BEYOND FUEL INJECTION 101

BUILDING A COMPLETE SYSTEM

DWIGHT FRYE | *Photos by Wally Dixon*

THE OPPORTUNITY TO LEARN MORE has always been a huge draw for me. That's one reason why I decided to build the 180-hp engine for my RV-7, and the fuel injection system that would give it gas.

The decision led me to the "Fuel Injection 101" class at Airflow Performance Inc., in Spartanburg, South Carolina. The class was fantastic, and I quickly understood more about fuel injection than ever. I shared with Airflow Owner Don Rivera my plans to do my own engine build at Superior Air Parts. I clearly showed my excitement about getting my hands dirty building my own engine, and in a fit of generosity, Don made the unusual offer to let me come down and build my own fuel injection system. I didn't give him any time to retract the offer.

The system I built is a mechanical fuel injection system. This means that all the regulation of fuel flow is performed by mechanical means rather than by use of sensors and electronics. While electronic fuel injection is common in modern cars, it is more common to see mechanical fuel injection systems in aircraft. They perform their task by taking advantage of the physical characteristics of fuel and air to maintain a perfect ratio of the two feeding an engine.

Since Airflow Performance never had a customer build his or her own fuel injection (FI) unit before (and may never again!), there were no assembly manuals or other prepared guides available to use. The plan was for me to work alongside the experienced FI system builders (Kyle Day and Don) as they gave step-by-step instruction. This allowed me to move at my own pace and have every step quality-checked by someone who knew the systems intimately.

A mechanical fuel injection system can be divided roughly into three major parts. There is the regulator, which acts as the brains for the unit. If you have seen an FI system, it is commonly the large circular assembly to which the fuel lines connect. The next major portion of the system is the throttle body. This is the portion of the system through which the engine breathes, and to which the throttle cable attaches. Finally, there is the fuel distribution assembly, which delivers the metered fuel to the individual cylinders. It is often bolted to the top of the engine and has a central body, the flow divider, with "legs" that reach out to each cylinder (thus earning itself the common name of "spider").

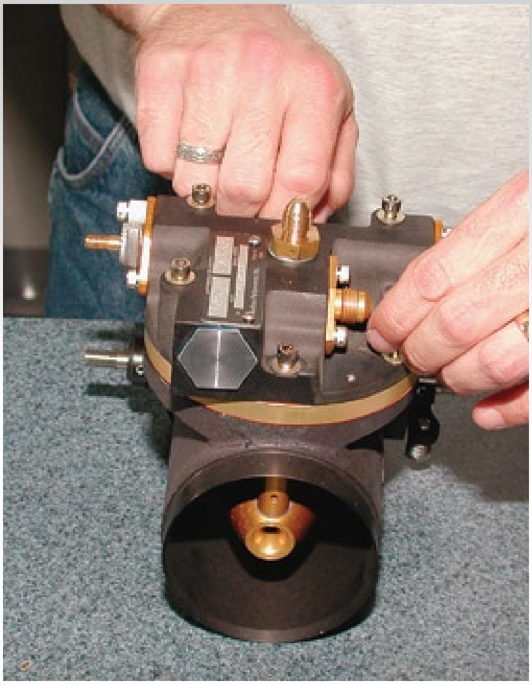
The fuel supply goes into the fuel side of the regulator, through the main jet, and through a metering valve, and then a metered flow of fuel comes back out to the fuel distribution components. Beside that flow is the air. It flows in through the high gain venturi, to which a pressure differential is created which is applied into the air side of the regulator. The goal of the entire fuel injection system is to always provide the right amount of fuel for the amount of air flowing through the engine.

That goal is accomplished by an elaborate collection of parts. There are roughly 170 parts in the fuel control unit, 20 parts in the flow divider, and an entire kit (which includes mounting hardware, hoses, and other parts needed for a complete installation) is about 220 to 250 pieces, depending on which kit you order.

The steps were simple. The first item to assemble, test, and calibrate is the regulator. This took most of the first day. The regulator is mated with the throttle body, after which the entire assembly is tested and calibrated together. The flow divider was then assembled. Those two steps took another long day. Then the final fuel distribution components (and a few other miscellaneous items like hoses, etc.) were assembled, a step that took another half day to finish. Finally, the entire kit is boxed for shipping. It made for a long but very educational weekend.

