Bearhawk #164 “Three Sigma” Checkout Report

Date: 8 - 16 Mar 08

Objective: Verify available fuel flow exceeds the required fuel flow for all attainable flight attitudes.

Background:

14 CFR §23.955

(a) *General*. The ability of the fuel system to provide fuel at the rates specified in this section and at a pressure sufficient for proper engine operation **must be shown in the attitude that is most critical with respect to fuel feed and quantity of unusable fuel**. These conditions may be simulated in a suitable mockup. In addition—

(1) The quantity of fuel in the tank may not exceed the amount established as the unusable fuel supply for that tank under §23.959(a) plus that quantity necessary to show compliance with this section.

(b) ***Gravity systems***. The fuel flow rate for gravity systems (main and reserve supply) must be **150 percent** of the takeoff fuel consumption of the engine.

(c) ***Pump systems***. The fuel flow rate for each pump system (main and reserve supply) for each reciprocating engine must be **125 percent** of the fuel flow required by the engine at the maximum takeoff power approved under this part.

AC 90-89A *Amateur-Built Aircraft and Ultralight Flight Testing Handbook* Chapter 1 Section 11.1.e states that this should be done with “the aircraft’s nose at an angle 5 degrees above the highest anticipated climb angle.”

The point of this test was to make sure that sufficient fuel would flow to the engine at any angle occurring in flight. The worst case scenario for fuel flow is during a maximum power climb. The engine is demanding the highest fuel flow, while the vertical distance (pressure head) between the fuel tanks and the carburetor is at a minimum. Some portions of the fuel system are actually flowing uphill in that condition. Confirming that the fuel system will provide 150 percent of the required fuel flow gives an extra margin to ensure that the required fuel flow will be available.

The Lycoming Engine Operator’s Manual for the 260 HP Lycoming O-540 quotes a fuel flow rate at sea level and full throttle of 25.3 gallons per hour. AC 90-89A suggests that in the absence of actual data, the fuel flow can be estimated using a Brake Specific Fuel Consumption (BSFC) of 0.55 pounds per brake horsepower per hour. Therefore

$$260\text{ BHP} * 0.55\frac{\text{pounds}}{\text{hour BHP}} = 143\frac{\text{pounds}}{\text{hour}} * \frac{1\text{ gallon}}{6\text{ pounds}} = 23.8\frac{\text{gallons}}{\text{hour}}$$

This estimate is close enough to the book value to lend confidence in the book value.

The required fuel flow for a gravity system is then 1.5 * 25.3 gallons per hour = 37.95 gallons per hour. This is equal to 0.6325 gallons per minute, or 3.795 pounds per minute. With the fuel pump ON, the requirement is reduced to 1.25 * 25.3 gallons per hour = 31.625 gallons per hour. This is equal to 0.5271 gallons per minute, or 3.163 pounds per minute.

Based on a report from Pat Fagan of a climb rate of 1500 feet per minute at 60 KCAS, the climb angle was calculated at 13.4 degrees. Based on available aircraft data, the Fuselage Reference Line Angle of Attack was estimated at 5.2 degrees. This was consistent with the AC 90-89A recommendation to add 5 degrees to the maximum climb angle. Therefore, the desired pitch angle for the fuel flow test was 18.6 degrees. On #164 there was a -0.4 degree correction to the indicated pitch angle at the measuring point (front of the right door sill). Thus, the desired indicated pitch angle was 19.0 degrees.

Additional information on doing the fuel flow test can be found in Tony Bingelis' *Firewall Forward* on page 175.

Procedure:

1. Fuel airplane with 3 gallons per tank.
2. Reverse and chock tailwheel.
3. Place lifting cables around axles (2 per side)
4. Use cranes on each side to lift each wheel. Lift both sides evenly, keeping the wings level. The indicated pitch angle should be 19.0 degrees. The main gear tires should be about 22.6 inches above the floor.
5. Turn fuel selector to OFF.
6. Remove fuel line from carburetor. Connect 90 degree fitting to fuel line with open end pointing down. Tie up next to carburetor inlet.
7. Tie funnel and tube in place
8. Weigh empty gas container for tare weight.
9. Place funnel tube in gas container.
10. Open fuel selector to BOTH for 1 minute, then close to OFF.
11. Weigh gas container. Subtract tare weight to determine the amount of fuel drained in one minute.
12. Repeat steps 6-9 with fuel pump ON.
13. Repeat steps 6-9 with fuel pump OFF and fuel selector in LEFT.
14. Repeat steps 6-9 with fuel pump OFF and fuel selector in RIGHT.

