Fuel Systems for Homebuilt Airplanes

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I'm one of those people who reads accident reports, and subscribes to several publications where they're featured. Over the years it keeps re-occurring to me that fuel system related accidents are by far the most frequent single type of non-pilot-error accidents, especially the serious ones, and especially in homebuilt airplanes. Many fuel system related accidents also involve pilot error, such as inaccurate knowledge of fuel quantity and mismanagement of fuel selector valves. However, it is my feeling that these are chiefly system errors more than pilot errors, because such systems often invite pilot error.

There are essentially three types of fuel system emergencies. The first and most important are those occurring on take-off or initial climb, when there is insufficient time, however well managed, to correct the situation. The second can best be called running out of fuel. Some of these are also system-invited by such things as having tanks whose capacity varies with the attitude of the airplane when fueled, or gauging systems of poor accuracy. The third major type are those that occur on approaches and go-arounds. Most of these are definitely system related.

On take-off and initial climb, sudden engine stopping or serious power loss occurs more frequently in homebuilt than factory airplanes. This is probably a reflection of repeated experience and standardization by the factory airplane builders. However, some of these employ antiquated systems and non-ergonomic practices, fuel selector valves being the most prominent. It is absolutely amazing how often fuel selector valves are mismanaged under stress by even the most experienced pilots. Another frequent one is the vapor-lock incident or accident. Almost all of these are system related. One of the many causes is the engine driven fuel pump which is such a good 'teapot" for boiling fuel. When the boost pump is plumbed in series, rather than parallel, and when the engine (and pump) is hot from waiting for take-off, or from lean cruise followed by descent many "carburetor ice" accidents occur, both on approach or go-around, and on liftoff. The only reliable thing that carries the calories out of that hot fuel pump on the engine is the flow of fuel itself. When the throttle is at idle (for descent or waiting for takeoff) there is precious little flow, so bubbles form and have a hard time getting through the small openings into the carburetor needle valve orifice or fuel injection servo unit.

When power loss occurs on go around or take-off, even it proper and immediate valve switching is done (if that is what is needed), the time required for reestablishment of sufficient flow into carburetor or servo unit is often too long. Part of the problem is due to the tremendous demand of the engine for fuel at full throttle . . . it's usually 2-1/2 to 4 times the usually thought-of cruise flow, and catch-up in this circumstance is hard to accomplish. Also, this is a time when boost pumps cavitate from air inhalation from an empty or near-empty tank.

Homebuilt airplanes have a tendency to have fuel system accidents early in their careers, during the learning and sorting-out phase of the pilot/builder as well as the airplane. Fuel system accidents include not only outright failures of devices in the system, but things we rarely think about, such as:

- *Not knowing how much fuel you can put into a tank because of attitude sensitivity or venting.*
- *Small vent tubes easily obstructed by a single drop of water or an insect.*
- *High pressure boost pumps cavitating with interruption or surge in flow.*
- *Fuel selector valves sticking or not having clearly defined detent positions.*
- *A leaking gascolator gasket admitting air bubbles into the system, yet leaks little or no fuel.*
- *Vibration-induced cracking and leakage of spare fuel tanks.*
- *Split flares in metal tubes producing leaks, or inlet of air into system.*
- *Inadvertent flap valves in fuel hoses produced by improper insertion of connectors.*
- *Foreign bodies in the tank jamming boost pump piston or breaking carbon vanes of high*

pressure pumps.

- *Inadequate sized elbows or other fittings in the system producing bubbles in the flow of fuel.*
- *Foreign bodies obstructing finger screens, gascolator screens or filters that are too small.*
- *Leaky carburetor floats.*
- *Leaky fuel injector servo diaphragm (beware of the shelf life).*
- *Leaks in diaphragms and edges of diaphragm in engine driven pumps.*
- *An unsupported vibrating fuel hose that partially obstructs flow.*
- *Worn or grooved connector fittings that leak air or fuel.*
- *High pressure systems (fuel injection) are considerably more critical with respect to leaks and obstructions than low pressure systems, for obvious reasons, and experience bears this out. Also fire hazards are greater with high pressure systems due not only to the higher pressure but because of the increased footage of plumbing and larger number of connections in the engine compartment. Boost pump failures and pump priming failures are also more prevalent here.*
- *Gravity fuel systems, while seemingly simple and reliable, are plagued by very small supply pressures and ease of interruption. For instance, the minimum pressure required by most current carburetors is 1/2 lb./sq. in. This requires a gravity column of 18 inches -not counting any losses for tubes, filters, valves, elbows, connectors, etc. - or the occasional sticking of a float needle valve. For small engine applications only, where small flow requirements prevail.*
- *Air being sucked into the flow of fuel can be as obstructive as vapor lock bubbles. This is another reason to have little or no suction component to the fuel system. Fuel leaks are* ***much*** *easier to find than air leaks because air leaks don't always leak fuel.*

