The Ramp Head Merlin

Torque Meter

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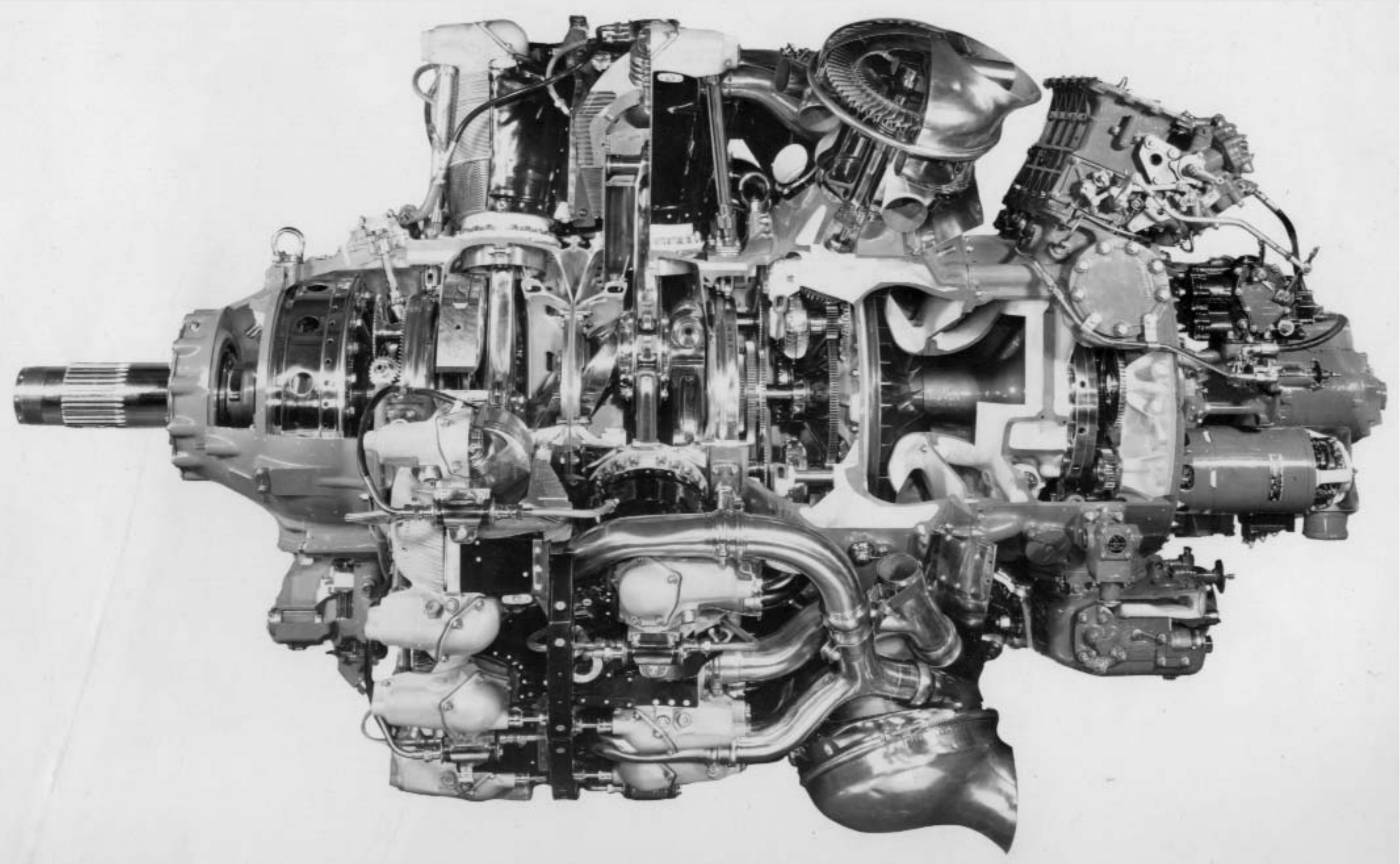

Curtiss-Wright Power Recovery Turbines

The Impact of the Engine on the Airframe

Turbocompounding the Wright Way

by Tom Fey

Engine designers have a long history of trying to extract as much power as possible from a given engine, and this is especially true of aircraft engines since there is a large penalty for carrying extra weight, be it fuel, engine, or airframe mass. There is significant energy in the engine exhaust stream, and it is an art form trying to put that energy to efficient use. Stanley Hooker reported that the jet efflux from a Rolls-Royce Merlin engine was worth up to 150 hp (10% of power output) at high power settings. While this is a valuable and relatively simple way to put exhaust energy to work, turbo-supercharging, which uses the pressure of the exhaust gas, and turbocompounding, which uses primarily the velocity of the gas stream, are other ways to boost efficiency.

