Wright R-3350 “Cyclone 18”

By Kimble D. McCutcheon

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. It is hard to believe that a record-setting engine such as this had one of the most difficult developments of any aircraft engine ever to see production. This was largely due to an extremely compressed schedule that tried to do in two years what ordinarily took five. The development also took place in public whereas normally the growing pains of a new engine happen behind the closed doors of test cells, engine development labs, and in private flight tests.

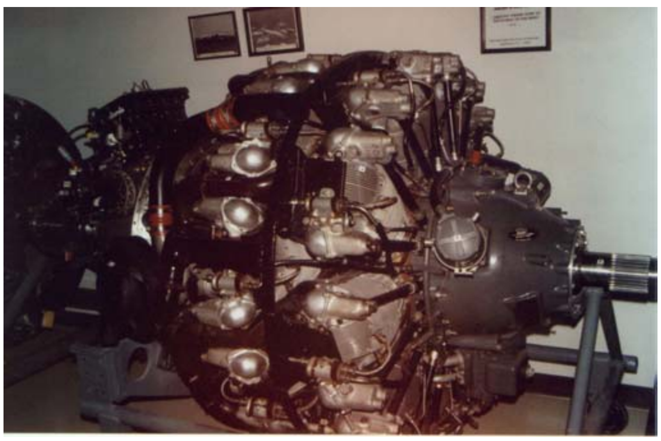

Figure 1. Wright R-3350 "Cyclone 18"

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 in³ and that cylinders of more than 207 in³ were impractical. The key to larger air-cooled engines was to stack rows of cylinders. Both Pratt & Whitney and Wright had experimented with multi-row engines during the 1930s, and had gradually solved the numerous problems of crankshaft construction, cooling, and vibration (or so they thought).

By November of 1935 Wright was ready to tackle development of the R-2600, its 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. Since Wright had the R-1820 cylinder and a few multi-row near-misses and failures to its credit, development of the R-2600 went smoothly. 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 and 42" of manifold pressure. 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. Production of the R-2600 stopped at the end of WWII.

The Wright Company in the late 1930s was in no way prepared for what was to come with the hostilities of WWII and particularly with the development of the R-3350 on a short fuse. Although they had ceased production of liquid-cooled engines in 1936, by 1939 they were at it again with the development of the liquid-cooled R-2160 Tornado, one of the most complex aircraft engines ever conceived. This 42-cylinder engine pushed the state of the art, robbed engineering talent from the R-3350, and was eventually abandoned when the R-3350 project got into real trouble in 1943. Wright had also vigorously pursued the production and sale of R-1820s into the domestic DC-2 and DC-3 transport market. They 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. They had licensed a number of other companies to build Whirlwinds and single-row Cyclones.

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. Wright suddenly found itself with the largest and most important engine program of the War. More than 30,000 engines would be required for the B-29 program, plus others for the B-32 and Navy. To further complicate issues, many strategic materials such as mica[1] and core sand[2] were in short supply due to hostilities in India and Madagascar. Although substitute materials were found, many hours of engineering time were required to prove the substitutes. The R-3350 had been running at Wright since 1936 and some had been flown in Naval and industrial experimental test programs, but 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

[1] Mica was used for spark plug insulators.

[2] Core sand is the material used to make molds for complex metal castings.

bomber programs, quite a different picture would emerge.

With the raid on Pearl Harbor on Dec. 7, 1941 and assault on the Philippines in January of 1942, Japan achieved control of all the islands near her homeland. It became clear that war on Japan would have to be waged from China, and that priority of the B-29 program must be the highest possible. The U.S. enlisted China to build a base to support B-29 raids on the Japanese home islands and depended on Naval and Marine forces to hold the Pacific in the meantime. March of 1944 was set as the target date for B-29s to be operational in China. Fifty thousand Chinese coolies began base construction while aircraft, engines, training, and logistical support for the 175 aircraft in the initial unit began their slow progress in the U.S. General Hap Arnold personally saw that nothing got in the way of this goal. Production machinery, tooling, and subcontractors were put in place before either the XB-29 or XB-32 flew.

