The Story of Those Pistons

Introduction

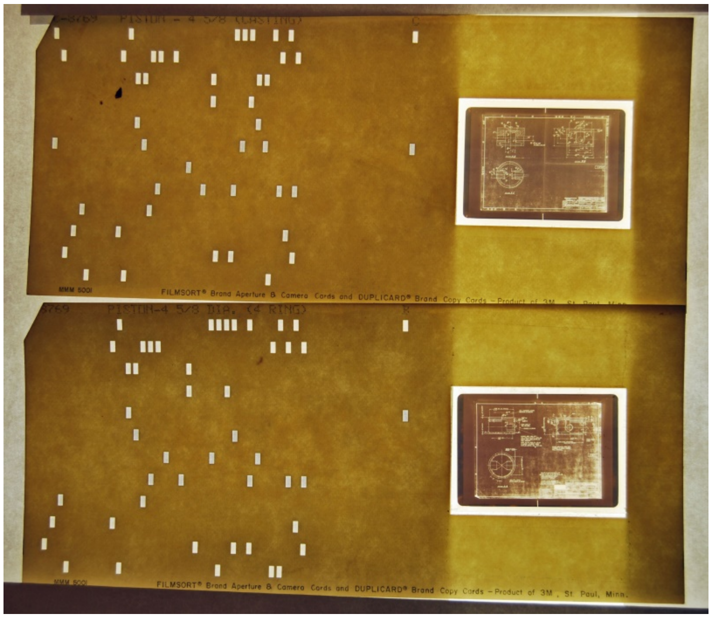
When Col Jack restored the Waco RNF he commissioned a repair shop at Gillespie Field, El Cajon, CA to overhaul the Warner engine. That proved to be a bad decision; the mechanic did not understand the engine and made mistakes made the engine initially unusable. I was totally ignorant of engines in general (never worked on them as a kid) and it took a while to understand how the radial should operate and find out how the one I inherited was wrong. I finally discovered Al Holloway who helped me in person and over the phone for years as I learned and corrected the problems. When I finally discovered the valves had been miss-timed, I took the engine to Al to have it fixed.

I got over ten hours of good operation on the engine after correcting the valve timing before shear pins in the accessory shaft let go. I dismounted the engine again and took it to Al, this time commissioning a new overhaul. Al corrected several things found after opening the engine, but the one thing he couldn't correct was the set of illegal pistons someone had installed in a previous overhaul. Neither Al nor I could find suitable replacement pistons so I started on a long journey to make replacements. (Remember that confession about being totally ignorant?)

Original Piston

The first break I got that made development of replacement pistons even possible came when Harmon Dickerson provided me copies of the engineering notes on the original design. Harmon also later provided me an original piston that had developed a crack. It was useful in analyzing the constituent alloy as required by the FAA to prove the pistons used the same alloy called out in the reference drawing.

The piston engineering drawings that Harmon provided were on "aperture cards" and the first effort converting those to a digital format where the photographed drawings could be cleaned up. (The photos on the aperture cards were copies of copies of copies and suffered from repeated smudging.)



The original Warner SS-50 piston is a four ring design that was cast from an alloy (SAE 39) that has been obsolete since the mid-1940s. There was no direct replacement alloy and that proved to be a crucial issue in producing replacement pistons.

Illegal Pistons

The pistons found in my engine were of a type Al Holloway had seen before. Out of 14 pistons in two sets, 13 pistons had cracks in under 200 hours of service. Looking at the pistons removed from the engine it was not difficult to tell why. The pistons were of an inferior casting process (actual alloy unknown) that led to a poor grain structure. As a result, some areas of the piston broke off without any apparent physical interference. (See flake off bottom of pin boss in photo below.)

In addition to the inferior molding, whoever prepared the pistons in my plane attempted to establish and equalize required weight by grinding out material inside some pistons with a hand-held die grinder and bounced it all over the insides of the pistons. The photo below is typical. No wonder cracks started with all those stress risers being pounded.

Replacement Options

Replacement options were the following.