This is only a partial list of potential problems, but it is a sufficient list to illustrate the character and magnitude of the problem. Often the homebuilder (and the homebuilt designer) gives the fuel system inadequate consideration, or simply follows one of several standard production examples. Too often they don't realize the pitfalls of small variations from specific applications, or lack an overall understanding of the problems, and/or the shortcuts that homebuilders are likely to take for their own convenience. I believe that the underestimation of the critical nature of the fuel system is the largest single source of poorly designed or fabricated fuel systems.

Following is an outline-type summary of fuel system items to observe when designing or building your fuel system.

Fuel Tanks

Into which a known amount of fuel can be put each and every time (not attitude, tilt or vent sensitive). Of reliable mechanical construction, unlikely to develop leaks with time and vibration and unlikely to present an unusual hazard in a crash landing. This requires substantial resistance to rupture on impact or deformation. Must not have low spots behind baffles and in comers for collection of water. Vibration is worse in 4-cylinder airplanes than others, and must receive generous respect as a destroyer of structures and producer of leaks.

Fuel Tank Caps

Must not leak fuel, air or water. Expensive, but available and necessary. Look at those caps - take them apart and examine them. Small details are important here.

Sump

Adequate depth and size, with screen and drain valve as necessary. Do not tolerate a main tank without a real sump. Auxiliary tanks, with good lowpoint drains and a "no take-off" restriction 0. K. without sump.

Unporting

Protection Prevention of fuel being thrown away from sump outlet by uncoordinated flight or turn just before take off, by use of slosh gates or check valves and baffles in tank. Necessary.

Vents

3/8" tubes or larger to prevent a frozen drop of water from obstructing. As short a run as possible, especially if horizontal (because of water droplet precipitation), with non-icing opening (any one of several types). Backup second vent highly desirable.

Valves

As simple a system as possible with all on or off if possible. An amazing number of accidents occur from pilot misplacement of valve handle or valve sticking, even from handles breaking off. Also even when properly changed, a long interval is required before engine starts. Selector valves are inherently dangerous and should be recognized as such. One alternative is a separate ball-type valve for each tank, arranged so that the handle position is obvious. Also these valves are more reliable and don't stick.

Boost Pump

Must be inside sump or have short gravity-fed inlet, otherwise very often will not reprime if run dry, especially fuel injection boost pumps. Do not try to suck fuel uphill or forward. It pulls bubbles into the fuel inviting cavitation. Acceleration occurs forward and upward on take-off and climb for a sustained period of time and fuel moves backward and down, and that's where the inlet of the boost pump should be if it is not in the sump. Protect inlet of pump with screen or filter adequate to protect the pump from jamming due to foreign body. Such filter must be inspectable and cleanable. These are often provided in the pump body by the manufacturer.

Fuel Routing

Should be direct from boost pump through filter to carburetor or fuel injector servo. Have engine driven pump plumbed in parallel, not series, so that possible vapor lock in engine driven pump will be bypassed. A check valve may be necessary, depending on pump type.

Engine Driven Pump

Requires shroud for positive-pressure ventilation to cool it, thus minimize fuel boiling (due to accessory case and oil temperatures which heat it).