As large-displacement piston engine technology peaked in the late 1940s and early 1950s, turbocompounding was studied by a number of manufacturers including Allison, Pratt & Whitney, and Napier, to increase horsepower, but even more importantly, specific fuel consumption (sfc) of their engines. More power on less fuel meant larger loads carried over longer distances for the same-size airplane, an efficiency mantra that drives design even today. Turbocompounding (TC) of the 18 cylinder Wright R-3350 improved sfc by 15-20%, which is a very significant figure that allowed non-stop intercontinental flight (Miami to Paris, Los Angeles to Stockholm, Tokyo to Seattle, New York to Rome) to become reality.

The Wright approach to turbocompounding the R-3350 TC18 utilized the velocity component of the exhaust stream, not expansion, to return horsepower directly back to the crankshaft. The exhaust pipes are of constant 2-inch diameter from exhaust port to nozzle box, so pressure is not raised by the geometry of the exhaust system. The Wright power recovery turbines (PRT) are called "blowdown" turbines, a relic from the

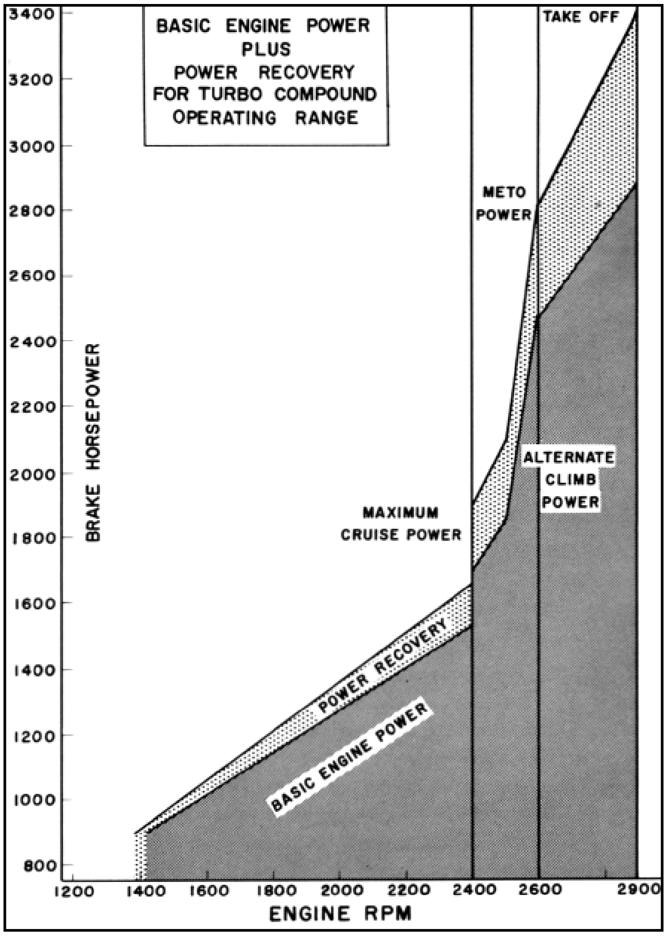

Fig. 1. Contribution of Power Recovery Turbines

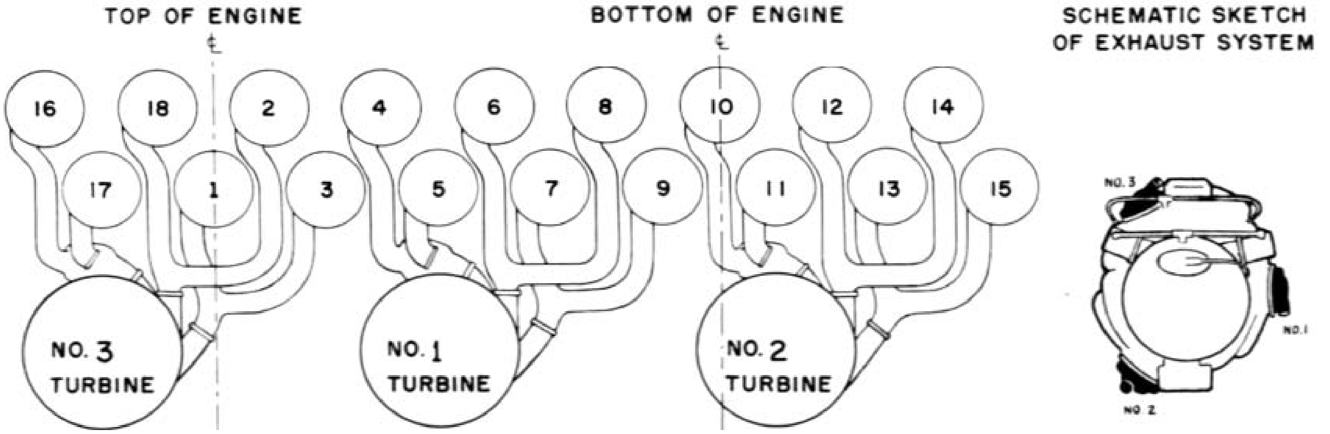

Fig. 2. PRT Schematic

steam age where steam was vented and allowed to "blow down" to atmospheric pressure without doing work. Using the blow down principle was advantageous because it generated essentially no backpressure to the engine, thus the power-generating section of the R-3350 was unaware that 500 additional horsepower at takeoff, or 200 hp at max cruise, was being transmitted to the propeller shaft (fig. 1). Another benefit of the Wright TC system is that the system is both independent and self-regulating, requiring no gauges, sensors, waste gates, linkages, or other controlling elements for operation.

Wright initiated work on turbocompounding in 1942 using a 9 cylinder Cyclone and a single turbine as a test bed. As they worked towards the R-3350, their first prototype used six turbines, each fed by three cylinders. Exhaust impinged the turbine from inlets spaced 120° apart. Individual pipes were deemed desirable because they eliminated the potential scavenging problems from siamesed cylinders and provided more