REGULATOR ASSEMBLY

We started building around noon on Friday, literally within minutes of arriving at the Airflow facility. I worked with



LEFT: Engraving the fuel controller data plate.

RIGHT: Bolting the regulator to the throttle body

LOWER LEFT: Dwight and Kyle attaching the data plate to the regulator body.

LOWER RIGHT: Regulator parts before assembly (with the throttle body in the background).

technician Kyle on the first assembly tasks. He built an FI regulator beside me, so I could see and copy what he did. Step one was to pull out my buildsheet, which was generated based on the type of aircraft I was building and the engine I was going to install. My dataplate was then engraved. This noted the model number, serial number, and other identifying information. We attached it to the regulator body, making this the first pair of parts assembled.

Measuring the ambient atmosphere and power demanded by the pilot, the regulator is the heart of the fuel injection system because it maintains the appropriate fuel-air mixture. The regulator measures and meters the fuel, and the regulator's task is air, the goal being to maintain an appropriate fuel-air ratio at all times. This task is performed by two different interconnected pieces of the regulator.

The first piece of the system is the "air side" of the regulator. It connects via small air passages to a static input and a venturi input. Each input has a different pressure (with the venturi pressure being lower due to the air being accelerated by the venturi through the throttle body), and each input goes to a different side of a diaphragm in the regulator. These two pressures end up providing a force against the diaphragm. This diaphragm is about the size of an audio CD and is made out of orange rubberized fabric, tough and impervious to fuel and most solvents. Imagine the air side of the regulator as one side of a balance scale, with its job being to measure the amount of air being pumped through the engine.

The second piece of the system is the "fuel side" of the regulator. Like the air side, it also has two small passages, but passes fuel rather than air. A small piece of plumbing called the main jet performs a job similar to the venturi on the air side. Once again, there are differing pressures on the two sides of the diaphragm in this side of the regulator, which ends up with a force being placed against the diaphragm. This diaphragm is smaller and is made out of the same rubberized orange fabric. Imagine this as the other side of a balance scale, measuring the amount of fuel flowing through the system.

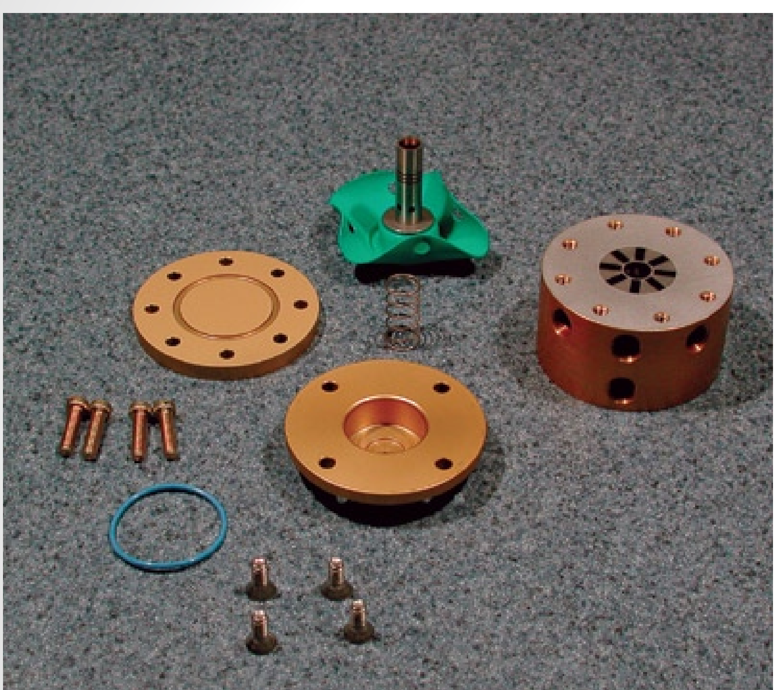
Like a balance scale, the two sides are tied together with a rod that ties them into a single system. If a valve were placed on the pointer of the balance scale so that, as fuel flowed through the fuel side, the valve was adjusted to keep the two sides in perfect balance, then you would have a mechanical fuel injection controller. There is, in fact, a small ball valve tied to the connection between the two diaphragms such that this is exactly what happens.

