on another floatless carb design. The new CECO carb was selected for the Wright R-3350 and the P&W R-1830. All B-29's used the CECO carb except for a few which were converted to fuel injection just before the end of the war. After the war, CECO gave up the carb business, largely because the Army had adopted fuel injection on all its large engines, and Navy and airline business was not considered sufficient.<sup>41</sup>

## A Brief Note on Fuel Injection Systems

The Wright Brothers' 1903 and 1909 engines had no carburetor. Fuel was metered into intake manifolds and was basically left at a constant rate after starting. A carburetor basically meters fuel flow to maintain fuel/air ratios, but for the limited range of temperature, speed, and altitude, they could be successful with constant fuel flow. It would not be inaccurate to call their approach on these engines as "fuel injection". A significant point of confusion is that many people think fuel injection involves injecting the fuel directly into each cylinder, where all fuel/air mixing therefore takes place in the cylinder. This particular type of fuel injection should be referred to as "direct fuel injection" to reduce confusion.

Wikipedia summarizes this very well: "The term "fuel injection" is vague and comprises various distinct systems with fundamentally different functional principles. Typically, the only thing all fuel injection systems have in common is a lack of carburetion."<sup>57</sup>

Per the article above, carburetors were usually retained through the classic days of piston engines on aircraft and certainly in all the primary engines we featured in this tour. These pressure carburetors eliminated the old float and its problems during maneuver, and while the carburetor metered, and therefore varied fuel, the mixing of metered fuel and air was no longer in the carburetor but simply downstream... in various chambers, manifolds, or even superchargers, but the mixing was essentially complete before entering the cylinder through the intake valve. A potentially confusing artifact is the "B-26 Fuel Injection System" with a big Bendix carburetor and 28 small chrome tubes that "injected aviation fuel directly into each cylinder of the 28-cylinder radial engine and produced easy starting and smooth engine operation"<sup>34</sup>. While this is accurate, it should be noted that this system was only ground tested by Pratt & Whitney and never implemented in production systems. This was, however, a rare example in the U.S. at that time of a direct injection system.

Several German engines (Junkers Jumo, Daimler-Benz, and BMW) used direct fuel injection during WWII<sup>57</sup>. I am not aware of any British or U.S. engines that used direct fuel injection through WWII and the 1950's. Direct fuel injection gradually became widespread in automobiles starting in the 1960's and more recently are the common approach not only in automobiles but smaller piston engines used in general aviation.

## Water injection

Water-methanol injection is a way of permitting short bursts of exceptionally high power; by adding a little water into the mixture, the combustion temperatures are brought down below dangerous levels. The alcohol is not the essential element, its function being largely that of an anti-freeze for the water in the tank. It seems to have been an American invention originally, but all the combatants in the World War II used it.<sup>2</sup>

## Brief Background on the Rolls-Royce Merlin Origins

Rolls-Royce took up the challenge of matching the D-12 and came up with an engine at first called the F and, later the Kestrel. Its designer was Arthur Rowledge, who had been the designer of the Napier Lion but had moved to Rolls-Royce. Rolls-Royce was far more successful than Curtiss at building durable gear sets. The Kestrel weighed 865 pounds compared with the D-12's 680 pounds, but some of this additional weight went into a supercharger and its drive mechanism, while the D-12 remained unsupercharged throughout its production life. The Kestrel used four valves per cylinder, but a single camshaft and rocker arms. The exhaust valves had hollow stems partly filled with sodium, which sloshed back and forth for better heat dissipation, this being one of the first applications of an improvement that soon became universal. The excellence of the Kestrel set the RAF firmly on the road to its World War II commitment to liquid cooling.<sup>2</sup>

The Kestrel had two descendants of major importance. One was the big Rolls-Royce R used in Schneider Cup racers. The other of course was the Merlin. It was basically an upsizing of the Kestrel to 1650 in.<sup>3</sup> and proved to be an engine that seemed to have no limit to what could be done with it. Originally intended to produce 750 hp it was already giving 950 when the Hurricane flew in November 1935 and 1050 hp for the first Spitfire in 1936. Early wartime models were rated at 1175 hp and by late in the war it was giving a dependable 1660 hp.<sup>2</sup>

In all these engines (*Kestrel, R, Merlin*) the basic structure consisted of cast aluminum crankcase with en bloc water jackets and cylinder heads, also of cast aluminum. Also, in all these engines the valves were seated in inserts embedded in the aluminum head, and thus had better valve cooling than the original Hispano-Suiza design. Cylinder barrels were uniformly of steel.<sup>3</sup>

The Merlin was arguably the greatest liquid-cooled engine during World War II. It started out with 1000 hp, and by the end of the war it developed 2000 hp. It was also built in quantity in the US by the Packard Motor Car Company. The American answer to the Merlin was the Allison V-1710, a good reliable engine that never caught up to the Merlin.<sup>9</sup>

Rolls-Royce was generally superior to other organizations in designing efficient centrifugal blowers, but was lagging in fuel injection. In 1940, Spitfire pilots found that the fuel-injected Me 109 could escape them in a dive because of the hesitation that the carbureted Berlin displayed in a nose-over.<sup>2</sup>

In addition to the fighters, the Merlin served well in the Lancaster, Wellington, and Halifax bombers, but in retrospect, it seems that radials, had they been available in sufficient quantities, might have done a better job. Just after the war, Canadair built some DC-4's under license as the North Star with Merlin engines. While it had a good safety record, the Merlins were inferior to the Pratt & Whitney R-2000 (in the standard DC-4) relative to maintenance costs, time between overhaul, and in-flight failures. Also passengers found the Merlins noisier than the radials.<sup>2</sup>

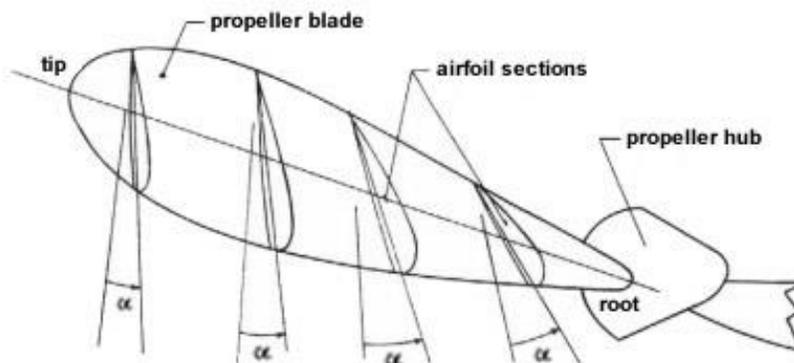
## Scaling

When a cylinder design is scaled up the power and heat generated all increase by the cube of the enlargement factor, but the surface area and the ability to dissipate heat increases only by the square of the enlargement factor. Thus, cooling arrangements that were barely adequate for the original design are apt to be inadequate for the enlarged version.<sup>2</sup>

## Propeller Technology

Propeller sections are wing-like airfoil shapes and performance of a propeller is thus directly determined by the angle-of-attack (AOA) of the various sections during flight. While typical airfoils might produce their maximum lift shortly before stall around 20-25 degrees AOA, maximum lift also corresponds with maximum drag. For best propeller efficiency, it is best to operate at modest AOA such as 4-6 degrees, where lift over drag (L/D) is a maximum. At this condition, the best ratio of propulsive thrust to engine horsepower is obtained, because thrust corresponds with airfoil lift, while engine power corresponds with airfoil drag.

The AOA for a section of the propeller is a combination of aircraft speed and the rotational speed of the propeller. For a fixed rpm, sections near the tip of the propeller travel at higher velocities than sections closer to the hub because of the larger circumference (or path of travel) each revolution. For this reason, all propellers have a characteristic twist such that sections near the hub have higher pitch angles than sections near the tip (see illustration). In this illustration, note that the increasing pitch angle from tip towards hub (or root) should not be confused with AOA, but is simply the physical angle between the local airfoil section and the plane defined by the rotation of the propeller.



It was learned that the best propeller design would incorporate a means of rotating propeller blades to optimize airfoil section AOA's for best efficiency for variations in aircraft flight speed and propeller rotational speed.

In the early days of flight, propellers were limited by technology of the day to fixed, wooden propellers. On the other hand, variations in airspeed were not great and fixed propellers were not a serious limitation. For example, in WWI the difference between minimum speed at landing and max speed in flight might be only 80 mph. After WWI, there were rapid increases in maximum speeds and hence the range of operating speeds. In parallel, squeezing more power out of

engines often meant higher and higher engine speeds, and a new challenge to propeller efficiency was realized - as propeller tip speed approached transonic speeds (near the speed of sound, or roughly 750 mph), efficiencies near the tip fell off rapidly (independent of angle-of-attack). In combination, higher aircraft speeds and higher engine rpm's drove the development of three new features that soon became standard and necessary features to produce competitive aircraft designs:

1. Metal propellers to better withstand stresses from higher power loadings as well as higher rotational speeds, while allowing for thinner blades, improving efficiency at higher speed
2. Variable-pitch propellers, to better optimize propeller efficiency at varying conditions of airspeed and propeller rpm, and
3. Reduction gearing, that meant propellers could be rotated at a fraction of engine crankshaft speed, to avoid transonic tip losses.

Variable-pitch propellers started with models that could only vary pitch before flight by a mechanic making an adjustment to choose the best angle for the most important part of an upcoming flight! They were referred to as

“ground adjustable” propellers. Perhaps the best example is the unique flight of Charles Lindbergh from NY to Paris. His Ryan monoplane used the type of prop that could only be adjusted before flight, and Lindbergh made a daring compromise between the best pitch angle for a 30+ hour cruise and a different pitch angle that would be best for his brief takeoff run. His skill (and/or luck?) was evidenced that on takeoff from NY it was reported that he only cleared power lines by a mere 20 feet!

The next modest improvement in variable-pitch propellers was a design that allowed the pitch to be changed by the pilot in flight, but it allowed only selection between two settings, and not continuous pitch variation. This at least allowed good efficiency during the low-speed takeoff without sacrificing cruise efficiency at higher-speed cruise conditions.

The final refinement in propeller technology that became standard in the mid-30's, was the constant-speed propeller. For constant-speed propellers, two approaches evolved. One was a hydraulic implementation, and the other electronic, and both were used through WWII. Over time the electric version has for the most part fallen out of use. For either implementation, a speed governor, or CSU (constant speed unit) maintains a constant speed (set by the pilot) by continuously varying prop blade pitch angle. For example, if the rpm creeps above the speed set by the pilot, the CSU increases the prop blade pitch angle, which increases AOA and draws more power from the engine, reducing the speed of the prop back towards the desired constant speed. An extension of this idea is “feathering” which allows the propeller blades to be streamlined with the airflow, stopping rotation and significantly reducing drag in flight. This is very useful if an engine fails on a multi-engine airplane, improving single engine performance for safety. A step beyond that is to allow the blades to be rotated such that the outer portion of each blade is at a negative angle of attack producing reverse thrust, providing a method to reduce landing distances.

Significant propeller developments with the approximate dates are:<sup>3</sup>

- |      |                                     |
|------|-------------------------------------|
| 1921 | Aluminum blades, fixed pitch (Reed) |
| 1929 | Variable-pitch, 2-position          |
| 1931 | Hollow steel blades                 |
| 1935 | Constant speed props                |
| 1938 | Feathering props                    |
| 1945 | Reversible and feathering           |

## Reduction Gear Influence on Configuration

In the direct drive engine, an inverted construction offers the advantage of a higher location of the propeller shaft. If the reduction gear is simple spur gears, the complications of dealing with oil distribution in an inverted engine can usually be avoided. If the reduction gear results in the propeller shaft remaining concentric with the crankshaft (e.g., Farman-type gearing), the inverted design may still be of benefit.<sup>2</sup>

## Ignition Systems

In four-cycle engines other than diesels, combustion is ideally initiated by one or more spark plugs in each cylinder that are timed to fire shortly before top dead center at the end of the compression stroke. In all such systems, a very high voltage (tens of thousands) has to be created across the spark plug gap, from a relatively low voltage, and this is accomplished through the use of an electrical transformer (often called a coil or inductor) and periodic interruption of the lower voltage.