cooling time between exhaust pulses for the turbine blades. Through experimentation and analysis, they soon discovered that siamesing exhaust from two cylinders, thus six cylinders feeding each of three turbines, could save 200 lbs and reduce ducting complexity, windage, and cooling air pumping losses. It also simplified manufacturing as exhaust piping for each turbine was identical.

It seems a relatively simple thing to take exhaust gas, blow it over a turbine wheel to drive a gear train to the crankshaft. But simple it is not.

Fig. 3. PRT Underside

As can be seen in the diagram (fig. 2), four of the six cylinders per turbine are siamesed similarly, namely adjacent cylinders from the same row connect together and feed a 120° arc of the PRT nozzle box. Since both exhaust valves are open simultaneously for only a very short time, scavenging is not a problem. However, the other two cylinders (i.e. 16 + 17 for turbine 3) are in different rows, causing both exhaust valves to be open for 95° of crank travel. This could cause exhaust from the just-opening rear cylinder to flow into the nearing-end-of-exhaust stroke front cylinder, creating havoc. This was remedied by adjusting the geometry and placement of the junction of these pipes closer to the nozzle box to eliminate backflow and actually improve scavenging. Exhaust pipes are made of N-155 alloy steel 0.062" wall thickness and are joined to the nozzle boxes (also made of N-155) with tight-fitting ball joints 2" in diameter (fig. 3).

The design of the turbine assembly is remarkably complex. Exhaust gas at 1500° F and flowing at 2,200 feet per second (Mach 2.0) enters a ramped nozzle box that incorporates curved, split guide vanes to direct the gas to the turbine blades (buckets) at a 15° angle for maximum recovery of energy. The gas impinges the hollow, undercambered turbine buckets, imparts its energy, loses velocity, flows upward into the open space in the large Inconel flight hood, and out the flight hood exhaust port which is 6" in diameter. The turbine spins at 19,000 rpm (rim speed 949 feet per second) at take-off and 16,000 rpm in cruise. However the PRT, like the engine itself, must manage the demons of heat rejection and vibration dampening lest they melt and harmonically fracture the machine.