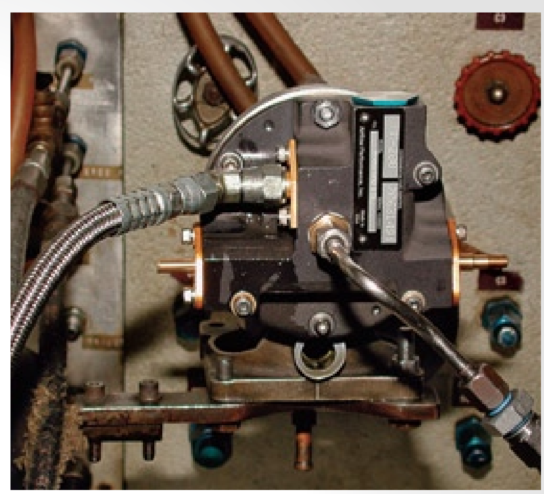
As the throttle is opened, more air flows through the system, the balance starts to tip in favor of the air side, and the valve opens a tad. This causes more fuel to flow

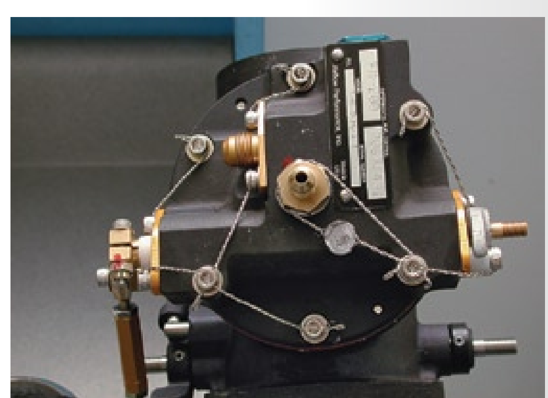
LOWER LEFT: Flow divider parts. The flow divider is more complex than many might assume.

RIGHT: Regulator "fuel side" calibration.

LOWER RIGHT: Fuel controller lockwired and completed.







TOP LEFT: Milling the hole for the locking roll pin

LOWER LEFT: Assembling regulator to throttle body

LOWER RIGHT: Marking a fitting after performing airflow calibration. This is during the calibration of the entire unit where we are running volumes of air through the airflow bench as well as having it hooked up to the fuel flow bench. This allows a complete "real world" testing of the completed fuel controller unit.

until the system is in balance again. If you close the throttle, the fuel side becomes heavier and tips the scales. The valve closes a tiny bit and everything balances again. The ratio between the fuel and air sides is always maintained, which is the recipe for a happily running engine!

As I assembled this system, I was continually amazed that all control is performed via simple mechanical interactions. Air pressure balances fuel pressure, and the two are tied together physically by a tiny connecting shaft. When behavior needs to be adjusted for special situations (idling, for instance), other mechanical parts of the system assist with these special needs. Although there is a time and place for electronic fuel injection, the simple elegance of the mechanical system never ceased to amaze me.

Every step was an exercise in attention to detail. The next step in the assembly was to install two valves in the throttle body portion of the unit. There are two valves that control the flow of fuel through the system. One is a mixture valve, which adjusts the fuel-air ratio and is connected to the mixture control the pilot uses in flight. The other valve is an idle valve, and it is connected to the throttle control. It comes into play when the throttle is completely retarded and helps adjust the fuel controller to provide a smooth idle.

We placed O-rings on these rotary valves and made sure they were not twisted or crimped. While the O-rings don't have a specific orientation, they need to be installed so that they are not twisted. This can be easily seen by noting that the mold line on the rubber runs cleanly around the O-ring once installed. Rotary valves were oiled to aid in their insertion in precisely machined passages and then slipped into their appropriate spots. They were then checked to make sure the O-rings weren't cut going in, since the clearance of the barrel to the rotary valve is so tight. The valve was clocked to a position close to the final adjusted position going in to help speed calibration later on in the process. Calibration fine-tunes this position to get it correct for each assembled unit. These valves live on the fuel side, with one each for idle adjustment and for mixture adjustment. The main jet, inlet fitting, and outlet fitting were then installed. An unused outlet position (the fuel controller is highly configurable) was closed off with a plug.