In automotive systems before modern electronics, a battery was used as the low-voltage system (typ. 12 volt) and three separate components were employed. The distributor interrupted the low voltage with breaker points and also directed the high voltage pulses to the correct cylinder plugs. The ignition coil stepped up the interrupted low voltage to an (interrupted) high voltage for firing spark plugs. Finally, an alternator was used to maintain charge on the battery.

Magneto ignition systems have been used on aviation piston engines almost exclusively because they were lighter systems, primarily avoiding the need for batteries or independent low-voltage systems. A magneto ignition system is typically self-contained, with functions of power generation, voltage interruption, transformer, and distribution to separate cylinders in one discrete package.

## Magnetos

A magneto is an electrical generator that uses permanent magnets to produce periodic pulses of alternating current. Unlike a dynamo, a magneto does not contain a commutator to produce direct current. It is categorized as a form of alternator, although it is usually considered distinct from most other alternators, which use field coils rather than permanent magnets.<sup>30</sup>

Magnetos were adapted to produce pulses of high voltage in the ignition systems of gasoline-powered internal combustion engines to provide power to the spark plugs. Use of such ignition magnetos for ignition is now limited mainly to engines without a low-voltage electrical system, such as lawnmowers and chainsaws, and to aircraft engines, in which keeping the ignition independent of the rest of the electrical system ensures that the engine continues running in the event of alternator or battery failure. For redundancy, virtually all piston engine aircraft are fitted with two magneto systems, each supplying power to one of two spark plugs in each cylinder.<sup>30</sup> [There is a very slow move away from magnetos in aircraft engines to electronic ignition systems similar to your car but the FAA has a “death grip” on turning loose of the old technology.](#)

## Supercharger

Early piston engines were “naturally aspirated”, meaning that the intake of air to cylinders was affected only by the flow of atmospheric air to fill the vacuum created by the intake stroke of the piston. As operational altitudes increased, the decrease in atmospheric pressure and density reduced the quantity of air that could be admitted, significantly reducing the power of the engine at altitude. As aircraft speeds gradually increased to the 300+ mph range, some very slight improvement resulted from modest increases in air pressure/density due to ram pressure from forward flight, but the solution to reduced power at altitude was addressed by supercharging of the air presented to the cylinder on the intake stroke.

Supercharging is simply the process by which atmospheric or ambient air is compressed to higher pressure and density by an air compressor, which is typically a centrifugal impeller. Early superchargers always used a mechanical drive system to run the compressor, extracting the necessary shaft horsepower from the engine by means of gearing and shafts. Supercharging was developed for automobiles about the same time as for aircraft, but for automobiles the goal was to increase power output on the ground, rather than compensating for decreasing power at altitude. Early automobile systems often used a positive-displacement “blower” instead of a centrifugal compressor, and such engines were therefore sometimes called “blown engines”.

A significant improvement over the mechanical supercharger was the “turbosupercharger”, in which the energy to drive the centrifugal compressor was high-speed turbine wheels powered by the exhaust gasses. Since these basically recovered “waste energy” from the exhaust instead of taking horsepower right off the crankshaft, these turbosuperchargers were significantly higher in efficiency, and especially at higher altitudes. Over time the term “turbosupercharger” was typically shortened to “turbocharger”. Mechanical superchargers remained in service because the turbochargers required costly high-temperature materials. Automobiles often use turbochargers today, and the remainder of this article refers only to aviation applications.

Some forms of supercharging became standard in the 30’s and 40’s for both military and commercial aircraft as operational altitudes continued to rise. While the primary objective was to maintain power as altitude increased, some controls were needed to make sure that an engine was not “overboosted” at low altitudes beyond design limits in terms of cylinder temperatures, pressures, and detonation limits of fuels of the day. These controls included ability to regulate airflow as well as the speed of the compressors.

While supercharging became common, the specific means of supercharging varied considerably. For mechanical superchargers, options included one or two centrifugal compressors and the ability to turn on or turn off compressors, typically through clutch arrangements. A related development was instead of the compressors being driven directly by mechanical linkages, variable-speed systems for the compressors were developed that might change the speed ratio relative to the main engine or even variable speeds for a fixed engine speed. An obvious development included the marriage of mechanical supercharging with turbocharging, where the turbocharger added pressure on top of that produced first by the mechanical supercharger.

The increasingly complex supercharging systems resulted in significant increases in system complexity, weight, cost, and control challenges. Although they enabled significant power at higher speeds and altitudes, they also added to the responsibility of flight crews to maintain safe and efficient operation with monitoring of instrumentation and adjustment of various “boost controls”.

A final complication for this discussion is that while boost pressure ratios increased, so did the temperatures of the compressed air. It soon became clear that the advantage of higher pressure and density would soon be lost by excessive cylinder temperatures, that required pulling back the power to allow reasonable reliability and engine life. These higher air temperatures soon necessitated large “intercoolers”, with additional components, ducting, valves, instrumentation and controls. It becomes clear that the more complex systems, especially with turbocharging, were prioritized and therefore limited in WWII to strategic bombers and a few special fighter applications.

Holding power to high altitudes has been almost entirely due to supercharging, definable as the pressurization of the intake by a blower. The first turbosupercharger was built by Rateau in France in 1913. The benefit of the turbosupercharger is that it gives the most boost at high altitudes, where it is most needed. This is because the same lowered atmospheric pressure that makes supercharging necessary also reduces back pressure against the exhaust, and so the turbine delivers more power higher up.<sup>2</sup>

In 1917 William F Durand, Director of NACA learned of Rateau’s work in France, and knowing that Dr. Sanford Moss had worked on turbines years earlier at Cornell as a graduate student and he asked the president of GE if Dr. Moss might

provide help in developing a turbocharger for the new Liberty engine. Moss built a high-RPM supercharger, driven by engine exhaust flow, and tested it in 1918 at Wright Field in Dayton, Ohio. As a result of this test, the government awarded its first supercharger contract to GE. Later in 1918 Moss attached his turbo-supercharger to a Liberty V-12 aero engine and tested it near Pikes Peak. The test engine was able to maintain far higher air intake-charge densities at high altitude than an unassisted Liberty Engine. Moss installed a 356 hp turbocharged engine on a LePere LUSAC biplane, which set international performance records, including in 1921 an altitude mark in excess of 40,000 feet; more than double LePere's operational ceiling. After his retirement from GE in 1938, Moss was awarded the Collier Trophy in 1940 for his work on the turbocharger.<sup>48</sup>

## Glenn Curtiss

After the Wright brothers, Glenn Curtiss was America's best-known aviation pioneer. He came originally to aviation as an engine builder. His reputation as a maker of motorcycle engines led to a request for a motor for a new dirigible. Curtiss became the fastest man in the world by traveling over 120 miles an hour on a motorcycle powered by a V-8.<sup>2</sup>

In 1907 Curtiss joined the Aerial Experiment Association headed by Alexander Graham Bell, and thus began his distinguished career as designer and builder of both airplanes and engines and as a pilot.<sup>3</sup>

## Two-stroke Engines

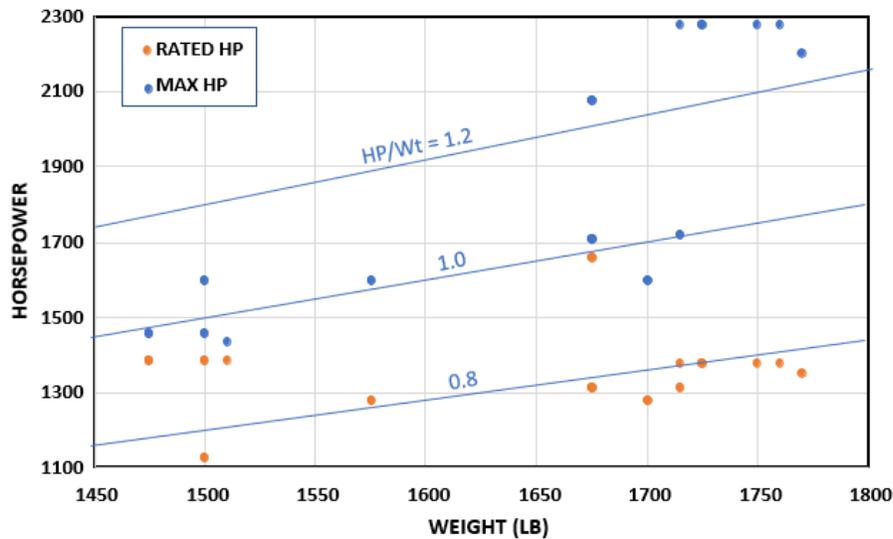
Two well-known American pioneer engines use the two-stroke principle. The great appeal of the two-stroke design lay in the smaller number of moving parts as compared with the four-stroke engines, and increased reliability. In particular, there are no valve springs to break and no lubrication system to fail. Two-strokes do have the disadvantage of excessive fuel consumption, often having a specific consumption 60% higher than comparable four-strokes, and the type largely died out for aviation use when the reliability of four-strokes reached acceptable levels. The first of the two-stroke specialists was Elbridge, a maker of marine engines in Rochester New York who began making airplane engines. The other well-known American two-stroke was the Roberts, made in Sandusky, Ohio, as late as 1919. The later Roberts engines had an arrangement of auxiliary intake ports in an effort to hold down the fuel consumption. Two-strokes use a lot of fuel because the same stroke that admits fuel also expels the exhaust (called scavenging). Some of the unburned fuel escapes and some of the exhaust stays in the cylinder.<sup>2</sup>

## A Caution on Power Ratings

In the early days of aviation piston engines, it was common to note different power ratings were occasionally offered, sometimes noting some configuration changes and/or changes in engine weight. Pretty soon multiple ratings proliferated such that it is usually a total waste of time to compare different engines as though power or even power/weight or power/displacement are good indicators of technology.

As illustrated in the figure below, many more recent engines offered many dozens of ratings with a wide variety of performance. This data shows rated HP at max HP for 25 different versions of the Packard Merlin, plotted against engine weight. The max weight is 20% higher than the minimum, and the highest horsepower ratings exceed the lowest by more than 50%. About the only constant in this sample is 12 cylinders of 1649 in<sup>3</sup> displacement. The variations are due to variations in supercharger and turbocharger configurations, boost settings on each, rpm at rated horsepower, and often other factors such as fuel octane rating, water injection, or time limitations.

## WEIGHT AND RATED POWER OF PACKARD MERLIN & V-1650 MODELS



## Piston Engines Today

Piston engines are very much in service and are still being built in large numbers for use in smaller aircraft used in general aviation. The days of the big radials are pretty much limited to use in “war birds” which preserve restored aircraft from WWII and the 1950’s. Today radials in the 100-400 hp range are manufactured in Romania, the Czech Republic, and Australia. The applications for these modern radials are typically for homebuilt aircraft including aerobatic and replica aircraft.<sup>42</sup>

Typical piston engines for general aviation are air-cooled, with 4 or 6 horizontally-opposed cylinders and hp ranging from around 100 to over 300, and popular sources include Continental, Textron Lycoming, and Rotax (Austria). At present there are well over 200,000 piston-powered aircraft in the US alone. In recent years, they have benefitted significantly in power, fuel economy, and durability from significant technological advancements. Some of these advancements include:<sup>45</sup>

- Fuel injection systems, which eliminate carburetors and enable more precise fuel/air control
- Turbocharged diesel engines (using jet fuel)
- FADECs (Full Authority Digital Electronic Controls) that monitor parameters and regulate electronic ignition and fuel injection, considerably reducing pilot workload (e.g., no need to lean or enrich fuel/air).