Results:

The tail wheel was reversed, placed into the position it would caster to if the fuselage was being backed up. Because of the geometry of the tail wheel, it was most stable in this position. In the normal locked position it was possible that side loads would cause the tail wheel to unlock, causing the fuselage to move unexpectedly.

The tail wheel was chocked to prevent the fuselage from moving forward or aft.

Lifting cables formed from 1/8 inch control cable were placed around the axles as shown here.

As shown here, the cable was formed in a double loop. This reduced the load on each strand by half of what the load would be for a simple loop. The picture above shows on double loop cable. This was from a previous attempt. For the lift, two independent double loop cables were used on each side. If, for some unforeseen reason, one cable was cut or otherwise broke, the other cable would support the axle long enough to get the tires back down to the floor.

Two shop cranes were used to lift the nose of the airplane to the maximum climb attitude. Since the axles were hanging below the cranes, the system was stable. Any side loads on the airplane might cause it to swing back and forth, but it would not tip over.


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Notice the tail wheel was reversed and chocked.

Other suggestions for getting the required pitch angle:

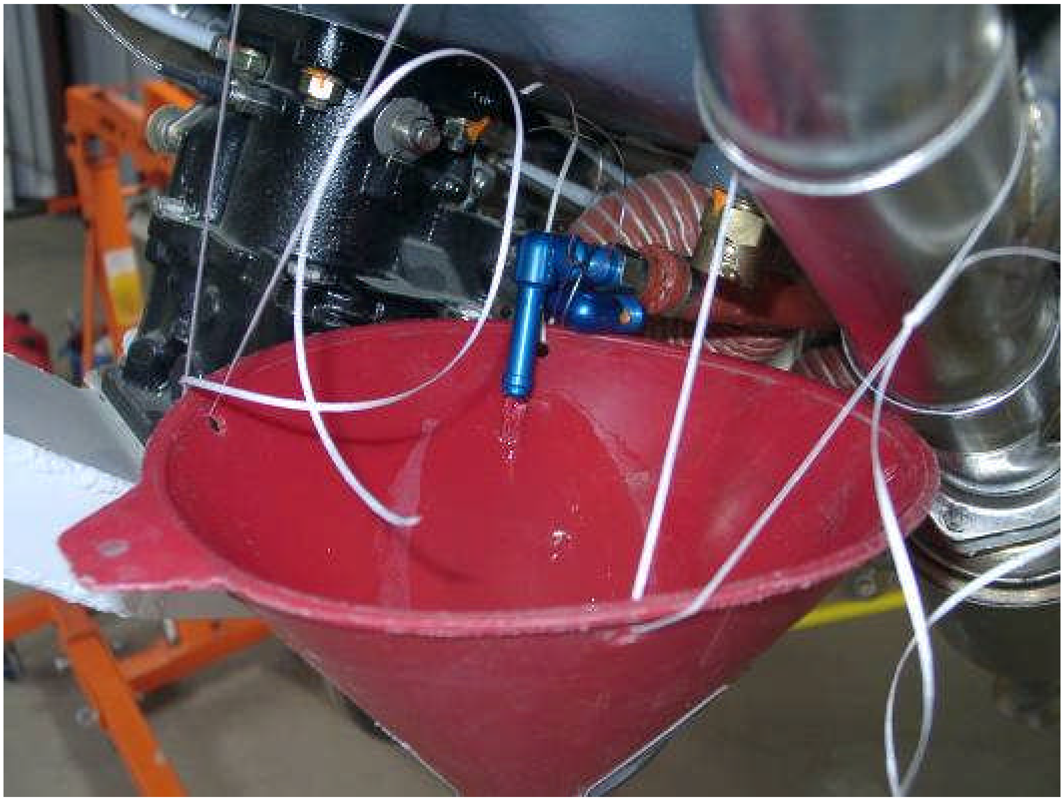
1. Dig a hole for the tail wheel instead of raising the nose. This is probably the best solution if you can get away with digging holes wherever your airplane is based.