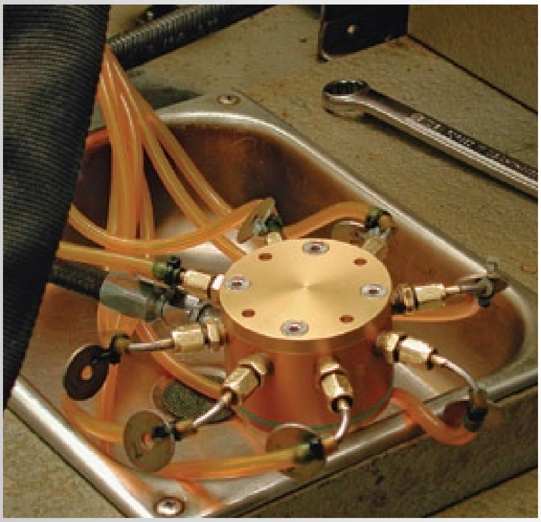
Once the fuel side was built up, we went into the test lab for the first of many calibration and leak tests. Everything that flows fuel is checked for both flow rate and leaks, with checks happening at critical phases of the assembly process. Leak checking is simple. The regulator is connected to a fluid supply, and pressure is applied. It is then visibly checked for leaks. Fuel flow is a little more complex. With those first tests completed successfully, the regulator comes off the test bench for the next assembly step. The "air side" diaphragm is added to the growing regulator assembly. With that done, the regulator went back to the test bench.

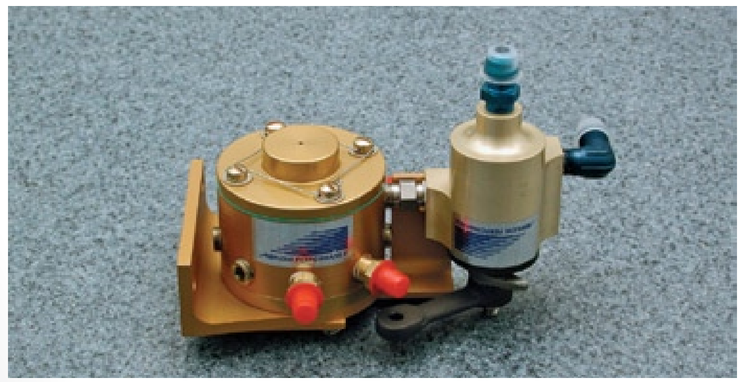
An elaborate fuel-flow test bench sits in a corner of the Airflow lab. Fixtures allow us to put a regulator in place,

RIGHT TOP: Torquing the final fittings on the flow divider.

LOWER LEFT: Flow testing the flow divider. This is a critical test showing that the flow divider is doing its job.

LOWER RIGHT: Final flow divider assembly, with purge valve.





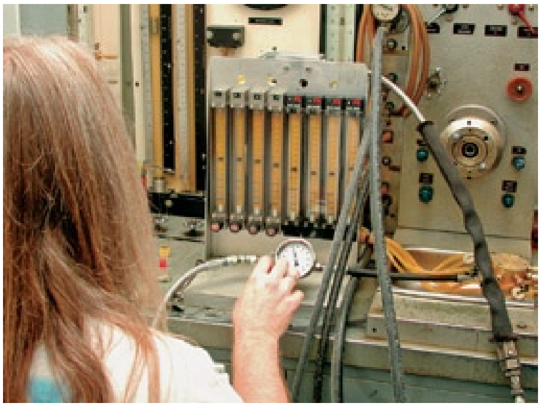
hook up fuel lines, and actually cause the regulator to perform while displaying precise fuel-flow measurements. It has a pump that can drive variable amounts of fuel pressure into the regulator. It also has hookups so that a controlled amount of air pressure can be placed on the air side to simulate air flowing through the system. Measurements are read from vertical tubes through which the simulated fuel flows. Inside these vertical tubes are calibrated indicators, which rise as the volume of fluid flowing through the system increases. This test bed is calibrated such that variables that might affect the flow, such as the specific gravity of the fluid, are carefully controlled. This gives fuel-flow measurements within a few tenths of a pound per hour. The inputs and outputs are connected from the flow bench, and pressures are applied to the regulator. These tests allowed us to make sure there were no leaks and that basic regulator operations were functioning. The first set of tests only checks the fuel side for basic flow and leaks, but the second round actually tests the regulation function.