Used Original Pistons

Good used original pistons would have been preferred because of compatibility and cost but none could be found. The difficulty in finding used original pistons might have been what led people to use the deficient counterfeit ones like in my engine. The following two pictures show what the original piston looked like inside and out.

New Design

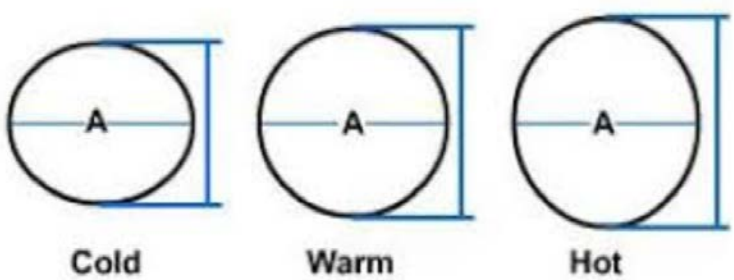
People have designed new pistons for production by forging for other engines. But a new design has to be qualified to FAA standards and that requires a great deal of expensive engineering analysis and test, not to mention time. I wanted a working engine so I could go flying. Also, while others have produced new pistons for old engines, those engines remain in operation in significant numbers allowing some hope of recovering development costs through additional piston sales. The low number of Warner SS-50 engines still in operation make that hope futile.

The advantage of starting and staying with the original piston design is that you "only" have to show that your replacement is at least as good as the original which is assumed to be totally adequate having been certified with the engine. (The Warner SS-50 engine is the second engine ever certified to government standards.)[1]

Mold New Pistons

Molding was certainly and option, especially since the original pistons were molded. Molds for the piston would be a significant initial expense but was conceivably doable. The real problem with molding (which is a similar problem for forging) is that modern molding alloys contain a significant amount of silicon which was not in the original alloy. The silicon provides better flow of the molten metal but results in a part with significantly higher coefficient of thermal expansion than the original allow. That greater expansion invalidates the original design.

When pistons heat in operation, they expand more in the direction where there is more metal mass. Along the axis of the piston pin is one place where this happens because of the mass of the pin bosses in the piston to contain the pin. Because of this, pistons are "cam ground"; they are not round but rather smaller diameter at the pin axis than orthogonal to it so that as the piston expands in use it becomes round.



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[1] At AirVenture several years ago I saw a Warner SS-50 with pistons forged by the Arias company out of Los Angeles. It was an original design, but that made the engine and the plane it was installed in Experimental Exhibition. I guess that's one way to go and the cost savings from not having to qualify the piston to FAA requirements offsets the limitations of operating in the Experimental Exhibition category.

The cam grind in the Warner SS-50 piston accommodated the expansion of the original allow but would provide overexpansion with a modern molding alloy and cause the piston to jam the cylinder wall in operation.

Forge New Pistons

I talked to a lot of forging companies. They were reluctant to forge a four-ring piston with a ring at the skirt bottom for reasons I never fully understood. They also would have trouble replicating the detailed interior shape of the original piston design. In addition, modern forging alloys also contain significant silicon and have a higher thermal coefficient of expansion than the original piston design can tolerate.

CNC

I finally chose to use extruded stock with an appropriate thermal coefficient of expansion and carve the pistons using Computer Numerically Controlled (CNC) milling. Using extruded stock provides for uniform grain structure much improved over even the legitimate cast original pistons.

I had the original engineering drawing turned into a three dimensional (3D) model using Computer Aided Design (CAD). The 3D CAD model also produced an engineering drawing similar to the original piston engineering drawing with dimensions and comments making it easy to compare the two and illustrating fidelity of the new design to the original. I shopped the internet until I found a company willing to CNC two sets of pistons from the CAD 3D model for a reasonable price.

Replacement Piston

However a replacement piston is made, it has to be qualified for use in the certified engine according to FAA rules. That includes paperwork and submission by a Designated Engineering Representative (DER). DERs are not all the same. Even those with engine experience have experience with different kinds of engines. I was lucky to finally find Joe Gast (now retired) who knew radial engines.