## Notes on Engine Manufacturers

**Allison:** The Allison Engine Co. was owned by GM from roughly 1929 until it was absorbed in 1995 by Rolls-Royce plc. James Allison had numerous corporate iterations in Indianapolis following his activities in automobile racing, eventually leading to the Allison Engineering Co. It was sold to Eddie Rickenbacker in 1927, and in 1929 shortly after Allison’s death to another owner, who in turn sold it to GM. Finally, Allison was sold in 1995 to Rolls-Royce plc, where the brand name is preserved as the AE engines.<sup>29</sup>

**Pratt & Whitney Aircraft** In 1926, Frederick B Rentschler left Wright Aeronautical and took with him much of the design staff, including George J Mead<sup>2</sup> and George Wilgoos,<sup>9</sup> and formed Pratt & Whitney, which took its name from a Hartford Connecticut machine-tool builder that provided finance. The first design, developed almost as rapidly as the Liberty, was the R-1340 Wasp.<sup>2</sup>

In 1925 Rentschler ended his association with Pratt & Whitney Machine Tool and merged Pratt & Whitney Aircraft with Boeing and other companies to form the United Aircraft and Transport Corporation (UATC). In 1934, the federal government of U.S. banned common ownership of airplane manufacturers and airlines. Pratt & Whitney was merged with UATC's other manufacturing interests east of the Mississippi River as United Aircraft Corporation, with Rentschler as president. In 1975, United Aircraft Corporation became United Technologies.<sup>49</sup>

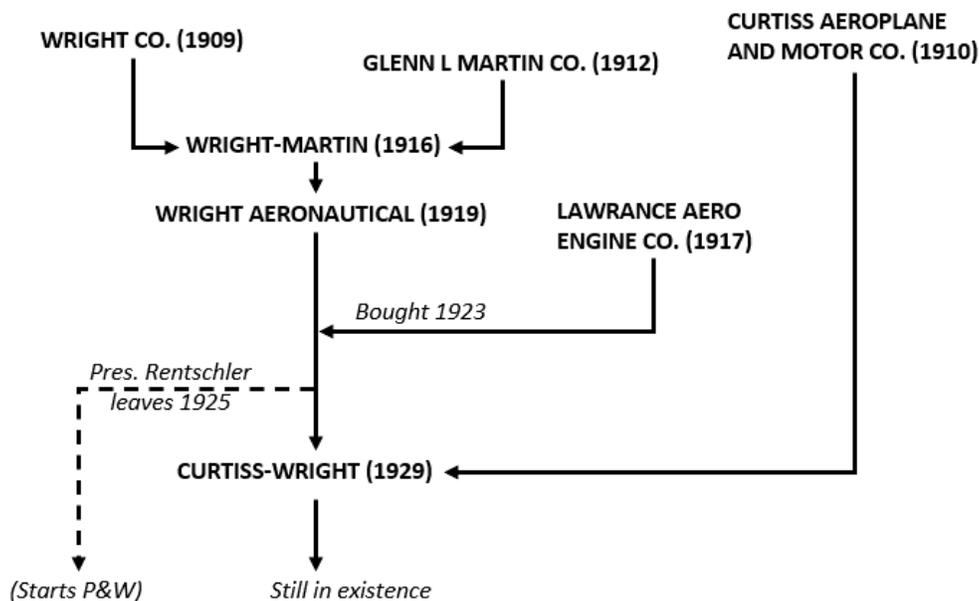
In 2020, United Technologies merged with Raytheon Company to form Raytheon Technologies, with Pratt & Whitney becoming one of the new corporation's four main subsidiaries.<sup>49</sup>

**Curtiss, Martin, Lawrance, and Wright:**<sup>29</sup> (Reference the figure below)

*In the US, it is important to realize it was not uncommon for one company to make aircraft, engines, and even operate their own airline up until 1934.*

The Wright Co. merged with the Glenn L. Martin Co. in 1916 to form Wright-Martin. This was renamed in 1919 as Wright Aeronautical, which bought and absorbed the Lawrance Aero Engine Co. in 1923. Finally, Wright Aeronautical merged with Curtiss Aeroplane and Motor Co. in 1929 to form Curtiss-Wright. Aircraft production ended shortly after WWII, and the last significant Wright engine was the Wright J65 turbojet, which was a license-built version of the Armstrong-Siddeley Sapphire jet. Curtiss-Wright has considerably diversified, and is still in existence.

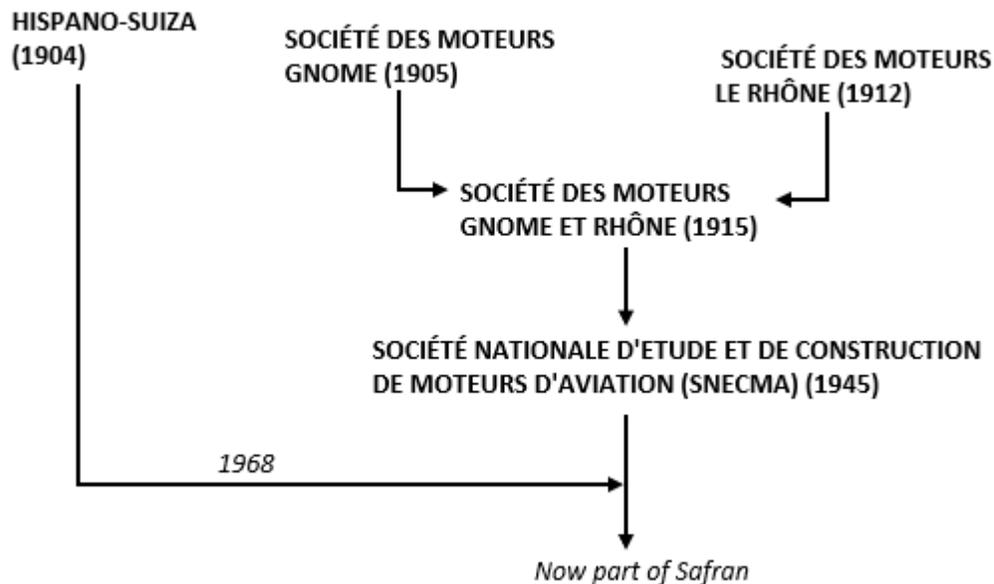
It should be noted that the Martin Co. that merged with Wright was the first incarnation of the Glenn L Martin Co. The Martin that merged with Wright had been formed in California. Only a year after that merger, Glenn Martin left the new company and formed a new Glenn L Martin Co. in Ohio in 1917. He moved that company to Middle River, Maryland in 1929, and it is that 2<sup>nd</sup> Martin company that lived on as Martin-Marietta and now Lockheed-Martin.



**Gnome, Hispano-Suiza, and Le Rhone:**<sup>29</sup> (Reference the figure below)

Gnome and Le Rhone both started in Paris, France, and after some serious competition merged in 1915 to become Gnome and Rhone. With the obsolescence of rotaries around 1920 they converted to other types and built British engines under license and eventually of their own design. What was left of them at the end of World War II was nationalized in 1949 as SNECMA.

Hispano-Suiza continued to make aircraft engines, aircraft cannons, and automobiles and after WWII continued in aerospace products including Rolls-Royce jet engines under license. Basically it remained independent until 1968, when it was absorbed by SNECMA.



**Hall-Scott Motor Car Company:** Started in California in 1910, Hall-Scott built engines for automobiles, trucks, and airplanes. Founder Elbert J. Hall worked with Jesse G. Vincent of Packard on the Liberty engine design in 1917. Hall-Scott got out of the aircraft engine business but continued to make automotive and truck engines and was bought by American Car and Foundry in 1925 and later cut loose in 1954 as an independent Hall-Scott. Apparently it faded away around 1960.<sup>29</sup>

**Salmson:** This French company began in 1890 building pumps and compressors, then automobiles and auto engines and finally aircraft and aircraft engines from before WWI and into the 1940's. It continued building cars into the 1950's and is still in existence.<sup>29</sup>

**Packard:** The simplest story... Packard Motor Company was formed in 1899, and made aircraft engines by the 1920's including two in the EY Gallery – the diesel(!) DR-980, a 9-cylinder radial, and the 3A-2500, a big V-12. After its famous Merlin during WWII it continued to produce large marine engines and experimented with some jets but mainly went back to cars. Merged to form Studebaker-Packard in 1954, and by the early 1960's the Packard name was no longer in use.<sup>29</sup>

# BACKUP ENGINE INFORMATION

## Fiat A-12

Six vertical water-cooled cylinders of 1326.1 cu in. Rated at 200 HP but guaranteed to deliver 255 hp at 1500 rpm. Integral head and barrels from individual steel forgings with valve ports and water jackets welded on. Overhead camshaft – packed with heavy oil sufficient for 12 hours running. Double carburetors. Gear type oil scavenge pumps at 3 locations and separate gear pump for oil delivery under pressure. Pistons of aluminum. Cooling water circulated by centrifugal pump and two magnetos furnished ignition.<sup>4</sup>



*Fiat A-12, at tail of Caproni (NMUSAF photo)*

The Fiat A-12 engine is a six-cylinder, liquid-cooled, in-line engine of 260 hp. It was used in such aircraft as the S.I.A. 7B1, Fiat R-2, S.A.M.L. S-2 reconnaissance aircraft, and the Caproni Ca. 46 bomber.<sup>20</sup>

## Anzani (On Bleriot Monoplane – removed Feb. 2023)

Anzani was a well known Italian maker of motorcycle engines. The aircraft in which Bleriot flew across the English Channel in 1909 was powered by a 3-cylinder air-cooled radial engine, commonly called a fan engine because the 3 cylinders resembled the folding fans that women used in the day. The novel, unsymmetrical arrangement of the cylinders was partly because of concerns of too much lube oil getting in cylinders if they were pointed down, causing either hydraulic lock or fouling of the spark plugs. The fan design also conveniently fit in the vee shape of a typical motorcycle frame.<sup>4</sup>



*Anzani 3-cylinder "fan engine" in Bleriot monoplane (Robeson photo)*

Fan-type engines were inherently rough running since there is no way to get an even firing order, but their compactness led to their having a fairly good power-to-weight ratio. The Anzani that powered Bleriot's cross-channel flight was typical. It gave 24.5 hp from 206 in.<sup>3</sup> displacement at 1600 RPM and weighed 145 pounds. The intake valves were automatic, and the cooling fins went only halfway down the cylinders. Cooling was marginal. On Bleriot's famous flight, an overheating engine nearly put him in the water, and only a fortunate rain shower that cooled off the motor allowed the flight to be completed. A more lasting contribution by Anzani was the development of the first practical air-cooled "static" radial engine. The first Anzani radials were built in 1910, had three cylinders, and were not noticeably advanced over the fan-types in cylinder and head design.<sup>2</sup>

Most of these types were fitted with Zenith carburetors. They were produced in Italy, England, and some other countries to a lesser extent. The model on the Bleriot Monoplane had cylinders made from cast iron with integral cooling fins, and were spaced 72 deg apart. It used Bosch magnetos. The crankshaft had a single crank pin and in place of ordinary crank checks there were disks that served both as flywheels and balance weights. The shaft was mounted on two plain bearings and the outer cylinder connecting rods were forked so as to straddle the plain rod of the center cylinder.<sup>4</sup>

## Roberts Model 4-X

The Roberts airplane engines all operated on the two-stroke cycle. They were built by the Roberts Motor Company of Sandusky Ohio (now operating as the Roberts Motors) from the designs of Mr. E. W. Roberts, a pioneer engine designer who was an assistant to Mr. Hiram Maxim in the 1890s.<sup>4</sup>

His early four-cylinder water-cooled two-cycle engine was rated at 50 hp at 1400 RPM and weighed 170 pounds. The cylinders were cast from a proprietary material known as "Aerolite" and the water jacket was partly cored out of the casting and the remainder covered by an aluminum jacket caulked into grooves in the cylinder. These engines were of the usual 3-port type except that the opening for admission and exhaust was by a spiral tubular rotary valve instead of by means of the piston. A cellular bypass was provided to prevent backfiring or exclusions in the crankcase.<sup>4</sup>



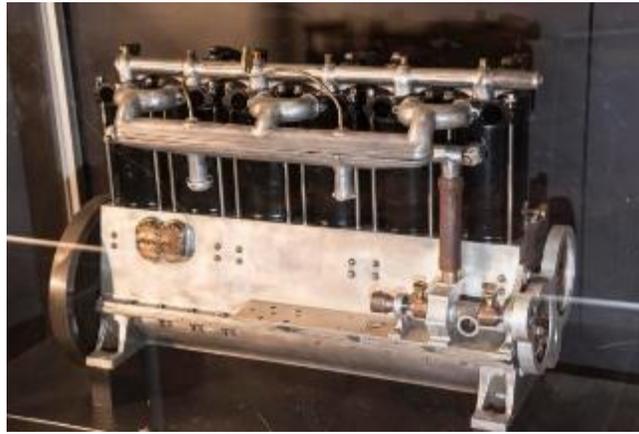
*Roberts Model 4-X (off starboard wing of SPAD VII) (NMUSAF photo)*