The turbine shaft is one-piece, hollow, stainless steel unit externally splined at the top to accept the cooling impeller and turbine rotor, and internally splined at the bottom to mate with the coupling shaft (fig. 4). It runs in silver-backed, plain steel bearings lubricated by engine oil via annular ports sealed by o-rings in the base of the PRT output shaft. Because of the pulsating nature of the exhaust stream upon the turbine wheel, the turbine shaft it is susceptible to both torsional and whirling vibration. The torsional vibration is buffered by a fluid coupling described later. The whirl vibration (like wobbling your index finger in a circle) is managed by an internal dampener that allows a small amount of movement (up to

0.03″ off-axis) at the top of the shaft. The upper shaft bearing is held in a dampener consisting of four steel plates splined (#62) to the PRT body interdigitated with five bronze plates (#63) that are splined to the upper bearing mount, all squeezed together by eight coil springs (#57) as shown in the exploded diagram. The damper does not rotate. Like a multi-plate disc brake, the plates provide a large friction surface to absorb the off-axis, radial motion of the turbine wheel. The absence of such a damper would require much stiffer and heavier components to handle the stresses. A special graphite-type seal mounted in a pleated bellows (#69) accommodates the whirl mode of the turbine shaft while sealing the lubricating oil from the top end of the PRT.

The 11.45″ diameter turbine wheel itself is made of high temperature alloy steel and has 58 oval-shaped cooling holes approx. 0.5″ long and 0.125″ wide (fig. 5) that allow cooling air forced from an impeller below the wheel to flow vertically through the holes, into the cooling cap, out through the cooling cap exhaust and into the flight hood exhaust port . Cooling air is ducted from an inter-row cowling air trunk to a 2.8″ diameter inlet at the base of the PRT. The air flows up the open space between the stainless steel PRT outer housing and the internal body (shaft support), through ports in the internal housing near the top of the assembly, and into the center of the impeller (fig. 6). All this allows the turbine wheel to run at 600 to 700° F, hot enough to ignite paper, but 800° cooler than the exhaust stream.

In order to isolate the cooling air from the hot exhaust stream to maintain proper pressure differentials and flows, a double-walled, 12-lb cooling cap is employed to collect the air from the turbine cooling holes (fig. 7). The cooling air is then dumped into the engine exhaust stream via a double-walled, off-center, 1.85″ diameter port (fig. 8). The cooling cap is sealed by a stepped labyrinth seal. Hot exhaust pushing past the first cooling cap seal is siphoned off through the space between the inner and outer cooling cap bodies and vented from the concentric cooling cap exhaust port (fig. 9). Early designs used a cooling cap with a centrally-placed cooling cap exhaust port, but the concentric/tangential unit shown here flowed 100% better at altitude. Small details make a difference!