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. All this production capacity at Boeing, Wright, and Chrysler was being put in place before the design of the "combat rated" engine was finalized. Numerous changes would be made to the engine design before production engines were shipped. 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 by a group of heroic B-29 production personnel bent on timely bombing of Japan.

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. Exhaust ports on the front cylinders faced forward, and ports on the rear row faced backwards. 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 in² per cylinder) and the ability to repair battle damage via fin replacement.

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.

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. The initial secondary balancers were hastily contrived and required few changes to existing engine parts. Later designs were considerably simplified. See Figures 3 and 4.

Wright used a supercharger developed in-house for the R-3350, considerably improving on the ones previously designed by General Electric. A top-mounted Chandler-Evans carburetor fed the supercharger. Early R-3350s had very sharp supercharger inlet elbows, which hurt supercharger efficiency. The elbow was redesigned in later engines. This, along with other systematic improvements resulting from extensive experimentation, produced superchargers by the end of the war with efficiencies as good as any in the world.

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. Few of these engines were alike, due to the dynamic nature of the development program at Wright, and different requirements for the end users. All three aircraft flew for the first time in September. Problems were immediate and widespread. The XB-32 engines had very high oil consumption, and a team of Wright technicians had to repair all engines shipped prior to October 1, 1942. Runaway propellers were traced to small oil passages in the nose case and a work-around had to be devised. Carburetion and ignition were unsatisfactory, and vendors were changed. There were exhaust fires, fires after shutdown from excess fuel, hard starting due to hydraulic locks. Reduction gear failures started to occur during extended climbs, forcing the addition of external oil lines from the accessory case to the nose case to shore up low nose case oil pressure. Cylinder cooling was a problem.

Four months of flight testing passed with only 365 engine hours being accumulated on four different aircraft and 26 engines. One aircraft, XB-29 No. 1, required 17 engines just to log 99 1/2 hours!