2. Roll the main gear up onto a trailer of an appropriate height.

3. Build one or two boxes of the appropriate height for the main gear to rest on. Build ramps or use ramps such as Item Number 55424 from Harbor Freight to get the wheels up onto the boxes. Find a way to ensure the boxes won't fall over while pushing the airplane up the ramps. Secure the wheels on top of the boxes (chocks or otherwise) so that they won't move.

The fuselage was raised to an indicated pitch angle of 19.0 degrees, for an actual pitch angle of the fuselage reference line of 18.6 degrees.

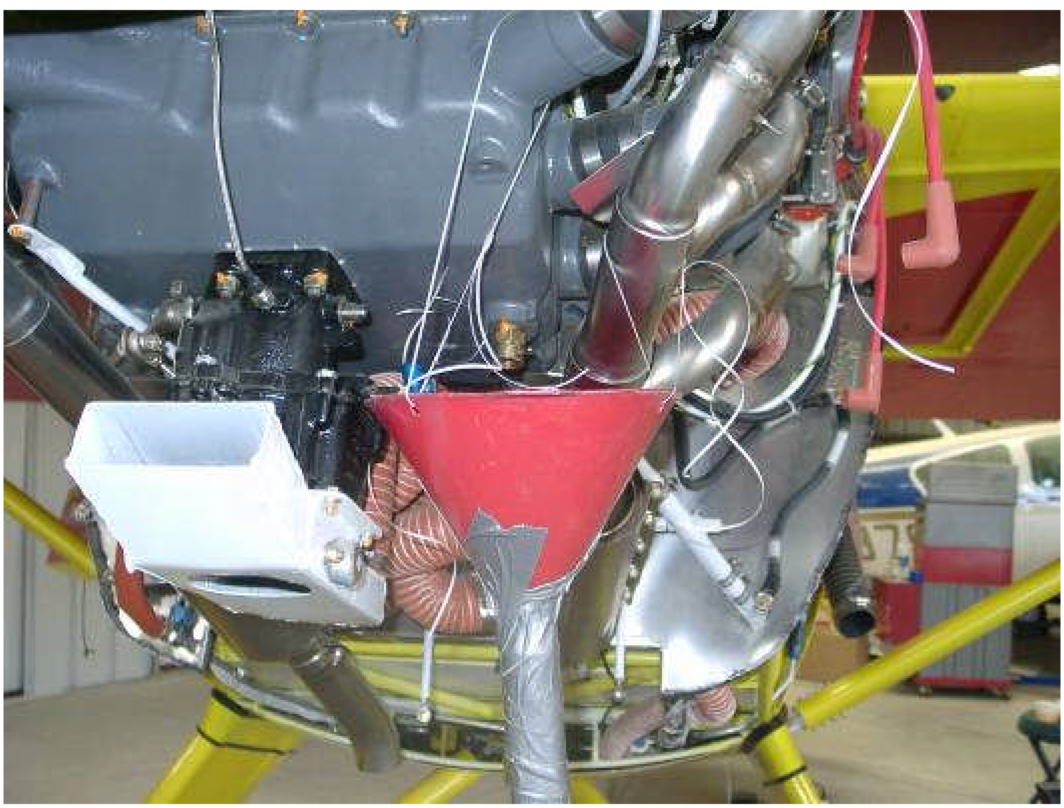
With the fuel selector in OFF, the fuel line was removed from the carburetor. A 90 degree fitting of the same size as the fuel lines (3/8 inch) was attached to the fuel line to turn the fuel flow in the desired direction. This fitting was tied to the carburetor so that the measured flow would at the proper height. As stated in *Firewall Forward*, "open end must be at the same level as carburetor inlet." If the tube is continued downhill, the siphoning effect will artificially increase the fuel flow, yielding an invalid test.