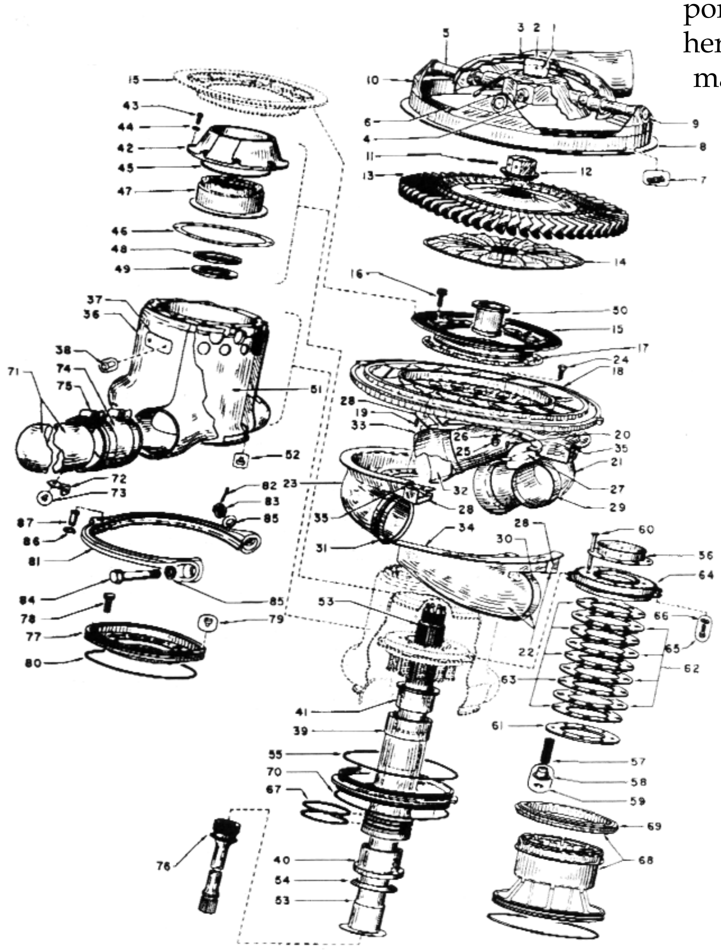

Fig. 4. PRT Exploded View

Fig. 5. Turbine. Arrow indicates bucket triggering hole.

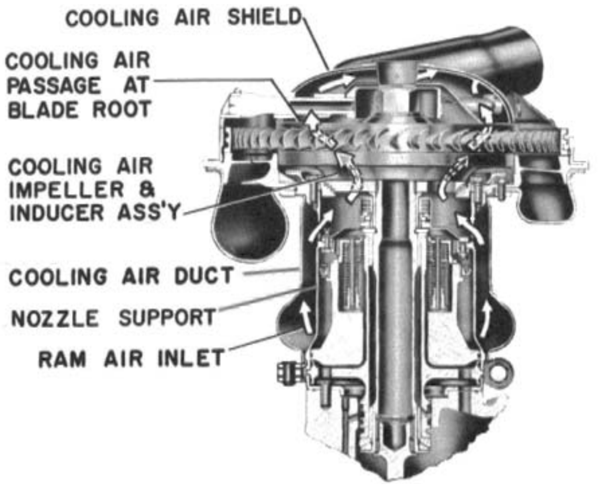

Fig. 6. Turbine Cooling System

The 58 hollow turbine buckets are roughly 1.375″ long, made of brittle but heat and corrosion resistant Haynes Stellite-31 alloy, and are welded individually to the periphery of the wheel (fig. 10). There are small knife cuts in the wheel separating each bucket from each other, presumably for thermal or vibratory isolation. Interestingly, there are four 0.125″ diameter holes in the turbine disc at 12, 3, 6, and 9 o'clock with oversized knife cuts bracketing three of the four holes. These are "bucket triggering holes", which means if the turbine ever exceeds 24,000 rpm, the buckets will be shed starting at these holes, preventing an even worse overspeed and the malevolent energy it would possess. In addition to the 0.3″ thickness of the cooling cap ring, the flight hood (weighs 16 lb, 0.4″ thick) has a guard ring that contains the shed buckets until they are spit out of the exhaust "with little energy" according to the manual.

The drive train from the PRT consists of a stub shaft that connects the PRT turbine shaft to a bevel gear inside the PRT section of the engine. The PRT section is an 11″ section located between the power and blower sections which contains the PRT reduction gearing and is unique to the turbo-compound engines. As shown in the diagram (fig. 11), the bevel gear mates with a spur gear. The spur gear shaft drives one half of a fluid