Pistons were made from cast iron. Ignition was by a magneto provided with a helical gear for turning the amateur to advance and retard spark. The mixture was supplied by a single carburetor, and lubrication was by splash.<sup>4</sup>

Roberts later went on to larger six and 12-cylinder engines.<sup>4</sup>

## Wright 6-60

The Wright 6-60 was a water-cooled six-cylinder vertical engine of 405.9 in.<sup>3</sup> displacement. It was rated at 60 hp at 1400 RPM and said to develop from 72 to 75 hp at 1560 RPM. The dry weight was approximately 300 pounds. Most of the original design features of the four-cylinder engine were retained. The cylinders had integral water jackets of cast iron and were held down by long studs from lugs on the cylinder head. To carburetors supplied 3 cylinders each.<sup>4</sup>



**Wright 6-60 (off starboard wing of SPAD VII) (NMUSAF photo)**

## Sturtevant 5A

The B.F. Sturtevant Co. of Hyde Park, Boston, Massachusetts, began constructing airplane engines in 1911. Their engines have been limited to water-cooled vertical and vee types.<sup>4</sup>

The Model 5-A was rated at 140 hp at 2000 RPM and was arranged for either direct propeller drive or reduction gears having a ratio of 0.6. The dry weight is 514 pounds, and water added another 36 pounds. Duplex carburetors furnish the mixture, and the gear pump provided lube pressure.<sup>4</sup>

Cylinders were cast in pairs from aluminum and fitted with steel liners. Detachable cylinder heads were also cast in pairs of aluminum. The camshaft was located in the vee and operated through pushrods and rockers the single inlet and single exhaust valve located in each cylinder head. Pistons were often aluminum alloy, cooling water circulated by a centrifugal pump, and dual ignition was supplied by magnetos.<sup>4</sup>



**Sturtevant 5A, against wall across from SPAD VII (NMUSAF photo)**

## Curtiss V2-3

In 1916 and 1917 Curtiss produced R-3 and R-4 airplanes for the U.S. Army Signal Corps, some of which the 1st Aero Squadron used during the Mexican Punitive Expedition. The Curtiss V2-3 engine, rated at 200 hp, powered both those airplanes; however, it had a poor power to weight ratio -- almost four pounds for every 1 hp -- which hurt aircraft performance. By comparison, the World War I Liberty engine had a ratio of two pounds weight per horsepower.<sup>20</sup>

The V2 was a water-cooled V-8 with a 5.00" bore, 7.00" stroke and 1,099.6 in<sup>3</sup> displacement, was rated 200 hp at 1,400 rpm. Its staggered individual forged-steel cylinders were machined all over and fitted with welded-in-place Monel sheet water jackets. Single 2.5" clear-diameter inlet and exhaust valves seated directly on the flat cylinder head. The inlet valve used a coil spring while the exhaust valve used a hairpin spring. Each valve was operated by a separate push rod and rocker arm from a camshaft mounted in the Vee. The four-throw crankshaft ran in five plain bearings. Side-by-side H-section connecting rods used a tube to deliver oil to the piston-pin bearing. The aluminum pistons were ribbed inside and fitted with two rings. Dual ignition was supplied by two eight-cylinder magnetos, and two Zenith carburetors, located on either side of the engine, each fed four cylinders. Oil was pumped from the sump to the bearings at about 60



**Curtiss V2-3 (off port wing of SPAD VII) (NMUSAF photo)**

psi by a gear pump. Fuel consumption was 0.54 lb./hp/hr. while oil consumption was 0.03 lb./hp/hr. Dry weight was 690 lb.<sup>38</sup>

## Hall-Scott Engine

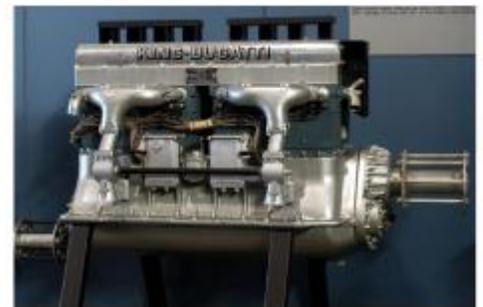
*This engine, in the Standard J-1 (with fabric partially removed) is identified in NMUSAF signage and website as a Hall-Scott A-4, but it is most likely an A-7 or perhaps A-7-a. The A-4 was a V-8 engine and this is obviously an inline 4-cylinder engine.*



*Hall-Scott engine in Standard J-1 (with fabric partially removed) (Robeson photo)*

## King-Bugatti U-16

A French engine designed in WWI by Ettoire Bugatti (an auto designer) started as a vertical 8-cylinder inline engine, and lacking applications they transformed it into a 16-cylinder with two inline 8's on the same crankcase. The two crankshafts were geared to a common central propeller shaft, which was hollow to permit firing a French 37-mm cannon through the center. The engines were shipped to the US and were deemed unsuitable for production, so it was redesigned at the Duesenberg Motors Corp., Elizabeth, NJ under the direction of Charles B. King. The redesign was put into immediate production but when the Armistice killed virtually all production, only about 40 had been built.<sup>4</sup>



*King-Bugatti U-16, under Fokker D. VII (NMUSAF photo)*

Known as the King-Bugatti, it was rated at 420 HP and weighed 1248 lb. dry (38 lb. more with water).<sup>4</sup>

Each half had two cast-iron four-cylinder blocks with integral heads, and the crankshafts consisted of a four-row flat crank in front and another, rotated 90° from the first, in the rear. The crankcase, gear case, cam covers, and water jacket enclosing plates were aluminum. It developed 400 hp and was relatively light thanks to using high speed instead of large displacement to develop its power. Only a single prototype was built in France, but rights were obtained in America. The American version was somewhat redesigned by a Colonel King. Apparently no example of the Bugatti-King ever flew, although it performed well on the test bench.<sup>2</sup>

The ignition was changed from magnetos to units with distributors on each end of the camshaft. Four carburetors with float chambers were used. The plates for the water jackets were made of aluminum instead of the sheet steel in the French design.<sup>4</sup>

## Bentley B.R.2

The third French rotary was the Clerget, and the British Navy Commander Walter Owen Bentley, the same Bentley who built great sports cars of the 20s, to Flanders to look into the overheating problem on its Clergets. Just before the war, Bentley had improved the performance of cars he had imported by installing some of the first aluminum pistons ever made, and he turned to that metal from the solution to the Clergets heat problems. Reasoning that the trouble lay in the relatively low heat conductivity of ferrous metal, he designed a new Clerget cylinder comprising a thin steel sleeve in an aluminum shell. This proved successful in the Clergets and Bentley next undertook a redesign of that engine.<sup>2</sup>

Bentley Rotaries, or BR's, were first built by the Humber Co. in England and designed by Capt. W. O. Bentley, trying to obtain lighter weight and higher efficiency than the Clerget engines widely used in England. Aluminum was used wherever possible to reduce weight.<sup>4</sup>

The result was first the BR1 of 150 hp, then in 1918, BR2 of 230 hp. The BR2 went into the Sopwith Camel's successor, the Sopwith Snipe, which was probably the best fighter of the war. There were to be no new rotaries after the big Bentley BR2.<sup>2</sup>

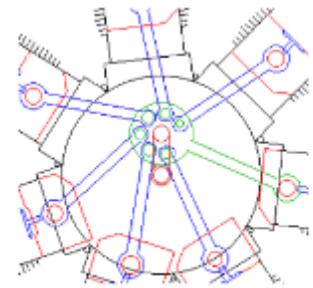
The B.R.-2 is a 9-cylinder air cooled rotary with 1522.4 cu in displacement. Compression ratio was 5-5.2. Rated HP was 200 but was said to develop from 230-250 at 1300 rpm. The carburetor is described as "block tube mixing valve type". At rated HP, gas consumption was about 20 gal/hr. and oil consumption was about 2.5 gal/hr.<sup>4</sup>

The cylinders barrels are cast aluminum with steel liners shrunk in place, and are held down by long bolts from lugs on the detachable heads. Pistons are also of aluminum. There is one inlet and one exhaust valve per cylinder. "The connecting rods are of the articulated type and all have tubular sections. The master rod, which is mounted on ball bearings, is similar in construction to those used on the Gnome engine."<sup>4</sup>

The approx. dry weight is 500 lb.<sup>4</sup>



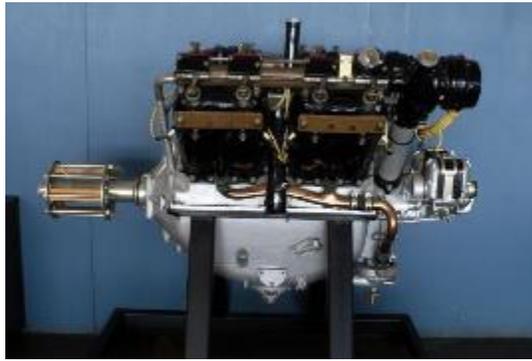
*Bentley B.R.2, between EY entrance and Caproni (Robeson photo)*



*The diagram above is from a separate web article on the Gnome but the green outline of the master rod is helpful*

## Lorraine-Dietrich 8Be

The La societe industrielle Lorraine-Dietrich 8Be was a single overhead cam 90° V-8 direct drive engine which produced 270 hp at 1900 rpm and weighed 573 lb. It was water-cooled and normally-aspirated, and had a displacement of 993.8 in<sup>3</sup>.<sup>17</sup> *(NMUSAF website incorrectly states it is currently in storage and also reports displacement as 94 in<sup>3</sup> instead of 994 in<sup>3</sup>)*



**Lorraine-Dietrich 8Be (NMUSAF website)**

The L-B 8Be was used in the SPAD S.XVI, and on 4/11/1918 this type was the first aircraft used by a US air unit (*e.g., after Americaine/Lafayette Escadrille*) in combat in WWI. About 1000 SPAD S.XVI's were built and six were used by the US. One flown by Billy Mitchell is now in the NASM at Udvar-Hazy.<sup>17</sup>

## R.A.F. 1A

R.A.F. stood for the Royal Aircraft Factory, an experimental station located in Farnborough, England.<sup>4</sup>

The R.A.F.-IA was an improvement of its earlier -I, an air-cooled 90-degree V-8 engine. The IA model developed 105 HP at 1800 rpm and weighed 440 lb. Compression ratio was 4.2. They were to be used only as tractor engines because of the cooling arrangement. Propeller speed was reduced through reduction gears.<sup>4</sup>

Cast-iron cylinders had integral horizontal cooling fins around the barrel and longitudinal fins across the head. Pistons were originally cast iron and later aluminum. A light steel flywheel also served as an oil circulating pump, the system of lubricating being gravity and splash. A carburetor with a single float and 2 mixing chambers was at the rear and below the engine. Ignition was provided by two magnetos.<sup>4</sup>



**R.A.F. 1A, between EY entrance and Caproni (NMUSAF photo)**

## Anzani 10

Anzani 10-cylinder radials used two rows of five cylinders driving a crankshaft with two crank pins.<sup>4</sup> *The one on display does not give sufficient info to identify the engine specifically (there were six different sizes of their 10 cylinder). Since it is stated to be 90-100 HP it appears to be one of these:*

- 738.1 cu in, 100 HP at 1100 rpm and 110 HP at 1200 rpm. Dry weight 300 lb.
- 764.9 cu in, 95-100 HP at 1250 rpm. Dry weight 363 to 384 lb.