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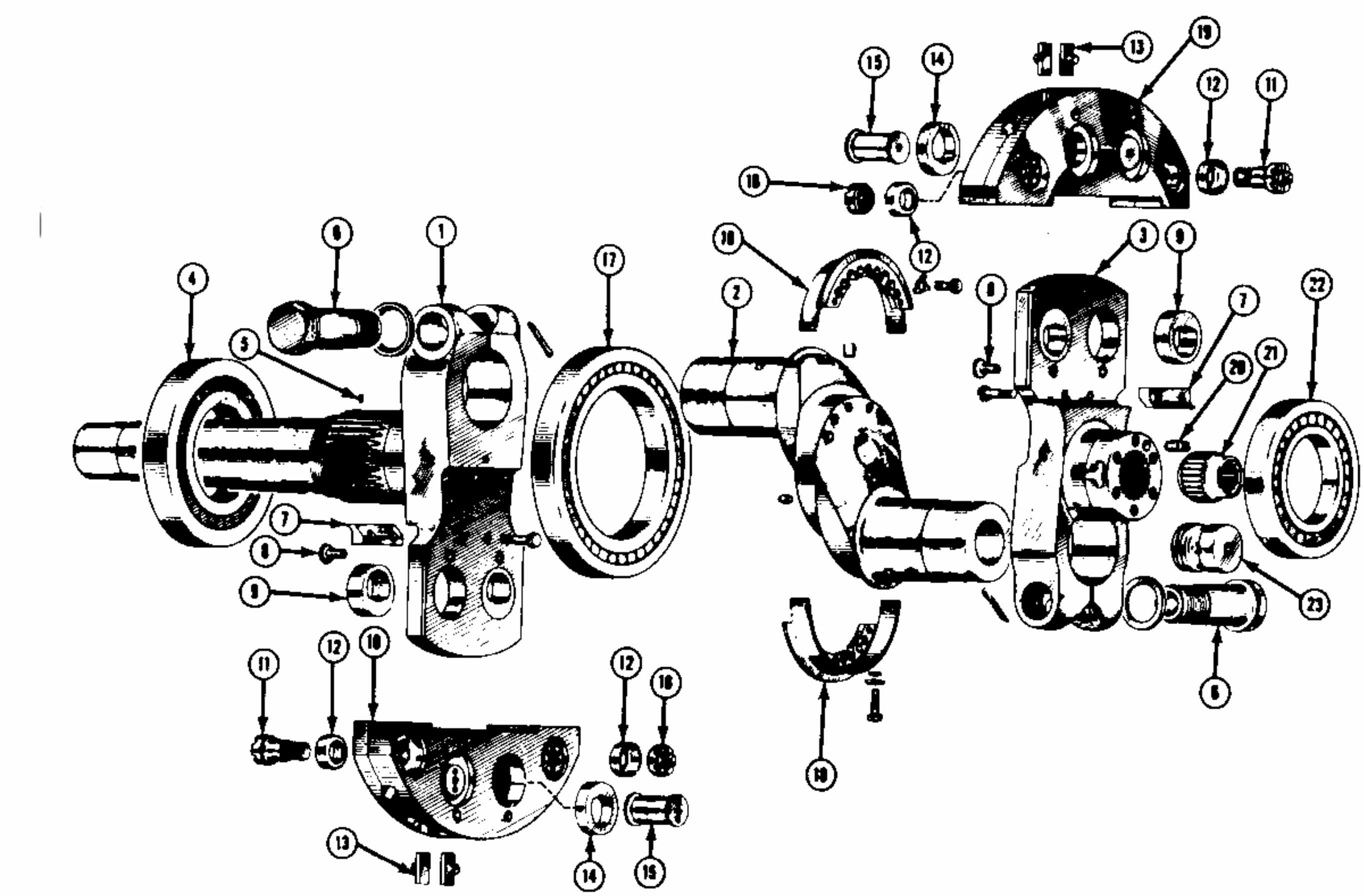

1. Crankshaft front section
2. Crankshaft center section
3. Crankshaft rear section
4. Crankshaft front main bearing
5. Crankshaft reduction gear aligning pin
6. Front and rear crank cheek cap screw
7. Front and rear counterweight stop
8. Front and rear counterweight crank cheek bushing retaining pin
9. Front and rear counterweight crank cheek bushing
10. Front counterweight
11. Front and rear counterweight bolt
12. Front and rear counterweight bolt locking cup
13. Front and rear counterweight bushing lock pin
14. Front and rear counterweight bushing
15. Front and rear counterweight pin
16. Front and rear counterweight bolt nut
17. Crankshaft center main bearing
18. Crankshaft center main bearing support (both halves)
19. Rear counterweight
20. Crankshaft rear cam drive gear locating pin
21. Accessory drive and starter shaft to crankshaft coupling
22. Crankshaft rear main bearing
23. Crankshaft crankpin plug