To catch the fuel and direct it to a suitable container, a funnel and hose were used, which my balmy helpers immediately labeled a “beer bong”. The outlet of the funnel was 1/2 inch in diameter, and the tube had an inside diameter of 1 inch (chosen because it fit on the funnel the best). The funnel was chosen to have an outlet larger than the fuel lines to ensure the fuel would not back up in the funnel and possibly overflow, not only making a hazardous mess, but also invalidating the experiment.

The tube was pushed onto the funnel and held in place with the homebuilder’s best friend, namely duct tape.

Holes were drilled near the top of the funnel to tie it up under the fuel line. I used avionics lacing cord because I had a lot of it left over. Any suitable string, cord, or wire could be used.



The tubing was almost too large to fit into the gas container, but it did fit. The stiffness and curvature of the tube would not let the gas container sit squarely on the floor, so a Gas Container Stabilizing System (GCSS) was rapidly conceived and assembled, as pointed out in the following photo.

After the test was completed, the pitch angle was checked again to determine if the cranes had leaked down significantly. Strangely enough, the pitch angle had increased (!) by 0.1 degree. This was suspected to be because of the reduced weight (unlikely) or experimental uncertainty (more likely).

The first funnel picture shows the fuel flowing during a test.

The calculations of fuel flow are summarized below:

Fuel Selector Position	Fuel Pump	Initial Fuel Quantity in Tank(s) (gallons)	Fuel Flow (pounds/min)	Fuel Flow (gallons/hour)	Requirement (gallons/hour)	Margin (gallons/hour)
BOTH	OFF	3/3	1.74	17.4	38.0 (150%)	-20.5
BOTH	ON	2.85/2.85	3.85	38.5	31.6 (125%)	6.9
LEFT	OFF	2.53	1.50	15.0	38.0 (150%)	-23.0
RIGHT	OFF	2.53	1.46	14.6	38.0 (150%)	-23.3

All gravity modes (fuel pump OFF) fell well short of the required fuel flow. This is assuming that no fuel pump is used at all, including an engine driven fuel pump.

With the electric fuel pump (Facet 40108) ON, the fuel flow requirement was less, but, as expected, the fuel flow was greater. In this case, the flow was 6.9 gallons per hour over the requirement.

The fuel flow with the fuel selector in LEFT or RIGHT was slightly less than in BOTH. Either tank individually supplied sufficient fuel flow for cruise flight.

Lowering the fuselage was done with great care, realizing that hydraulic jacks are difficult to lower in a controlled fashion and go from not moving to moving too fast with a very small rotation of the relief valve. The objective was to bring both cranes down simultaneously keeping the wings more or less level. The aircraft was successfully lowered to the ground with no damage.

Analysis:

The climb angle simulated in this test was rather extreme, simulating approximately best rate or angle of climb performance. This sort of climb would most likely be used for obstacle clearance on takeoff or for getting to pattern altitude rapidly. In both cases, this attitude would only be maintained for short durations. Due to the low airspeed (60 KCAS), it is very likely that engine cooling would be insufficient for the high power setting. Engine cooling requirements would drive a faster airspeed and thus lower pitch angle, resulting in higher fuel pressure and thus higher fuel flow.

The fuel in the carburetor bowl would keep the engine running for a little while, but at high fuel flow rates would empty rapidly. The issue at hand is not a fuel stoppage, but insufficient fuel flow. The fuel that was flowing would continue to enter the engine, but the insufficient flow rate would result in a leaning of the mixture. This leaning would become apparent to the pilot by a reduction in power or an increase in engine roughness. While not tested, it is suspected that this reduction in power would last long enough to get the pilot’s attention before the mixture might become too lean to run. The pilot’s first response to any loss of engine power should be to lower the nose and establish a glide. If the problem was caused by insufficient fuel flow, the additional pressure head (height of the fuel above the carburetor) resulting from pitching down would likely increase the fuel pressure and fuel flow, thus solving the problem. The climb could then be continued at a lower pitch angle.