Fig. 7. PRT with Cooling Cap Installed

Fig. 8. Cooling Cap Air Outlet

Fig. 9. Underside of Cooling Cap

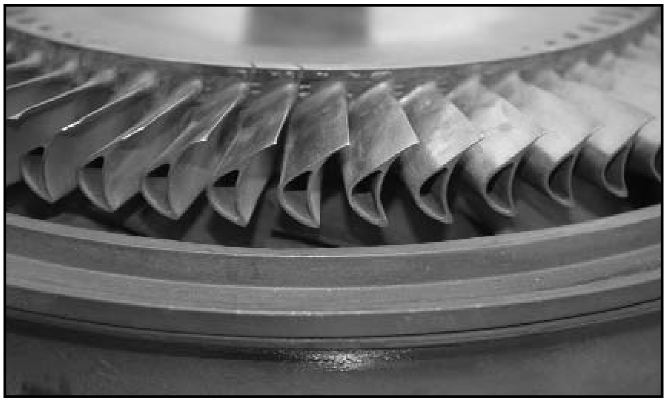

Fig. 10. PRT Turbine Bucket Detail

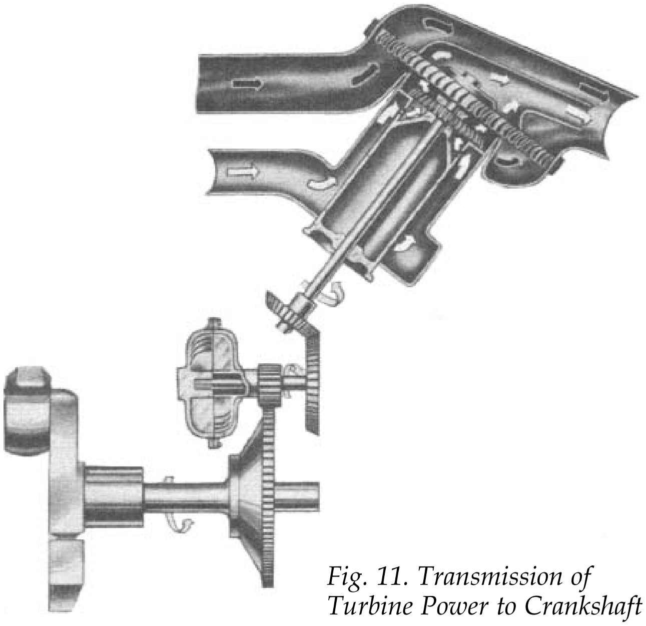

Fig. 11. Transmission of Turbine Power to Crankshaft

coupling, similar in design and function as the torque converter in an automatic transmission. The opposing half of the fluid coupling drives a spur gear concentric with the input shaft, and this spur gear meshes with a large spur gear on the crankshaft. The fluid coupling, supplied by engine oil at 50 psi, dampens torsional vibration and slips less than 2% at cruise. The coupling gradually drains at rest such that the PRT system is functionally disengaged at engine start-up, reducing loads on the starter motor. The mechanical reduction ratio is 6.52 to 1. Early versions of the fluid coupling, like propeller domes and hollow crankshafts, accumulated oil sludge from centrifugal forces, but this was remedied (or maybe just passed on down the line) by an improved flow pattern through the coupling.

The flight hood and cooling cap are indexed with tabs to maintain proper alignment, and are attached to the PRT body by a stout, two-piece clamp of U shaped cross section. Likewise, a single clamp of high nickel content secures the PRT to the crankcase.

There are a lot of unique things about the turbocompound Wrights. The TC18 first flew in the nose of a B-17 in 1949, went into production in May 1950, and by 1956 over 9,000 units had been produced, of which 80% were for military use. The TC18 was used most widely in Douglas DC-7s, Lockheed Constellations, and Lockheed P2V Neptunes. The Neptunes still fly today as fire bombers, and a few Constellations continue to fly the air show circuits in the USA, Australia, and Western Europe. Turbocompounded EC-121s flew extended missions off the coast of Vietnam providing radar coverage and direction to the war fought there.

Because the PRT dumps fresh air into an exhaust stream rich with unburned fuel at climb power (take-off power exhaust is still too rich to burn), flames often shoot from the flight hoods. During cruise, the flame size, color and position can be diagnostic for that engine. The flight hoods, which are considered an airframe part and are supplied by the airplane manufacturer, not Wright, have ceramic exterior coatings and glow orange-red during cruise.

The TC18 came in both carbureted and fuel injected versions, with and without water injection. Exhaust gas temperatures had to be carefully managed below 1,600° F to spare the turbines. Torquemeter readings were very important to power management because unlike other engines, power could not be accurately estimated by fuel flow, boost, and rpm because the PRTs add power to the crankshaft that is independent of the power generated by the power section. Like turbosuperchargers, PRTs generate increasing power with increasing altitude due to the greater pressure differential between exhaust and atmosphere. The complete PRT system weighs about 540 lb and is said to contribute 1 hp for every 0.9 lb of mass. According to Wright, a pressure turbine system would have required 1.3 lb of mass to generate 1 hp.