Fuel Lines and Devices

Should not be exposed to heat anywhere, for two reasons:

1. *To prevent vapor lock (bubbles whose surface tension make them resistant to going through small holes).*
2. *To prevent fire in case of accident, or fuel leak in flight*

Particularly avoid proximity of fuel lines or carburetors to exhaust pipes radiated heat is more intense than most people imagine. This heat acts as an ignition source in case of accident, or a fuel leak, or a crack in an exhaust pipe in flight. Metal heat shields are often necessary because most heat transfer in cowling is by radiation, not convection or conduction. Examples are the metal shields between an exhaust pipe and adjacent hoses or wires seen in many factory airplanes.

Fuel Lines

Should be of well engineered type and size and protected by fire-sleeve in engine compartment.

Fuel Filters

Gascolators are not sacred devices, not even very efficient ones. They were really designed for use with fuel tanks without sumps or sump drains. With sump drains they become unnecessary, or at best supplementary. Often they are sources of fuel leaks and air leaks into fuel systems. Also they are sometimes vulnerable to rupture in case of accident. Where tank sump drains are provided, good fuel filters of several types are better than gascolators and are safer, less prone to leaks and damage. Must be of adequate size and accessible to inspection, draining, cleaning or replacement. Beware of very small automotive filters which could obstruct in flight from a slug of dirt in the fuel. I am using a FRAM HPG-1 fuel filter in my Glasair. It is commonly used in racing cars and boats, has an excellent service experience. It has a 13 ounce capacity, a steel case into which you can put a drain valve. Expensive and bulky, but a good example of what is needed.

Water Detectors

Two brands are currently available (Wag-Aero; A.I.R. Corp., Oakland). A very good idea - either in sump or filter can.

Gauges

Reliable, backup simple mechanical type gauge or sight-tube gauge advisable for last few gallons in addition to standard gauges. Float switch with warning light is another good alternative (Aircraft Spruce). Fuel gauges are justifiably mistrusted, but they are also usually of low quality. Reliable separate gauging of the last 1/10 or so of fuel can be very accurate. Flow meters and totalizers are not a substitute for fuel gauging because they are so dependent on accurate knowledge of how much you start with. Be sure to have some back-up gauging or warning system beyond standard gauge system, or a reliable spare tank.

Spare Fuel Tanks, Header Tanks, Etc.

All have definite problems, including selector valve hazard, but they are a reasonable alternative it designed well. Using a vibrating firewall as one wall of header tank is a questionable practice unless it is specially reinforced and stiffened. (Touch that firewall in flight sometime.) Again think of a survivable crash landing or an in-flight fire. A VW-like standpipe in the main tank is one alternative to a spare fuel tank - or a separate tank within the main tank that fills automatically -or a spare tank that transfers into the main tank. Outer wing panels are the best location for spare tanks, for structural as well as safety reasons.

Air Inlet System To Carburetor or Fuel Injector Servo

Must be of adequate size and especially not obstructed by a too-small air filter. Better no filter than an obstructive one, because the obstructive one can seriously disturb fuel mixture and produce erratic throttle-mixture correspondence. Air filters are highly desirable but must receive the same design consideration as any other system and not simply yield to what is convenient (frequently seen in homebuilts). Be sure filter will also act as flame arrestor in case of start-up backfire - it can save your whole airplane. This is done by containing the filter in a blow-out and suck-in proof container. A curved elbow type of air entry into a carburetor is poor practice because of inertial lamination of airflow into the carburetor. A plenum, horn or diffuser entry is much better, and removes those dead spots at some throttle settings also higher power.

Overflow Drains

From engine pump, inlet spider, inlet plenum boxes as well as drains from filters and gascolators, must be overboarded in a safe place away from exhaust. A manifold collector and single drain often useful here.

Carburetor Heat Source

Standard and necessary. Can be easily combined with cabin heat. Pulling carb heat cable turns off cabin heat with two-way flap valve. Be sure to overboard any unused carb or cabin heat so there's a constant airflow over shrouded exhaust pipe. Otherwise that segment of pipe will bum through and become an early carbon monoxide and/or fire hazard.

Belly Protection

In case of gear-up landing, or gear collapse accident in fixed gear aircraft. Any exposed or vulnerable fuel-containing structures such as sump, filters, drains, gascolators, etc., should have mechanical protection. No drain valve or such structure should project where it can be easily broken off in a belly landing. Longeron-like braces in belly pan is an example of a mechanical protective structure. A strong belly plate under this area is another.