The test condition was for the maximum fuel flow at sea level. As the altitude increases, the density of the air decreases, thus reducing the amount of air that can be pulled through the carburetor. The fuel flow is then reduced in the same proportion as the air flow to keep the mixture constant. However, the maximum fuel flow for a given pitch angle is independent of altitude, so the ability of the fuel system to provide the required fuel flow increases as the altitude increases.

Smaller engines, such as the O-360, will have correspondingly lower fuel flow requirements.

Based on the fuel flow results, the estimated fuel flow for other pitch attitudes was calculated for full and empty tanks. The estimates shown here are all for the fuel selector in BOTH and the fuel pump OFF.

Pitch Attitude	Pitch Angle (deg)	Fuel Quantity	Pressure Head (inches)	Fuel Flow (gallons/hour)
Climb	18.4	Empty	10.7	17.4
Climb	18.4	Full	23.5	25.7
Ground	12	Empty	19.6	23.5
Ground	12	Full	30.2	29.2
Level	0	Empty	34.9	31.4
Level	0	Full	41.4	34.2

As shown here, the available fuel flow increases rapidly as the pitch angle is reduced. The ground attitude shown above is more representative of a sustainable climb angle for sufficient engine cooling. The level (cruise) attitude shows an available fuel flow well in excess of even the full power requirements.

Good airmanship would make it unreasonable to intentionally takeoff with only three gallons in each tank, other than perhaps in an emergency. It is possible that a pilot would be called upon to go around after a failed approach with this low a fuel state. However, in this case there is most likely no reason to be climbing at extreme attitudes. Additionally, if a Bearhawk can fly with a 180 HP engine, then it is not necessarily required to climb out with full power from a 260 HP engine, again reducing the fuel flow requirements.

In any case, the tests demonstrated that sufficient fuel flow was available for full power operation of a 260 HP Lycoming O-540 at any achievable attitude with the fuel pump ON. Similar results would be expected using an engine-driven fuel pump. The fuel pump creates a lower pressure at its inlet, creating a greater pressure differential between the tank and the pump, thus increasing the fuel flow. **Turn the fuel pump ON during high power operation, such as takeoff and climb, or install an engine driven pump. (R1)**

As installed, operation of the electric fuel pump could be monitored by observing the fuel pressure on the EDM-900. With the fuel pump ON, the fuel pressure would be about 5 to 7 psi. With the fuel pump failed or OFF, the fuel pressure would show 0 to 1 psi. If the fuel pump has failed, the airplane can still be operated, but with less margin on the available fuel flow. The risk could be mitigated by using lower power settings and avoiding extreme climb angles. The pilot should also be more aware of indications of engine power loss.

Additional Testing:

Eric Newton of http://mybearhawk.com/ was concurrently doing similar testing on Bearhawk #682 "Miss'ippi Mudbug". His fuel system also contained a fuel flow sensor intended for use in a gravity system, but did not include a fuel pump or check valve. Eric was getting similar results. However, he tested with and without the fuel flow sensor in the line. Without the fuel flow sensor the flow rate increased by 10 gallons per hour. Calculations estimated that the pressure drop through the fuel flow sensor was 0.4 pounds per square inch (psi), which was consistent with claims made by the sensor manufacturers. Assuming that the fuel systems were otherwise identical, an additional 0.6 gallons per hour could be attributed to the check valve, although this was probably within the limits of experimental uncertainty.

It would appear that the Bearhawk fuel system as designed is sufficient for the requirements of an O-540. However, the addition of a fuel flow sensor will noticeably degrade the fuel flow available. The loss of fuel flow from the sensor can be offset by the inclusion of a fuel pump, either electric or engine-driven. The fuel pump would only be required for high power settings, such as takeoff and climb. The fuel flow available without the fuel pump was sufficient for cruise power settings.

Conclusions: The fuel flow available was sufficient for high power settings and extreme pitch attitudes with the electric fuel pump ON, and was not sufficient with the electric fuel pump OFF. Estimates based on the test results predicted that sufficient fuel flow will be available at long-term sustainable pitch attitudes and cruise flight with the fuel pump OFF.

Recommendations: **Turn the fuel pump ON during high power operation, such as takeoff and climb. (R1)**