The first known radial-configuration engine to use a twin-row design was the 160 hp Gnome 'Double Lambda' rotary engine of 1912, designed as a 14-cylinder twin-row version of the firm's 80 hp Lambda single-row seven-cylinder rotary.<sup>39</sup>



*Anzani 10, between EY entrance and Caproni (NMUSAF photo)*

## Benz BZ.IV

*Insufficient info from museum signage to pick specific engine. great descriptions in Airplane Engine Encyclopedia on 160 HP and 230 HP versions but our signage says 200 HP. need to search for data plate info.*



*Benz BZ.IV, between EY entrance and Caproni (NMUSAF photo)*

## Renault 12-F

Louis Renault began making automobiles in 1898 in Billancourt, France and began making airplane engines in 1907. Renault engines are noted to be “fairly representative of airplane engine development in France” at the time.<sup>4</sup>

The 12-cylinder model was water-cooled and had a displacement of 1348.3 in.<sup>3</sup> and had a 50° vee form. It delivered 285 hp at 1550 RPM and had a compression ratio of 4.6. There were two centrifugal water pumps, and dual ignition was delivered by four six-cylinder magnetos. Engine weight was 836 pounds.<sup>4</sup>

The Type 12-Fe was rated at 300 hp but was said to deliver 315 hp at 1550 RPM and 327 hp at 1600 RPM. Compression ratio was up to 5.0 and complete weight was reported as 794 pounds. On this model only one water pump was used with a single impeller and double outlets (which distinguishes this version from the 285 hp model).<sup>4</sup>



*Renault 12-F, between EY entrance and Caproni (NMUSAF photo)*

## Curtiss K-12

Charles B Kirkham was working with Curtiss on an engine even more advanced than the Hisso, but Kirkham's engine, unlike the Hisso, required several years of work before it was ready for service. In order to obtain more power without increasing frontal area, he extended his design from 8 to 12 cylinders. To further reduce bulk, Kirkham abandoned the wet sump that made for a deep oil pan on the Hisso and went to a dry-sump system.<sup>2</sup>



Curtiss K-12 (between EY entrance and Caproni) (Robeson photo)

One of two early American engines to incorporate reduced frontal area among the design objectives, the K-12, designed by Kirkham for Curtiss used smaller displacement and higher engine speed to reduce the frontal area. The K-12 produced the same 400 hp as the Liberty but accomplished this by reducing displacement from 1649 in.<sup>3</sup> to 1145 in.<sup>3</sup>, but increasing speed from 1850 RPM to 2500 RPM.<sup>2</sup>

Internally, Kirkham introduced other changes from the Hisso concept, while retaining the essential features of an aluminum block and enclosed valve gear. His most important innovation was the use of wet, instead of dry, sleeves. By letting the sleeves come into contact with the cooling water, cooling was significantly improved. His other change was somewhat questionable: he used two camshafts for each block.<sup>2</sup>

To enhance "good breathing", Kirkham opted to use four valves per cylinder (rather than increasing the bore and using larger valves). The four valve design had the further advantage that the exhaust valves are smaller and easier to keep cool. Although most later V-12's used rocker arms, the two pairs of camshafts on the K-12 were never a source of trouble.<sup>2</sup>

V-12 water cooled with 60-degree vee and 1145.1 cu in displacement. Normal compression ratio 5.63. Rated HP 375, although 397 HP developed at normal speed of 2250 rpm. Propeller shaft driven at a ratio of 0.6 through gearing. Dry weight 678.5 lb. (water adds 38.3 lb.).<sup>4</sup>

Cylinders machined from steel forgings & are screwed onto detachable aluminum heads. Aluminum jackets around the barrel and form part of crankcase. Each cylinder has 2 inlet and 2 exhaust valves. Each pair of valves operated from overhead camshaft. Overhead camshafts enclosed in oil-tight cover.<sup>4</sup>

Ball & Ball duplex carburetor. One half castor oil recommended in lubricating oil (provided by gear pump. Engine is of the dry sump type, with oil carried in the base chamber *(I have no clue what a base chamber means)*). One magneto for each bank of six cylinders.<sup>4</sup>

The K-12 had three main problems. One problem was the challenges of consistently casting a good block of aluminum for the 12-cylinder design. A second problem was the use of a four-bearing crankshaft that led to poor bearing life. This was a design gamble that might have shortened the engine by not using the more traditional seven bearings. The third problem lay with the reduction gearing. This was a necessity for a 2500 RPM engine, but the design and manufacture of a suitable gearbox defeated Kirkham and the Curtiss organization.<sup>2</sup>

## Rausenberger (Rausie) E-6

Rausenberger airplane engines were built by the Dayton Aero Motors Co. of Dayton, OH. Chief designer was Mr. Rausenberger, who joined the Steel Products Engineering Co. of Springfield, OH, where the Rausie E-6, his latest design is now being built.<sup>4</sup>

Earlier models of the “Rausie” started with Models A and B, which were V-8’s of 45 and 75 HP. Models C and D followed as V-12’s with HP ramping up to 150 and 250.<sup>4</sup>

The Rausie E-6 is a six-cylinder water cooled engine of 707.9 cu in displacement, rated at 175 HP at 1550 rpm and weighs 510 lb. Compression ration is 5.5. Cylinders are formed from a steel barrel with a separate steel combustion chamber that is “screwed on and welded”. An aluminum water jacket is used. Pistons are aluminum. Lube oil provided by gear pumps and water by a centrifugal pump. Two carburetors supply 3 cylinders each and two magnetos furnish dual ignition.<sup>4</sup>



*Rausenberger (Rausie) E-6 behind Thomas-Moore S4C (NMUSAF photo)*

## Packard DR-980 Diesel

Packard DR-980 air-cooled diesel engine of 225 hp. Flight tested at Wright Field during the 1929-1932 period in the XPT-8 trainer, it was the Air Corps' first diesel aircraft engine. Its development was halted with the death of its designer.<sup>20</sup>

It is an American nine-cylinder air-cooled aircraft Diesel engine first certificated in 1930. The engine was unpopular despite its economy and reliability due to the unpleasant nature of its diesel exhaust fumes and considerable vibration when running; approximately 100 were built. In 1930, the DR-980 passed its 50-hour certification test with a continuous rating of 225 hp (168 kW) at 1,950 rpm.

Production of the DR-980 ceased following the death of Captain Woolson in an aviation accident in April 1930; his legacy was the award of the Collier Trophy in 1931 to the Packard Motor Car Company for its work with this type of engine. One recognizable feature of later DR-980s was the oil cooler, a spiral of metal tubing placed around the propeller shaft.<sup>46</sup>



*Packard DR-980 Diesel (NMUSAF photo)*

On 28 May 1931, a Bellanca CH-300 fitted with a DR-980, piloted by Walter Edwin Lees and Frederic Brossy, set a record for staying aloft for 84 hours and 32 minutes without being refueled. This record was not broken until 55 years later by the Rutan Voyager.<sup>46</sup>

On 3 June 1929 the first two-way, radiophone communication took place over the skies of the Packard Proving Grounds in Utica, (now Shelby Township, Michigan). Heretofore, gasoline powered aircraft caused too much electromagnetic interference for the weak voice signal to be heard over the static. Only a strong Morse code signal could be heard. As diesel engines neither have spark plugs, nor spark plug wiring the EM static was greatly reduced and allowed voice communication to be used. The two-way ground to plane voice communication was witnessed by the U.S. Department of Commerce.<sup>46</sup>

Although only about 100 were built, it was used in a dozen different aircraft, including designs by Waco, Ford, and Bellanca. The 980 refers to its displacement in cu. in., and its dry weight was 550 lb.<sup>46</sup>

In recent times, diesel engines are starting to be used in general aviation aircraft – largely due to fuel economy and use of kerosene or jet fuel instead of leaded AvGas.<sup>45</sup>

## Liberty 12A Inverted

The inverted Liberty is a conversion of the famous Liberty 12 engine. The change was made to improve pilot visibility and to make mechanic's access easier.

Another benefit was to raise the propeller centerline, and one aircraft, the Loening OA-1 amphibian was



*Liberty 12A Inverted (NMUSAF photo)*



*Loening OA-1 (Wikipedia photo)*

designed specifically to use the inverted Liberty so that the propeller cleared the amphibian's hull (protruding as shown in 2<sup>nd</sup> photo). The Lincoln Motor Co. made the Liberty on display in 1918, and Allison Engineering of Indianapolis converted it to the inverted configuration in 1926. Horsepower 425, weight 845 lb.<sup>34</sup>

## Curtiss V-1570 Conqueror

The Conqueror developed from a history of Curtiss engines beginning in the early twentieth century. It was the last of Curtiss liquid cooled engines.<sup>21</sup>

The Curtiss Aeroplane and Engine Co. began producing its famous Conqueror engine in 1926. Although similar in general principles of design to the earlier Curtiss D-12 engine, the Conqueror was larger and more powerful. Originally rated at 600 hp, the engine's performance in several later versions was improved to 675 hp. In the late 1920s and early 1930s, the V-1570 Conqueror was selected to power the Curtiss P-6 series "Hawk" aircraft as well as various other Air Corps types including the A-8, B-2, B-7, O-25 and P-16. After 1935, the Conqueror was superseded by more advanced liquid-cooled engines.<sup>20</sup>



*Curtiss V-1570, near P-6 Hawk (NMUSAF photo)*

The Conqueror was a direct development of the D-12. They could be installed on the same engine mounts as the D-12. The version on display was a geared version incorporating reduction gear. A direct-drive version was also available that weighed approximately 890 lb., and one direct-drive version also incorporated a supercharger. Dual overhead cams were used and driven by 3 spur gears to reduce frontal area. Two Stromberg carburetors were used and one double magneto supplied ignition.<sup>38</sup>

A unique application of the Curtiss Conqueror was in an early Bonneville speed race car named the Mormon Meteor II. A purpose-built Diesenberg Special was modified by replacing the earlier Duesenberg engine with a Curtiss Conqueror engine, and in 1936 it set speed records for both 24 and 48-hours. A later version called the Mormon Meteor III also used the Curtiss Conqueror aircraft engine and continued setting new records for endurance speed, including a 24 hr. record of 161 mph in 1940 that was not broken until 1990.<sup>47</sup>

### **TECHNICAL NOTES:**<sup>20</sup>

Model: V-1570-59

Type: 12-cylinder, liquid-cooled, Vee  
Displacement: 1,570 cu.in.  
Maximum hp: 675  
Maximum rpm: 2,450  
Weight: 1088 lb.<sup>21</sup>

## Almen A-4 Barrel Engine

The water-cooled A-4 barrel engine (18 cylinders -- two groups of nine each horizontally opposed) was the fourth experimental barrel engine built for testing at McCook Field, Ohio, by its inventor, Mr. J.O. Almen of Seattle, Wash. The project began in 1921 and by the mid-1920s, the A-4 passed its acceptance tests. The engine never went into production, however, reportedly because of limited funds and a growing emphasis by the U.S. Army Air Corps on air-cooled radial engines.<sup>20</sup>

This unique engine had a much smaller frontal area than other water-cooled engines of similar horsepower, thereby providing better streamlining and less air resistance. It was rated at 425 hp but weighed only 749 pounds (a power to weight ratio of better than one to two), a significant design achievement in the early 1920s.<sup>20</sup>



*Almen A-4 Barrel Engine in corner behind Martin B-10 (NMUSAF photo)*

## Pratt & Whitney R-985 Wasp Jr.

The R-985 air-cooled engine was first used by the Army Air Corps in 1932. At that time, it was rated at 300 horsepower. Over the next ten years, further refinements were made, and during World War II some variants produced up to 450 horsepower. The R-985 powered thousands of military aircraft of various types in addition to being installed in numerous civilian types of aircraft.<sup>20</sup>

The Wasp Jr. is one of the most successful reciprocating engines ever built. Pratt & Whitney introduced it as a complement to the highly successful Wasp and Hornet families of engines in 1930. The Wasp Jr. was essentially a Wasp of reduced dimensions. Pratt & Whitney and its licensees manufactured over 39,000 versions of the R-985 until 1953 for a wide variety of military and commercial aircraft, including light transports, trainers, sport aircraft, and helicopters.<sup>22</sup>



*P&W R935, beneath rear of AT-12 Kansan*

### TECHNICAL NOTES:<sup>20</sup>

Type: 9-cylinder, air-cooled, supercharged radial  
Displacement: 985 cu.in.  
Maximum rpm: 2,300  
Weight: 682 lb.<sup>22</sup>  
Maximum hp: 450

## Ranger L-440

The L-440 air-cooled, six-cylinder, inverted, in-line engine was manufactured by the Ranger Aircraft Engine Division of Fairchild Engine and Airplane Corp. Built in several versions ranging from 175 hp to 200 hp, L-440 series engines powered more than 6,000 Fairchild PT-19 and PT-26 during World War II.<sup>20</sup>