Fueling

Putting fuel into aircraft tanks deserves some thought. The flow of fuel through a hose and nozzle creates static electricity, and a discharge arc sometimes occurs to the filler neck of the airplane - explosion. So, in fiberglass or other composite airplanes, it is desirable to ground the metal fuel filler cap ring. This is true because any mass of metal plus adjacent semi-conductor fluid (gasoline with some moisture in it) has some capacitance. As such, it becomes the target for a static electric arc from the fuel hose nozzle (which may or may not be grounded) or the pouring spout of a jerry can.

This filler-neck grounding should be done with a wire (18 gauge or so is enough) attached with a good AN plated bolt and washer through the ,aluminum ring to a good plated crimpon fitting. These details are to minimize dielectric corrosion of the dissimilar metals. Aluminum bolt or rivet and wire could also be used. However, the experience with aluminum wires and connectors in the presence of moisture is poor. The wire should be mechanically supported properly into the cabin area where it is attached to the ground buss through a resistor (approx. 1 meg OHM 1 watt). This resistor limits the power of any static discharge. What it actually does is spread out the time of the discharge from instantaneous to several micro seconds. This then replaces the arc with a corona-like discharge which is probably below ignition temperature for gas fumes. In any case, when fueling, it is good practice to keep the nozzle in contact with the filler neck. If both the filler neck and the nozzle are grounded, there should be no problem. But you can't be too sure about some gas hoses and nozzles or ground connectors to airplane from the truck or pump. Finger screen in sump should be grounded - by grounding aluminum line or connector.

Fueling from plastic (polyethylene) cans should never be done because these materials have a very high static electric generation potential when gasoline flows over its surface, or it is rubbed against another material. Metal cans are much safer.

The preflight ceremony of draining sumps and other fuel devices should be taken seriously because it is here that you can best prevent the most terrifying of aircraft accidents - the engine stopping on take-off or initial climb. Water is the chief enemy, foreign bodies of all kinds, second. Always use a cup or container to drain fuel, so that you can am any water or debris that you drain. If you can't see it, you don't ever know how much to drain, and every once in a while it takes a lot. Fueling from some places can produce very large amounts of water and debris - much more than a cupful - even gallons. Old buried tanks with doubtful maintenance are guilty here, even some trucks have pro: produced such events. I know first-hand of several such events.

Cessna's experience in rocking wings and tail to dislodge water from wrinkled bladder tanks should be remembered - it was successful. This applies to other airplanes, too, such as taildraggers where low spots due to attitude become pockets for water -or nose draggers with multiple baffles. Water droplets on the floor of a gas tank seem reluctant to move toward the low spot (sump) unless agitated, especially with minimal dihedral wing tanks, apparently due to surface tension.

Water is soluble in gasoline to a limited extent, and this is particularly important in winter (see article by Niel Petersen Sport Aviation, December 1986). As fuel cools in the tanks overnight, some water precipitates out as droplets. This accounts for some of the .moisture of condensation' even when the tanks are full. Also if it is cold enough, these droplets can form ice crystals or slush, which can obstruct fuel outlet screens, even to the point of collapsing them in flight In the cold winter areas this can be important not only as a pre-flight consideration, but on long flights at altitude, where the fuel has time to become cold. Jet-powered aircraft use fuel heaters or water-dissolving additives ("Prist") in their fuel for this reason. However, their fuel has a greater solubility for water, and their flight altitudes are higher - but the problem is essentially the same.

Conclusion

This list is, of course, incomplete. My emphasis has been on those items which seem to me to be most important from a safe-design standpoint. Homebuilders suffer from "ran out of room" problems just when something like a fuel filter or an air filter demands a place, then compromise occurs, and the last items on the list get the poorest design. Don't yield to this - be willing to go back and rebuild or rearrange things so that fuel priority is properly respected.

One last thing. If; you must put fuel system components in the engine compartment (where all the heat and ignition sources are), group them together and build a good metal, positively ventilated, box around them. Place the vent exit as far away from the exhaust pipe as possible.

In fuel systems, the enemies are heat, water, leaks, foreign bodies, static electricity and devices that invite human error.

ABOUT THE AUTHOR

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