To test the regulation function, both fuel and air lines are connected to the regulator. Step one was to set the mixture control valve full rich and idle cutoff. The mixture control valve gets a control stop with arms installed. The arms, attached to the shaft of the rotary valve, limit the motion at either extreme of the valve's rotation. The control stop needs to be adjusted so that full rich and idle cutoff happen, respectively, just before the stops are hit. This ensures that you can achieve both full rich and full cutoff with plenty of margin for error. Once the correct position is found, the control stop is carefully center-drilled and a roll pin is pressed into place to keep the control stop from rotating on the valve shaft.

At this point we had a very compact unit. Circular in nature, it is like a sandwich of materials. There is the regulator body, a diaphragm, then the center body assembly (a gold-colored piece of aluminum about 1/3 inch thick), and another diaphragm. A tiny shaft ties the two diaphragms together, and one end of the shaft is a ball for the valve, with the other end of the shaft having a tiny nut threaded onto the end.

It is the adjusting of that tiny nut that sets the ratio between the fuel and air sides of the regulator. Measurements are taken and if the target number is not seen, the nut is adjusted by a turn or, as you close in on the target numbers, by fractions of a turn. The goal is to have 0 to 2 pounds per hour of flow, which balances the forces within the regulator and confirms that there is no leakage past the ball valve. Once the desired setting is identified, a locknut (torque to values measured in inch-ounces) is installed and secured with Locktite. At this point, the fuel side is complete and ready to be mated to the throttle body.

The venturi portion of the throttle body was one of the few subassemblies I could not build during the weekend. The venturi assembly requires the use of epoxy in conjunction with screws to assemble. We didn't have time for epoxy to oven-cure.



LEFT TOP: Confirming that we have balanced output on the flow divider.

LEFT BOTTOM: Leak testing an assembled hose

RIGHT BOTTOM: Trimming to size the firesleeve locking band.

Working with the already-constructed throttle-body subassembly, we first installed the linkage between the throttle lever and the idle valve. With this in place, the completed fuel controller was ready to undergo another round of testing.

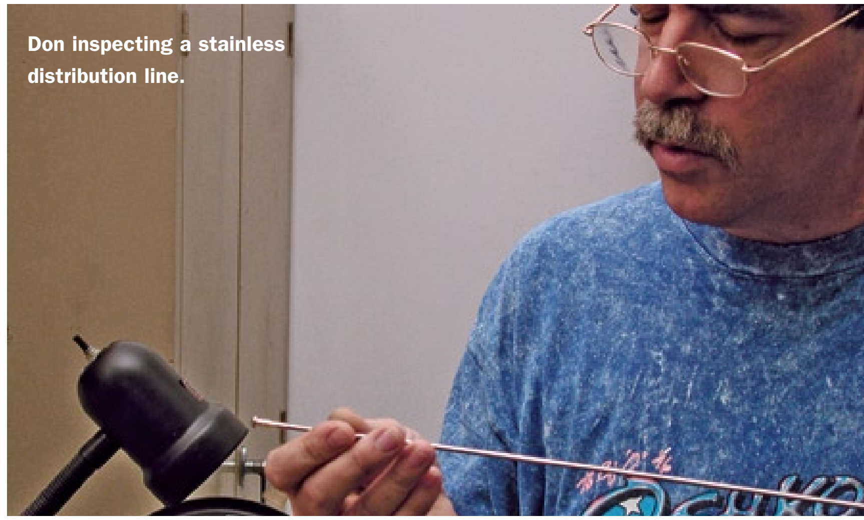
The next tests involved putting the assembled fuel controller on the airflow box and passing carefully calibrated volumes of air through the controller to ensure the entire assembly works the way it should. This is an amazing test fixture, which in many ways is a huge, carefully calibrated, very loud vacuum cleaner that can tell you exactly how much air is flowing through the system at any moment. One of the first steps was to adjust the idle valve so that it opened at exactly the right moment. This is to ensure that the fuel controller comes out of idle mode promptly and with no lag. With this set, the lock nuts on the linkage were secured and we moved on to the next round of tests.

The fuel controller was installed on the airflow bench, and connections were made to the fuel-flow bench. This allows a test of the entire fuel controller assembly as if it were installed on an engine. Both fuel and airflow is measured in pounds per hour so that the ratio between the two can be clearly identified—the goal being to always maintain the optimal fuel air ration of 8 pounds of air to 1 pound of fuel at all flow rates. For a Lycoming 360 type engine, like I intend to use, the specific target values are a fuel-air ratio of 0.085 to 0.087. Pounds are the preferred unit of measure because engines make power based on mass flow and not cubic feet or any other metric.