**Ranger L-440 at starboard wing of A-17 (NMUSAF photo)**

**TECHNICAL NOTES:**<sup>20</sup>

Type: 6 cylinder, in-line  
 Displacement: 441 cu.in.  
 Maximum rpm: 2,450

### Pratt & Whitney R-1830 Twin Wasp

In 1929 PWA started experimenting with two rows of 14 cylinders. The 2<sup>nd</sup> row, with cylinders staggered between the cylinders in the other row to improve cooling, allowed for increased power without increasing frontal area. Higher cylinder count also made for more, but smaller power pulses that resulted in smoother operation and improved life. This 14-cylinder engine was the R-1830 Twin Wasp and power ranged from 800 hp to 1350 hp. It would become the most widely used of any PWA radials. Including license-built version it had the biggest production run of any aircraft engine in the world with 173,618 produced up until 1951. Applications included DC-3, B-24, F4F Wildcat, P-36, and Vickers Wellington.<sup>10</sup>



**P&W R-1830, Installed on B-24 Liberator (NMUSAF photo)**

Aircraft in the NMUSAF powered by the R-1830 are the B-24D, OA-10, C-47D, P-35, and P-36A.<sup>20</sup>

### Pratt & Whitney R-2800 Double Wasp

Second in production run and possibly most famous descendent of the Wasp was the R-2800 Double Wasp with 2x9 cylinders. This 18-cylinder engine was about a year ahead of the other big 18 – the Wright R-3350 Duplex Cyclone designed for the new B-29. Both big 18's had significant cooling problems, but they plagued the Duplex Cyclone all the way through the war. PWA went from traditional fins cast or forged as part of the casting/forging and went to forged heads that were then cut with milling saws to produce thinner fins with greater cooling surface area. The first R-2800 produced 2000 hp, and eventually 2800 hp on an experimental version. With a 2-stage 2-speed supercharger, they were used in the Vought F4U, Grumman F6F Hellcat, and P-47.<sup>10</sup> **For the P-47, a GE turbocharger was used.<sup>33</sup> (It is not clear from these sources if the R-2800 retained mechanical supercharger(s) on the P-47)**



***P&W R-2800, at nose of P-47 "Ginger" (Robeson photo)***

Aircraft in the NMUSAF powered by the R-2800 are the B-26K, C-123K, P-47D (both), C-82, VC-118, P-61C, B-26C, C-46D and B-26G.<sup>20</sup>

Cylinders are built up of forged aluminum heads with integral valve mechanism housings, screwed and shrunk onto forged steel cylinder barrels. Forged aluminum sleeves in which deep-cut cooling fins have been machined (muffs), are shrunk over the central portion.<sup>33</sup> [Cooling fins had often been cast in, but because of the cooling challenges \(especially on a twin-row radial\), they were machined out of the forging, yielding much thinner fins and thus a larger surface area.](#)<sup>36</sup>

Each cylinder has one inlet and one exhaust valve. The inlet seats in a bronze insert and the exhaust on a steel insert, both of which arc shrunk into the head. Pressure baffles are provided to enhance cooling.<sup>33</sup>

Forged aluminum pistons are of the full-skirt type. Each piston is fitted with three compression rings, dual oil control rings and one oil scraper ring.<sup>33</sup>

Each of the two master rod assemblies consists of a one-piece master rod and eight "I" section articulated rods attached by knuckle pins. Master rod bearings are one-piece steel shells covered on the inside and outside with lead-silver. Each articulated rod has a bronze bushing on its piston pin end. The other end rides on a silver-plated knuckle pin.<sup>33</sup>

The crankshaft is machined from three steel forgings having two throws that divide at the crankpins and are joined together by face splines and bolts. The crankshaft assembly is supported by steel-backed lead-silver bearings mounted in the front, center and main crankcase sections. Reciprocating and rotating part weights are counteracted by weights, the front and a portion of the rear being mounted as bifilar dampers. Mounted at each end of the crankshaft are two counterbalances, revolving at twice crankshaft speed to eliminate second order "whirl".<sup>33</sup>

The crankcase is composed of three forged aluminum alloy sections held together by through bolts. The nose section houses the reduction gears and torque meter and has provisions for a full-feathering, reversible propeller governor.<sup>33</sup>

The supercharger section is attached to the rear of the main crankcase section and also houses an impeller. The intermediate rear case is attached to the supercharger section. It supports at its forward face a vaned diffuser plate and provides a mounting surface for a pressure carburetor. The rear section has mounting pads for accessories.<sup>33</sup>

The valve gear, induction system supercharger, ignition system, lubrication system, reduction gear and accessory drives are substantially the same as the Twin Wasp. The ignition system is optionally high or low voltage.<sup>33</sup> **Two distributors are mounted at the top of the reduction gear housing and conduits for the spark plug wires emerge from the back of the distributor housings.**<sup>36</sup>

Water injection equipment may be used with the "CA" Double Wasp to give added power for takeoff and emergencies.<sup>33</sup>

More R-2800's were produced (125,443) than any other PW engines except the R-1830 Twin Wasp (173,618).

### **Talking Points:**

- Aircraft in the NMUSAF powered by the R-2800 are the B-26K, C-123K, P-47D (both), C-82, VC-118, P-61C, B-26C, C-46D and B-26G.
- Over 125,000 R-2800's were built.
- Cooling fins were machined from an aluminum forging to yield thinner fins and more surface area.
- All applications used superchargers, and a turbosupercharger was added for the P-47 Thunderbolt.

## **Pratt & Whitney R-1340 Wasp**

In 1926, Frederick B Rentschler left Wright Aeronautical and took with him much of the design staff, including George J Mead<sup>2</sup> and George Wilgoos.<sup>9</sup> and formed Pratt & Whitney, which took its name from a Hartford Connecticut machine-tool builder that provided finance. The first design, developed almost as rapidly as the Liberty, was the 1340 in.<sup>3</sup> Wasp.<sup>2</sup>

They developed the 400 hp Wasp engine which preempted the Liberty. The Wasp developed the same power as the Liberty but being an air-cooled radial, it was much lighter and more reliable. Just as the Whirlwind put Wright Aeronautical on the map, the Wasp did the same for Pratt & Whitney.<sup>9</sup>

The first P&WA engine was the R-1340 Wasp, a 9-cylinder radial with many advanced features including a rotary induction blower, a split counterbalanced crankshaft, symmetrical front and rear forged crankcases, pushrod housings and accessories arranged to allow maintenance without dismantling the engine. It was rated at 410 hp at under 650 lb., and the USN placed an order for 200 engines after only 6 had been built.<sup>10</sup> **The high power-to-weight performance of the Wasp was primarily due to higher cylinder pressures.**<sup>2</sup>

The Wasp name came from Rentschler's wife, Faye, who thought the engine sounded like a wasp when running.<sup>50</sup>

The Ford Trimotor was the first civilian airliner to use the Wasp and other uses covered many types of aircraft including helicopters. By 1930 the R-1340 Wasp was up to 600 hp.<sup>10</sup>

While the Boeing 247 utilized the Wasp engine, Boeing's mistreatment of other customers led to the downfall of that aircraft. Boeing delayed deliveries of new 247's for about two years while they first completed all deliveries to United Air Lines Lines (both Boeing and United Air Lines were part of United Aircraft). Unwilling to wait this long, Jack Frye of TWA initiated a competing airliner known as the DC-2. Powered by Cyclones instead of Wasps, seating 18 instead of 10, and having full headroom instead of passengers having to step over the wing spar, the DC-2 made the 247 obsolete the first day it flew.<sup>2</sup>



*PW R-1340 Wasp, installed in T-6 Mosquito (Korea). Arrow shows location of Lincoln penny (NMUSAF photo)*

Apparently ever since someone noticed that a penny fit snugly in the insert below the shaft on the sump cover, it has been somewhat of a tradition to place one there. The reason for the penny in many R-1340's is typically ascribed to an old tradition of placing a new penny in the engine when it is overhauled, but others maintain the tradition simply relates to a "lucky penny". Either way, this is the reason the Wasp is often called the "penny engine".<sup>27</sup>

## Rotax 912 UL

The Rotax 912 is a horizontally-opposed four-cylinder, naturally aspirated, four-stroke aircraft engine with a reduction gearbox. It features liquid-cooled cylinder heads and air-cooled cylinders. Originally equipped with carburetors, later versions are fuel injected. Dominating the market for small aircraft and kitplanes, Rotax produced its 50,000th 912-series engine in 2014.[1] Originally available only for light sport aircraft, ultralight aircraft, autogyros and drones, the 912-series engine was approved for certified aircraft in 1995.<sup>32</sup>



*Rotax 912 UL on port side of MH-53 tail rotor (Robeson photo)*

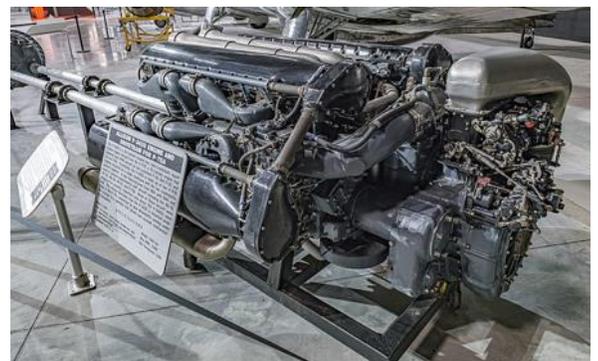
Applications include several hundred different types, but include the General Atomics MQ-1 Predator.<sup>32</sup>

General characteristics:<sup>32</sup>

Type:	Four-cylinder, four-stroke liquid/air-cooled engine with opposed cylinders, dry sump forced lubrication with separate oil tank, automatic adjustment by hydraulic valve tappet, dual CD carburetors, mechanical diaphragm pump, electronic dual ignition, electric starter, integrated reduction gear 1:2.273 or 1:2.43
Displacement:	73.91 in <sup>3</sup>
Dry weight:	132.3 lb. with electric starter, carburetors, fuel pump, air filters and oil system
Fuel type:	Unleaded: 87 octane AKI (Canada/USA)
Oil system:	Dry sump with trochoid pump, camshaft driven
Cooling system:	Liquid-cooled cylinder heads, air-cooled cylinders
Power output:	79.9 hp at 5,800 rpm

## Allison V-3420

The Allison V-3420 was of a very unique configuration, combining two V-1710 V-12 engines and therefore doubling its total displacement. Although it was never used in a production aircraft, it was a unique approach to providing power in the 2000+ hp class with a liquid-cooled engine, and flew briefly in four unique and rare aircraft.



*Allison V-3420 (Wikipedia photo)*

Allison started this effort with the X-3420, which joined the two V-1710 engines with a single common crankcase. That configuration required master and articulated piston rods and the technical challenge exceeded available resources, so in 1936 that approach was abandoned in favor of two V-1710's with a common crankcase but two separate crankshafts that were geared to a common output shaft. This resulted in a design known as the V-3420, but it was sometimes called either the W-24 or the DV-2420 (DV for "double Vee"). One crankshaft drove a large supercharger, and the other crankshaft drove various accessories. Although a GE turbocharger was planned, it never was incorporated. Using more than 90% parts common to the V-1710, it was initially offered with a takeoff rating of 2300 hp. It was first tested in 1938, and the novel design was also displayed at the NY World's Fair in 1939.<sup>54</sup>

Two versions were developed for potential use in aircraft. On the V-3420-A the two crankshafts turned in the same direction for single-rotation propellers. The V-3420-B had crankshafts that rotated in opposite directions, and was intended for contra-rotating propellers. The V-3420-B version only flew on the Fisher XP-75, which started in 1944 with an order for 2500 aircraft, but was cancelled only a few months later when performance of the planned long-range escort fighter was found to be lacking and the end of the war was in sight. Of the 14 built, the P-75A in the NMUSAF is the only surviving example.<sup>54</sup>

The V-3420-A flew on three different aircraft and was planned for a another one but development delays resulted in an embarrassing engine swap:

XLRB (Experimental Long-Range Bombers): In the mid-1930's the US Army Air Corps expressed interest in new long-range bombers and this resulted in the Boeing XBLR-1 and the Douglas XBLR-2:

The Boeing XBLR-1 was the first intended to use the V-3420-A with projected 2600 hp, but by the time it finally flew in 1937, delays by Allison in development forced Boeing to switch to the 850 hp PW R-1830 Twin Wasp. Although significantly hampered by the engine downsizing, the Boeing design, known as the XB-15 was the largest aircraft by weight ever flown to date, and had considerable innovations that Boeing used in later aircraft. The single example built was redesignated as the XC-105 cargo plane and flew unique missions over the next year and a half as the only one of its type.<sup>52</sup>