Figure 2. "Cyclone 18" crankshaft construction showing dynamic counterweights

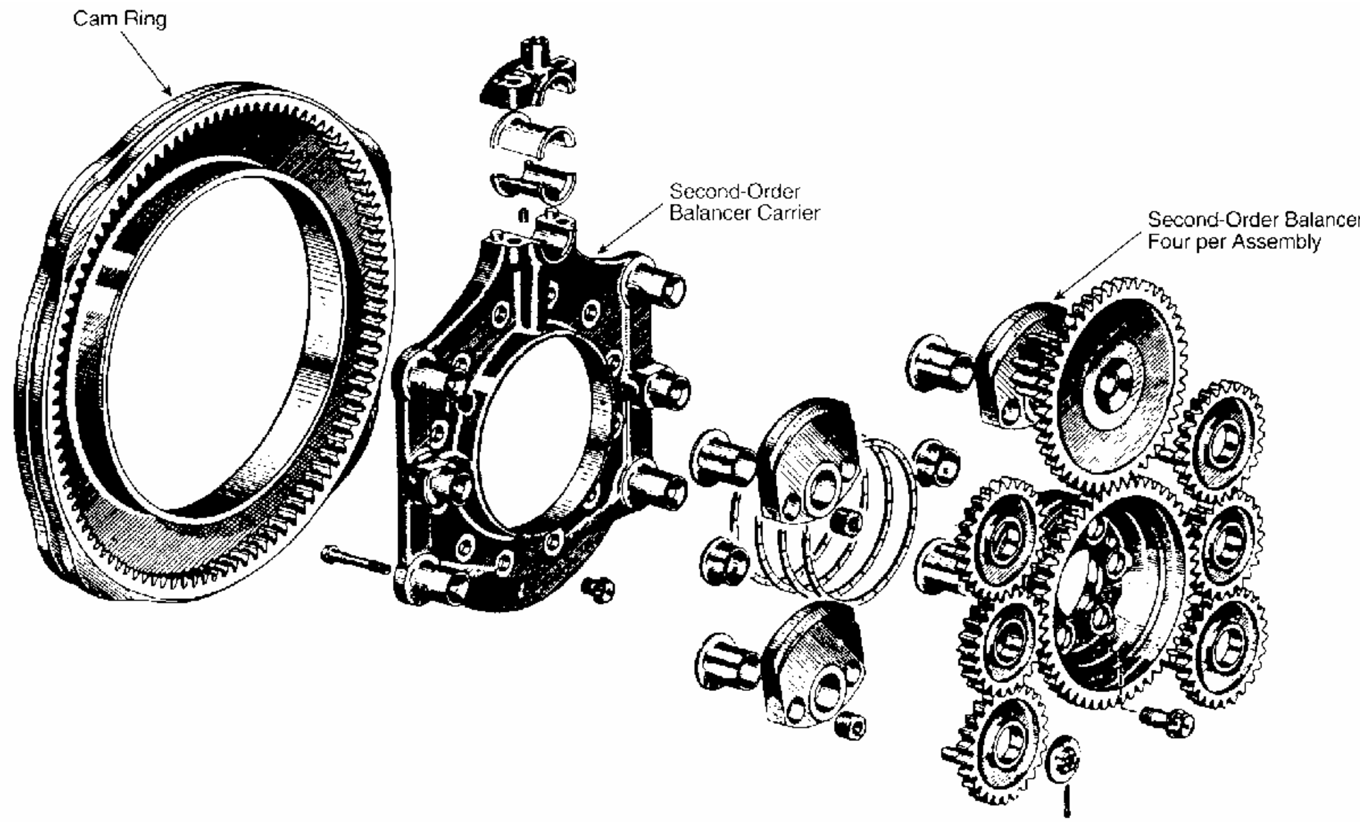

Figure 3. Early secondary balancers minimized changes to existing engine parts

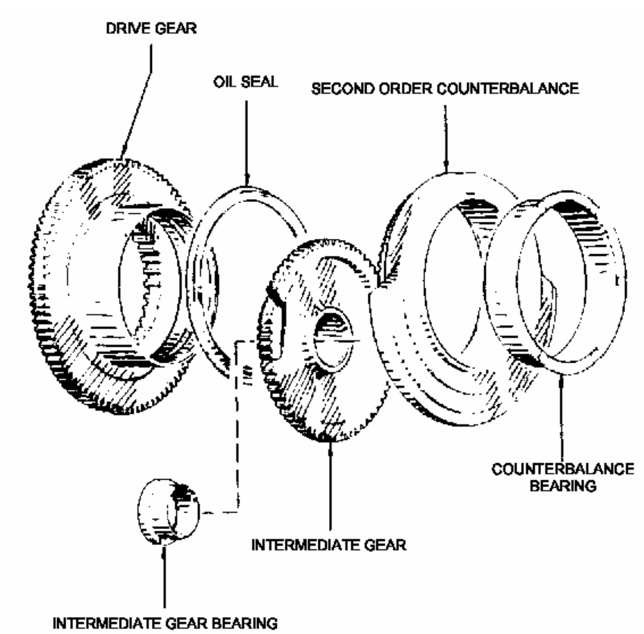

Figure 4. Later secondary balancers

On February 18, 1943 the second XB-29 prototype caught fire and crashed. All aircraft with the R-3350 were grounded while an investigation took place. A senate investigating committee chaired by Sen. Harry S. Truman blamed problems with the XB-29 program on the R-3350, and leveled charges of poor workmanship and inspection. Ultimately, the crash was blamed on the Boeing fuel tank filler design, not the R-3350.

Because of the investigation surrounding the XB-29 No. 2 crash, all engine failures were analyzed and numerous changes were proposed for the R-3350. Only the most critical were adopted. Other changes which affected the critical 1944 deployment schedule were delayed. One of the accepted change proposals sought to solve the reduction gearing and nose case problems through a redesigned nose case with thicker walls, larger oil passages, and modifications to the reduction gearing to tighten the manufacturing tolerances. 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.

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.

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. The logistical nightmare of just managing this level of change is daunting. But these very necessary changes were finally incorporated, though they did result in delays to the program.

RENEWED FLIGHT TEST PROGRAM AND TRAINING

The crash and its subsequent investigation along with fixes to the airframe and engine provided substantial delay to the program, but 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.

Airplanes and engines for training of pilots, crews, mechanics, and ground personnel were behind schedule. Only 21 B-29s had been delivered to operational units by October 1, 1943, and the average flight time for these aircraft was only about 70 hours. Bear in mind, these guys were supposed to be dropping bombs on Japan in six months! In spite of all the accelerated training programs could muster, crews were young and extremely inexperienced.

Service