Joe allowed me to do the majority of the work researching, writing, and documenting all stages of the design, production, and test planning which kept costs in control for what was originally to be pistons just for my engine.

The trick to keeping this within scope is to follow the original design as closely as possible and explain how the very few deviations could have no effect on design and operational integrity. The biggest deviation was the alloy used. That proved to be no problem since the thermal coefficient of expansion was the same and all other strength parameters were better than the original. Still, there are a lot of design aspects that had to be explicitly addressed with reasonable arguments and evidence to back up the claims of “at least as good as” the original piston.

The following pictures are of a replacement piston.

 

Qualification and PMA

Qualification

In order to use the new pistons in my engine, they had to be "qualified" through test.

Testing consisted of 25 hours of running on a test stand at various RPMs. During the test each cylinder was instrumented for cylinder head temperature (CHT). (There's no manifold pressure considerations with the Warner engine.) In addition, the FAA wanted the piston tops "instrumented" for maximum temperature experience. This was done with a set of temperature sensitive paints that we examined with a borescope after several hours of running that included maximum RPM. All qualification testing was accomplished on the test stand at Holloway Engineering.

CHT (per cylinder), RPM, and time were digitally collected, reduced in Excel spreadsheets, and plotted to support the qualification report. It was a lot of work, but it all went very smoothly thanks to Al Holloways support and the guidance of Joe Gast.

The final report was only 30 pages after all data was reduced to graphs with a few pictures to document temperature sensitive paint and other factors.

As of this writing the pistons have been performing in the engine for 110 flight hours since July 2014. Borescope investigation at annuals has shown absolutely normal cylinder wear to date.

PMA

After the Warner was reinstalled in the Waco, I decided to get PMA for the pistons. I instrumented CHT for each cylinder head with a unit from AeroSpace Logic, but had to do a field change because the unit was not STC'd for a seven cylinder engine. (It was STC'd for 4, 6, 8, and 9 and it only took a data change in the program logic to make it work for a 7 cylinder, but it still took the field change.)

I collected RPM, CHT, time, altitude, oil pressure and temperature, and airspeed from panel instruments by using a GoPro camera on my chest set to snap a picture every 10 seconds. I proceeded to fly about 20 hours to collect 10 hours of good data. (I forgot to turn the camera on and had some technical difficulties at times.) The photographic data was reduced by hand to a spreadsheet and plotted for the final PMA application report. The piston qualification report served as a good basis, but it was the PMA report where most of the mechanical engineering arguments had to be made about the pistons being at least as good as the original with no detrimental characteristics. The report with all its appendices was a significant volume. The data reduction, presentation, and validation was a real effort, too.

Part of a PMA is an FAA approved quality assurance plan. That plan describes how each produced item will be measured and inspected to ensure conformity with the technical drawings, alloy specification, and 3D model as translated into CNC code. It requires that all measurement instruments be calibrated and current when each part is inspected and approved. Al Holloway had such a plan and, as a repair station, had to have the calibrated test instruments for other reasons. I put the PMA in the name of Holloway Engineering to avoid the on-going pain of quality assurance—and occasional FAA MIDO inspections. It was never an effort to recover costs with the low volume of Warner engines in operation, anyway.

None of this—my replacement pistons or the PMA—would have been possible without the help of Joe Gast, Al Holloway, and Harmon Dickerson.

The second set of pistons, marked and qualified under the PMA, was installed in another Warner and those pistons are in operation today. The cost estimates for fabrication of additional pistons through the CNC process have been so high, no other potential user has elected to have them made under the PMA (at least as of this writing.) I someone needs pistons contact Al Holloway, Holloway Engineering, Gansner Field, 262 Spanish Creek Road, Quincy, CA 95971, (530) 283-2500, radial@inreach.com. If anyone knows of a 5-axis CNC shop that might fabricate the pistons at a reasonable price, please contact me and I'll send them the engineering package for bid.