The Douglas XBLR-2 started flight in 1941 using the Wright R-3350 engines being developed for the B-29. In 1943, the R-3350 engines were replaced by Allison V-3420-A engines, largely because Wright Field had already considered the V-3420-A as a backup to the R-3350 on the B-29 bomber. This unique huge 4-engined bomber basically served as a test vehicle until it was scrapped in 1949.<sup>53</sup>

The Lockheed XP-58 Chain Lightning, which was a larger version of the famous P-38 Lightning. Amazingly, Lockheed went through three different engines for the XP-58 before finally making its first flight in 1944 with the V-3420-A. It was cancelled the next year after disappointing performance and only one was built.<sup>54</sup>

The final aircraft that actually flew the V-3420 was a single XB-39. This unique aircraft started as the YB-29 and was a unique version of the B-29 specifically to evaluate the Allison V-3420 because of major concerns that issues with the Wright R-3350 would be successfully resolved. It first flew in December 1944, and although it showed a top speed of 50 mph better than the B-29 and a 3000 ft. higher service ceiling, it was never pursued for production since the B-29 with the R-3350 had basically demonstrated "adequate performance" with a huge production run already underway.<sup>54</sup>

# ENDNOTES, BIBLIOGRAPHY, & APPENDICES

## Sources Used in this document:

1. Graham White, "Pratt & Whitney's R-4360", in *The Piston Engine Revolution*, Fred Starr, Edward L. Marshall and Bryan Lawton (Newcomen Society, 2012)
2. Herschel Smith, *AIRCRAFT PISTON ENGINES From the Manly Balzer to the Continental Tiara* (Sunflower University Press, 1989)
3. C. Fayette Taylor, *AIRCRAFT PROPULSION - A Review of the Evolution of Aircraft Piston Engines* (Smithsonian Institution Press, 1971)
4. Glenn Dale Angle, *Airplane Engine Encyclopedia* (Otterbein Press, 1921)
5. "Wright R-1820 'Cyclone'"; by Kimble D. McCutcheon, *Aircraft Engine Historical Society*, last modified November 27, 2022, <https://www.enginehistory.org/Piston/Wright/WrightR-1820.pdf>
6. "Curtiss OX-5"; by Kimble D. McCutcheon, *Aircraft Engine Historical Society*, last modified November 27, 2022, <https://www.enginehistory.org/Piston/Before1925/CurtissOX5.pdf>
7. "Wright R-3350 'Cyclone'"; by Kimble D. McCutcheon, *Aircraft Engine Historical Society*, last modified November 27, 2022, <https://www.enginehistory.org/Piston/Wright/WrightR-3350.pdf>
8. "Case History of the R-2600 Engine Project"; by Jay Smith, *Aircraft Engine Historical Society*, last modified December 23, 2022, <https://www.enginehistory.org/Piston/Wright/R-2600/R-2600CaseHx.shtml>
9. Robert B. Meyer, Jr., "The Piston Engine and its Contribution to the Turbojet", in *Deputy for Propulsion TENTH ANNIVERSARY HISTORICAL SYMPOSIUM* (publisher unknown, 1986)
10. Paul Shillito, "How Pratt & Whitney Changed Aviation", YouTube video, 18:17, posted November 18, 2022, <https://www.youtube.com/watch?v=dMPcgaVboUQ>
11. Larry Dwyer, "Allison V-1710 – USA", *The Aviation History On-Line Museum*, updated October 12, 2013, <http://www.aviation-history.com/engines/allison.htm>
12. (Author unknown), "Le Rhône Rotary Engine", *The Aviation History On-Line Museum*, updated February 3, 2014, <http://www.aviation-history.com/engines/rotary.htm>
13. Larry Dwyer, "Curtiss D-12", *The Aviation History On-Line Museum*, updated October 12, 2013, <http://www.aviation-history.com/engines/d12.htm#:~:text=The%20Curtiss%20D%2D12%2C%20designed,used%20during%20World%20War%20I.>
14. JONES, E., "THE DEVELOPMENT OF THE WRIGHT WHIRLWIND TYPE J-5 AIRCRAFT-ENGINE," SAE Technical Paper 260061, 1926, <https://doi.org/10.4271/260061>
15. William Wraga, "The Wright Whirlwind 1919-1927", *Spirit of St. Louis 2 Project*, 2014, <http://www.charleslindbergh.com/plane/j5c.asp>
16. Graham Kozak, "Rolls-Royce vs. Packard: Who Built a Better Merlin?", <https://www.autoweek.com/car-life/classic-cars/a30763715/rolls-royce-vs-packard-who-built-a-better-merlin/>
17. Bryan R. Swopes, "11 April 1918", *THIS DAY IN AVIATION HISTORY*, 2018, <https://www.thisdayinaviation.com/tag/lorraine-dietrich-8be/>
18. Author unk., "Le Rhone Model C, 9 Cylinder, Rotary Engine", *National Air and Space Museum*, date unk., [https://airandspace.si.edu/collection-objects/le-rhone-model-c-9-cylinder-rotary-engine/nasm\\_A19200011000](https://airandspace.si.edu/collection-objects/le-rhone-model-c-9-cylinder-rotary-engine/nasm_A19200011000)
19. Sandy Skinner, "The Curtiss OX-5", Guset User, <https://fliptm15.com/rizg/kfoa/basic>, October 29, 2015
20. Various NMUSAF website articles, <https://nationalmuseum.af.mil>
21. Author unk., "Curtiss Conqueror V-1570, V-12 Engine", *National Air and Space Museum*, date unk., [https://airandspace.si.edu/collection-objects/curtiss-conqueror-v-1570-v-12-engine/nasm\\_A19710913000](https://airandspace.si.edu/collection-objects/curtiss-conqueror-v-1570-v-12-engine/nasm_A19710913000)

22. Author unk., "Pratt & Whitney Wasp Jr. R-985-AN-14B 'Dancing Engine'", *National Air and Space Museum*, date unk., [https://airandspace.si.edu/collection-objects/pratt-whitney-wasp-jr-r-985-14b-dancing-engine/nasm\\_A19761858000](https://airandspace.si.edu/collection-objects/pratt-whitney-wasp-jr-r-985-14b-dancing-engine/nasm_A19761858000)
23. Author unk., "Allison V-1710-33 (V-1710-C15), V-12 Engine", *National Air and Space Museum*, date unk., [https://airandspace.si.edu/collection-objects/allison-v-1710-33-v-1710-c15-v-12-engine/nasm\\_A19420027000](https://airandspace.si.edu/collection-objects/allison-v-1710-33-v-1710-c15-v-12-engine/nasm_A19420027000)
24. Author unk., "Engine No. 3", *The Wright Experience*, <https://www.wrightexperience.com/the-engine/>, date unk.
25. Author unk., "90-Year History of Prestone®", 2021, <https://prestone.com/about-us/#:~:text=HISTORY%20OF,PRESTONE&text=Since%201927%2C%20Prestone%2CAE%20has,laps%20ahead%20of%20the%20competition.>
26. Author unk., "Ethylene glycol", last edited December 26, 2022, [https://en.wikipedia.org/wiki/Ethylene\\_glycol](https://en.wikipedia.org/wiki/Ethylene_glycol)
27. Giacinta Bradley Koontz, "Mechanics in History: Penny For Your Thoughts", *AVIATIONPROS*, July 6, 2007, <https://www.aviationpros.com/home/article/10381550/mechanics-in-history-penny-for-your-thoughts>
28. Author unk., "Salmson Z-9", date unk., <https://www.enginehistory.org/Piston/Before1925/SalmsonZ-9/SalmsonZ-9.shtml>
29. Author unk., (various articles under names of individual manufacturers), <https://www.en.wikipedia.org>
30. Author unk., "Magneto", last edited June 9, 2022, <https://en.wikipedia.org/wiki/Magneto>
31. Author unk., "AVIATION PRIZE WON BY MOTOR BUILDER", 2023, <https://www.nytimes.com/1928/02/01/archives/aviation-prize-won-by-motor-builder-collier-trophy-is-awarded-to-c.html>
32. Author unk., "Rotax 912", last edited December 3, 2022, [https://en.wikipedia.org/wiki/Rotax\\_912](https://en.wikipedia.org/wiki/Rotax_912)
33. Kimble D. McCutcheon, "Double Wasp CA Series Description", revised July 6, 2020, <https://www.enginehistory.org/Piston/P&W/R-2800/r-2800.shtml>
34. Text from NMUSAF signage as noted January 10, 2023
35. Author unk., "Curtiss OX-5 Engine Overhaul Part I" and "OX-5 Engine Rebuild Chapters 2 and 3", both from *BlueSwallow Aircraft*, date unk. and December 17, 2013, <https://www.youtube.com/watch?v=NE4xpRuFcaQ> and <https://www.youtube.com/watch?v=y9I2wv7Jt84>
36. Author unk., "Pratt & Whitney R-2800 Double Wasp", *Wikipedia*, last edited January 8, 2023, [https://en.wikipedia.org/wiki/Pratt\\_%26\\_Whitney\\_R-2800\\_Double\\_Wasp](https://en.wikipedia.org/wiki/Pratt_%26_Whitney_R-2800_Double_Wasp)
37. Larry Dwyer, "Wright R-3350", *The Aviation History On-Line Museum*, Updated October 12, 2013, <http://www.aviation-history.com/engines/r3350.htm>
38. Kimble D. McCutcheon, "Selected Early Engines", *Aircraft Engine Historical Society*, last modified April 26, 2022, <https://www.enginehistory.org/Piston/Before1925/EarlyEngines/C/Cu.shtml#Cu>
39. V. Bentley, "How the radial aircraft engine works", *Canadian Museum of Flight*, May 2014, <http://canadianflight.org/files/Radial%20eng%20presentation1409-5.pdf>
40. Robert J. Neal, "Before the Liberty" in *A Technical & Operational History of the Liberty Engine* (Specialty Press, 2009)
41. Robert Schlaifer and S.D. Heron, *DEVELOPMENT OF AIRCRAFT ENGINES AND FUELS* (The Andover Press, Ltd., 1950)
42. Author unk., "The History of Radial Engines", *Flightline Weekly*, September 13, 2022, <https://www.flightlineweekly.com/post/the-history-of-radial-engines>
43. Bob Teter, "A history of aviation gasoline", *AIR FACTS*, April 11, 2022, <https://airfactsjournal.com/2022/04/a-history-of-aviation-gasoline/>
44. Author unk., "Octane Rating", *Wikipedia*, January 17, 2023, [https://en.wikipedia.org/wiki/Octane\\_rating](https://en.wikipedia.org/wiki/Octane_rating)
45. Stephen Pope, "Piston Engine Aircraft Technology", *FLYING*, April 6, 2012, <https://www.flyingmag.com/aircraft-pistons-piston-engine-technology/>
46. Author unk., "Packard DR-980", *Wikipedia*, November 1, 2011, [https://en.wikipedia.org/wiki/Packard\\_DR-980](https://en.wikipedia.org/wiki/Packard_DR-980)

47. Author unk., "Mormon Meteor", *Wikipedia*, December 9, 2022, [https://en.wikipedia.org/wiki/Mormon\\_Meteor](https://en.wikipedia.org/wiki/Mormon_Meteor)
48. Author unk., "Sanford Alexander Moss", *Wikipedia*, February 18, 2023, [https://en.wikipedia.org/wiki/Sanford\\_Alexander\\_Moss](https://en.wikipedia.org/wiki/Sanford_Alexander_Moss)
49. Author unk., "Pratt & Whitney", *Wikipedia*, March 19, 2023, [https://en.wikipedia.org/wiki/Pratt\\_%26\\_Whitney](https://en.wikipedia.org/wiki/Pratt_%26_Whitney)
50. Jack Connors, *The Engines of Pratt & Whitney: A Technical History* (American Institute of Aeronautics and Astronautics, Inc., 2010)
51. Dr. Dean C. Kallander, *Friends Journal*. "The Air Force Museum: 75 Years Old in 1998 The Early Years 1923-1944", Vol. 21, No. 1, Spring 1988
52. Author unk., "Boeing XB-15", *Wikipedia*, January 22, 2023, [https://en.wikipedia.org/wiki/Boeing\\_XB-15](https://en.wikipedia.org/wiki/Boeing_XB-15)
53. Author unk., "Boeing XB-19", *Wikipedia*, May 11, 2023, [https://en.wikipedia.org/wiki/Douglas\\_XB-19](https://en.wikipedia.org/wiki/Douglas_XB-19)
54. William Pearce, "Allison V-3420 24-Cylinder Aircraft Engine", *Aircraft Engine Historical Society*, June 6, 2021, <https://oldmachinepress.com/2017/04/20/allison-v-3420-24-cylinder-aircraft-engine/>
55. Philip S. Dickey, III, *The Liberty Engine 1918-1942, Smithsonian Annals of Flight, Volume 1, Number 3* (Smithsonian Institution Press, 1968)
56. Hugo T. Byttebier, *The Curtiss D-12 Aero Engine, Smithsonian Annals of Flight, Number 7* (Smithsonian Institution Press, 1968)
57. Author unk., "Fuel Injection", *Wikipedia*, May 19, 2023, [https://en.wikipedia.org/wiki/Fuel\\_injection](https://en.wikipedia.org/wiki/Fuel_injection)

Endnotes are typically applied only at the end of a paragraph, indicating all material in that paragraph was from that single source. For entries in short lists (e.g., bulletized), the appropriate endnote is applied to the previous line instead of applying to each item in the list.