The PRTs are quite efficient, capturing 43% of the available exhaust energy and turning it into crankshaft horsepower while the reciprocating portion of the engine converts only 30% of the thermal energy into horsepower. At take-off power, the R-3350 TC18 at 3,250 hp is flowing 22,000 lb of air and 2,300 lb (383 gal) of fuel per hour. At 1,800 hp in cruise, it flows 13,000 lb of air and 700-800 lb (125 gal) of fuel per hour. All this is cooled predominantly by the 5,850 ft^2 of cylinder fin area with help from rich fuel mixtures during high power and the oil coolers. The TC18 engines, particularly the commercial engines called “DAs” were known as temperamental parts eaters, however one has to consider a 1945 B-29 engine with take-off power of 2,200 hp was now an engine producing up to 3,700 hp at take-off, and running 1,800+ hp in cruise for 12 to 15 hours at a stretch, which are truly remarkable power figures.

Turbocompounding lives on today in the Saab/Scania 6 cylinder diesel truck engine (www.scania.com) where exhaust gases drive both a turbosupercharger and the turbocompounding turbine in sequence, claiming an 8% improvement in sfc.

Me and My PRT

Lacking the resources and commitment to rebuild an aircraft engine to running or even static condition, my second choice was to try to obtain and research an esoteric piece of ancient technology: a Wright Power Recovery turbine (PRT). The Wright R-3350 TC 18 engines were used on the last great propliners of the 1950s, extracting horsepower from exhaust gases and delivering it to the crankshaft through the PRTs.

Fascinated by its theory, design, materials, and construction, I was able to obtain a tired, dirty, and incomplete PRT through the generous largess of Graham White who drove it up from Florida to the inaugural 2004 AEHS convention at Rantoul, Illinois. Dozens of hours cleaning and scraping and wire brushing gradually shaped the 62-pounds of choice metals into presentable form. An Internet search found a Wright service manual. Fate smiled and I got it half price due to an error on the newly revised website. It turns out the PRT has its own manual, but the R-3350 manual is a bible of mechanical complexity and a joy to have.

Lacking a flight hood, I queried fellow AEHS member and turbocompound engine owner Bob Havermann about parts. A couple weeks later a 20 lb box containing a flight hood and clamp arrived at my door from southern California, no charge (no kidding) from a friend of Bob's. I washed it down and sealed the inside with polyurethane to encrypt any lead deposits lurking there. I printed up a few engine/PRT diagrams, cut a hole in a bar stool to act as a pedestal, and brought the whole thing to the second AEHS convention in Kalamazoo, Michigan.

The missing *piece de resistance* was the cooling cap, a heavy, complex, inferno-resistant piece of welded beauty. Phone calls and emails to a California engine shop got an exploded PRT diagram, parts list, and a promising lead, but no artifact. But the diagram and phone call made it clear that special tools and skills would be required to completely disassemble the unit. So be it.

Luck intervened once again, for when I visited the Octave Chanute Aerospace Museum in Rantoul last Fall, what was sitting on the ramp but two Wright TC18 QECs cut from a P2V! They were to act as spares for the EC-121 in the museum collection, but unknown to me was their utility was is in question and welcome on the ramp overextended. A few emails, a donation, and some luck brought a cooling cap in perfect condition to my door!

The moral(s) of the story are don't be afraid to ask, don't ever forget to say or show thanks, share what you have as generosity begets generosity, and beauty is truly in the eye of the beholder. Because of the remarkable materials used to endure its native environment, short of a direct meteor impact, my PRT will survive time, temperature, and me without maintenance. Now for my next mechanical foray, where can I get me some propeller hubs to take apart…

I'd like to thank Kim McCutcheon for providing the fascinating resource material and Graham White for the starting the adventure.

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Fig. 12. Fully Assembled PRT

Fig. 13. Partially Assembled PRT