By cutting all possible corners in training and logistical support, accepting far less than perfect engines, and putting up with horrible weather and facilities, the first two B-29s, each with a spare R-3350 slung in its bomb bay, landed in China on April 24, 1944. Hot weather and poor runways forced use of extremely high power settings for take-off and climb. This coupled with the need to close cowl flaps (and overheat the engines) in order to fly high-altitude formations 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. Persistent 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.

By October of 1944, a B-29 base was established at Saipan in the Marianas. This allowed the long-awaited raids on Tokyo. These began as high altitude raids with heavy losses due to mechanical problems. Eventually the strategy was changed to low-altitude fire bombing, with a marked improvement in success.

The B-29 and R-3350 contributed immeasurably to the Pacific War, eventually dropping the two atomic bombs that ended the conflict. After the War, the R-3350 remained in production and was refined into perhaps the pinnacle of piston engines. 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. Pilots who flew the R-3350 in Douglas Skyraiders as well as those who operated them in airline service, reported occasional reduction gear problems. Douglas, when they introduced the DC-7, switched from the R-2800s of the DC-6 to R-3350s. In order to get the performance of the Lockheed Super Constellations (also R-3350 powered), Douglas used very high power settings. 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”!

Specifics (981TC18EA Turbo Cyclone)

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 in³
Bore x Stroke:	6.125” x 6.312”
Compression Ratio:	6.7:1
Brake Mean Effective Pressure:	301.6 psi
Specific Weight:	0.99 lb/hp
Specific Output:	1.10 hp/in³
Cruise Fuel Consumption:	175.8 gal/hr @ 75% power
Cruise Specific Fuel Consumption:	0.38 lb/hp/hr @ 75% power
Cruise Oil Consumption:	5.6 gal/hr @ 75% power
Cruise Specific Oil Consumption:	0.015 lb/hp/hr @ 75% power
6 hr mission specific weight:	0.62 lb/hp/hr (engine + fuel + oil @ 75% power)
Fuel Required:	115/145 grade gasoline
Reduction Gear Ratio:	16:7
Supercharger Gear Ratio (low):	6.46:1
Supercharger Gear Ratio (high):	8.67:1

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