When two different sources are used within one paragraph, the use of two separate endnotes is clarified by using dark blue font in addition to the normal black font.

Summary data in this document is a mixture of paraphrases and notes from the cited source, but often are excerpts taken verbatim. Some material without endnotes are summaries of information readily available in many common sources.

## Additional references (not used in this document)

A- <https://www.enginehistory.org/Piston/Wright/C&WSpecs.shtml>

Comparative stats of about 50 engines (Curtiss, Lawrance, & Wright) from about 1913 to 1940

B- <https://www.enginehistory.org/Piston/Before1925/EarlyEngines/H/H.shtml#Ha>

Information on Hall-Scott engines (convinced me the engine in the Jenny with fabric removed is not an A-4 as indicated in NMUSAF signage)

C- <https://www.enginehistory.org/Piston/HOAE/Continental2.html>

Summary info on Continental Motors including O-470, which is not currently considered for the tour because it is located in the Cold War Gallery but is a great representative of tens of thousands of light aircraft.

## Appendix A – Piston Engines in NMUSAF Aircraft

List of piston engines in NMUSAF aircraft currently on display as of January 2023 (page 1 of 3):

GALLERY	VEHICLE	PISTON ENGINE(S)
PRES	Aero Commander U-4B	LYCOMING GSO 480
WW2	Aeronca L-3B "Grasshopper"	CONTINENTAL O-170
EY	Avro 504K	Le RHONE J
WW2	Beech AT-10 Wichita	LYCOMING R-680
WW2	Beech AT-11 Kansan	P&W R-985
SEA	Beech QU-22B	CONTINENTAL GTSIO-520
CWG	Beech T-34A Mentor	CONTINENTAL O-470
WW2	Beech UC-43 Traveler	P&W R-985
R&D	Bell Helicopter Textron XV-3	P&W R-985
WW2	Bell P-39Q Airacobra	ALLISON V-1710
PRES	Bell UH-13J Sioux	LYCOMING O-435
R&D	Bensen X-25A Gyrocopter	McCULLOUGH 418G
EY	Bleriot Monoplane	ANZANI 3-CYL FAN TYPE
WW2	Boeing B-17F Flying Fortress (Memphis Belle)	WRIGHT R-1820
WW2	Boeing B-29 Superfortress (Bockscar)	WRIGHT R-3350
CWG	Boeing KC-97L Stratofreighter	P&W R-4360
EY	Boeing P-12E	P&W R-1340
EY	Boeing P-26A	P&W R-1340
CWG	Boeing WB-50D Superfortress	P&W R-4360
CWG	Boeing YCGM-121B Seek Spinner	SNOWMOBILE ENGINE 20
WW2	Bristol Beaufighter	BRISTOL HERCULES
EY	Caproni Ca. 36	ISOTTA-FRASCHINI V.4B
CWG	Cessna LC-126	JACOBS R-755
SEA	Cessna O-1G Bird Dog	CONTINENTAL O-470
SEA	Cessna O-2A Skymaster	CONTINENTAL IO-360
CWG	Cessna T-41A Mescalero	CONTINENTAL O-300
CWG	Cessna U-3A	CONTINENTAL O-470
WW2	Cessna UC-78B Bobcat	JACOBS R-755
WW2	Consolidated B-24D Liberator	P&W R-1830
WW2	Consolidated OA-10 Catalina	P&W R-1830
EY	Consolidated PT-1 Trusty	WRIGHT "E" OF HISPANO-SUIZA DESIGN
CWG	Convair B-36J Peacemaker	P&W R-4360
WW2	Culver PQ-14B	FRANKLIN O-300
EY	Curtiss 1911 Model D	CURTISS 4-CYL INLINE
WW2	Curtiss AT-9 Jeep/Fledgling	LYCOMING R-680
WW2	Curtiss C-46D Commando	P&W R-2800
EY	Curtiss JN-4D Jenny	CURTISS OX-5
EY	Curtiss O-52 Owl	P&W R-1340
WW2	Curtiss P-36A Hawk	P&W R-1830
WW2	Curtiss P-40E Warhawk	ALLISON V-1710
EY	Curtiss P-6E Hawk	CURTISS V-1570
SEA	De Havilland C-7A Caribou	P&W R-2000
EY	De Havilland DH 82A Tiger Moth	de HAVILLAND GIPSY MAJOR 1
WW2	De Havilland DH 98 Mosquito	ROLLS-ROYCE MERLIN

List of piston engines in NMUSAF aircraft as of January 2023 (page 2 of 3):

GALLERY	VEHICLE	PISTON ENGINE(S)
EY	De Havilland DH-4	LIBERTY L-12
CWG	De Havilland U-6A Beaver	P&W R-985
SEA	Douglas A-1E Skyraider	WRIGHT R-3350
SEA	Douglas A-1H Skyraider	WRIGHT R-3350
WW2	Douglas A-20G Havoc	WRIGHT R-2600
WW2	Douglas A-24	WRIGHT R-1820
WW2	Douglas B-18 Bolo	WRIGHT R-1820
KOR	Douglas B-26C (A-26C) Invader	P&W R-2800
SEA	Douglas B-26K (A-26) Counter Invader	P&W R-2800
KOR	Douglas C-124 Globemaster II	P&W R-4360
WW2	Douglas C-47D Skytrain	P&W R-1830
EY	Douglas O-38F	P&W R-1690
PRES	Douglas VC-118 The Independence	P&W R-2800
PRES	Douglas VC-54C Sacred Cow	P&W R-2000
EY	Eberhart SE-5E	WRIGHT "E"
SPACE	Fairchild C-119J Flying Boxcar	WRIGHT R-3350
SEA	Fairchild C-123K Provider	P&W R-2800
GR	Fairchild C-82 Packet	P&W R-2800
WW2	Fairchild Model 24-C8F (UC-61J)	RANGER 6-390
EY	Fairchild PT-19A Cornell	RANGER L-440
R&D	Fisher P-75A Eagle	ALLISON V-3420
WW2	Focke-Wulf Fw 190D-9	JUNKERS JUMO 213
EY	Fokker D. VII	NMUSAF NOTES GIVE DIFFERENT OPTIONS
EY	Fokker Dr. I	OBERURSEL UR II
CWG	General Atomics Aeronautical Systems RQ-1 Predator	ROTAX 912
CWG	Grumman HU-16B Albatross	WRIGHT R-1820
CWG	Grumman OA-12 Duck	WRIGHT R-1820
EY	Halberstadt CL IV	MERCEDES D III
EY	Hawker Hurricane Mk.IIa	ROLLS-ROYCE MERLIN
SEA	Helio U-10D Super Courier	LYCOMING GO-480
WW2	Interstate L-6 "Grasshopper"	FRANKLIN XO-200
WW2	Junkers Ju 88D	JUNKERS JUMO 211
WW2	Kawanishi N1K2-Ja Shiden Kai (George)	NAKAJIMA NK9H HOMARE
EY	Kellett K-2/K-3 Autogiro	NMUSAF NOTES GIVE DIFFERENT OPTIONS
EY	Kettering Aerial Torpedo "Bug"	DE PALMA (UNK)
SEA	Lockheed EC-121D Constellation	WRIGHT R-3350
WW2	Lockheed P-38L Lightning	ALLISON V-1710
PRES	Lockheed VC-121E Columbine III	WRIGHT R-3350
WW2	Macchi MC.200 Saetta	FIAT A.74 R.C.38
EY	Martin B-10	WRIGHT R-1820
WW2	Martin B-26G Marauder	P&W R-2800
EY	Martin MB-2	LIBERTY 12-A
WW2	Messerschmitt Bf 109G-10	DAIMLER-BENZ DB 605D
WW2	Mitsubishi A6M2 Zero	NAKAJIMA SAKAE-12

List of piston engines in NMUSAF aircraft as of January 2023 (page 3 of 3):

GALLERY	VEHICLE	PISTON ENGINE(S)
EY	Nieuport 28	GNOME N-9
WW2	Noorduyn UC-64A Norseman	P&W R-1340
WW2	North American A-36A Mustang	ALLISON V-1710
WW2	North American B-25B Mitchell	WRIGHT R-2600
EY	North American BT-14	WRIGHT R-985
CWG	North American F-82B Twin Mustang	PACKARD V-1650
KOR	North American F-82G Twin Mustang	ALLISON V-1710
KOR	North American L-17A Navion	CONTINENTAL O-470
EY	North American O-47B	WRIGHT R-1820
WW2	North American P-51D Mustang	PACKARD V-1650
CWG	North American T-28A Trojan	WRIGHT R-1300
SEA	North American T-28B Trojan	WRIGHT R-1820
KOR	North American T-6D Mosquito	P&W R-1340
EY	Northrop A-17A	P&W R-1535
WW2	Northrop P-61C Black Widow	P&W R-2800
EY	Packard LePere LUSAC 11	LIBERTY 12
CWG	Piper J-3C-65-8	CONTINENTAL A-65-8
WW2	Piper L-4A "Grasshopper"	CONTINENTAL O-170
KOR	Radioplane OQ-14	RIGHTER (UNK)
CWG	Radioplane OQ-19D	McCULLOCH O-100
WW2	Radioplane OQ-2A	RIGHTER O-15
WW2	Republic P-47D (Bubble Canopy Version)	P&W R-2800
WW2	Republic P-47D (Razorback Version)	P&W R-2800
WW2	Ryan PT-22 Recruit	KINNER R-540
EY	Ryan YPT-16	MENASCO L-365
R&D	Scaled Composites Long-EZ "Borealis"	LYCOMING O-235
WW2	Seversky P-35	P&W R-1830
WW2	Sikorsky R-4B Hoverfly	WARNER R-550
WW2	Sikorsky R-6A Hoverfly II	FRANKLIN O-405
KOR	Sikorsky UH-19B Chickasaw	WRIGHT R-1300
KOR	Sikorsky YH-5A Dragonfly	P&W R-985
EY	Sopwith Camel F.1	CLERGET (UNK)
EY	SPAD VII	HISPANO-SUIZA V-8
EY	SPAD XIII C.1	HISPANO-SUIZA V-8
EY	Standard J-1	CURTISS OXX-6
EY	Standard J-1 (fabric removed)	HALL-SCOTT A-7 or A-7a
WW2	Stearman PT-13D Kaydet	LYCOMING R-680
WW2	Stinson L-5 Sentinel	LYCOMING O-435
WW2	Supermarine Spitfire Mk. Vc	ROLLS-ROYCE MERLIN
WW2	Supermarine Spitfire PR.XI	ROLLS-ROYCE MERLIN
WW2	Taylorcraft L-2M "Grasshopper"	CONTINENTAL O-170
EY	Thomas-Morse S4C Scout	Le RHONE C-9
WW2	Vultee BT-13B Valiant	P&W R-985
EY	Wright 1909 Military Flyer	WRIGHT 4-CYL INLINE
COT	Wright Modified B Flyer	RAUSENBERGER (UNK)
		GREEN INDICATES PRIMARY ENGINES ON TOUR
		YELLOW INDICATES OTHER ENGINES THAT MAY BE SEEN UNINSTALLED IN MUSEUM