While on the airflow bench, the system was tested at many rates. The airflow rates ranged from 0 pounds per hour (PPH) to 2,000 PPH. As we stepped slowly through the various airflow rates, we watched the matching fuel-flow rates. This confirmed the system regulated the correct amount of fuel for the amount of air flowing through the engine at each setting. Luckily, our initial calibration settings were on the money, so there was no need to change the main jet or make any other adjustments. All the values seen were well within desired ranges.

The performing of "real world" tests on a flow bench, where realistic amounts of air and fuel are pumped through the unit, are not typical to most overhaul shops that work on aircraft fuel injection, but unique to Airflow. These tests allow the fuel controllers to be completely validated before being shipped out. This type of testing is given to not only the new fuel injection systems Airflow builds, but to overhauls of other manufacturers' fuel injection systems as well. Seeing my system run through its paces during these tests gave me confidence that the unit I assembled was doing what it was supposed to do.

Throughout the assembly of the system, as each piece is tested and final-assembled, lock wire is used to ensure that nothing comes apart under vibration. Practice and care are needed to get the lock wire right, and it seems that doing so is an art. I'm pleased that all the lock wire on the


Don inspecting a stainless distribution line.

unit was installed by me and passed Don's scrutiny!

FLOW-DIVIDER ASSEMBLY

We then set the fuel controller aside and moved to working on the flow divider. This is the cylindrical unit that looks like a manifold, often mounted on top of the engine, from which fuel distribution lines radiate out to the cylinders.

At low flow rates (idle, for instance) there is very little back pressure from the nozzles. If one of the nozzles were lower than the others, then at low fuel flows all the fuel would run "downhill" to the lower nozzle, starving the other cylinders. The idle performance of the engine would be unacceptable, to say the least. Imagine a showerhead with only a trickle of water (low flow) running through the pipes. Only a dribble of water would come out of the lower holes of the showerhead, and the upper holes would have no flow at all. A flow divider solves this problem. It has to make sure an equal amount of fuel gets sent to all ports, even when the pressure is low enough that it would not occur on its own. The flow divider accomplishes this with the help of a vertical spool valve in the middle of the flow divider's body. The movement of this valve creates a changing port size for different flow rates and back pressures. When the back pressure is low, the valve is virtually closed, presenting a tiny outlet to the fuel. The outlet is sized to provide a more restricted exit for the fuel, which results in even flow, to each port that is connected to a nozzle line. As the flow rates increase, back pressure increases. As the pressure increases, the valve slowly opens and at a particular point (about 3 to 6 PSI) it moves into an area where the opening is no longer restricted. At this point, the diameter of the fuel restrictors in the injector nozzles provides adequate restriction to ensure balanced flow between all the cylinders.

To pull this off, the valve and port slots need to conform to very tight tolerances. The small cylindrical valve in the middle of the flow divider must slide freely with very small pressures. It is machined to *very* exact tolerances and must be lapped flush with the bottom of the flow divider's body to minimize leakage when in the closed position.

The body of the flow divider was one of the already-assembled components we used (once again due to time constraints, since it has to be assembled by heating the outer assembly to achieve a shrink fit). With the body already assembled, it was a matter of preparing the valve and the body to be mated together. Doing a final hand-lapping of the two together on a lapping plate does this. After that they are cleaned and the tiny slots in the divider core are checked for trash. With the parts prepared, the valve is slipped into the body, the bottom plate is installed, the top plate is carefully installed (so as to not pinch the diaphragm), and the whole assembly is bolted together. The various fittings and plugs (I needed only four of the eight available ports for my XP-360) are installed, and the purge valve is threaded into the inlet.

Like everything else that passes fuel in the system, the flow divider had to be tested and leak-checked. This uses a special fixture that has eight low-volume flow meters plumbed to measure each port. Test fittings are placed in every port, and the fuel supply is attached to the inlet of the flow divider. Fuel lines, one per outlet, are attached to each of the eight output ports on the flow divider. Each of these lines runs through one of the eight flow meters. The flow bench then is powered up, and fuel pressure is increased to start flowing fuel through the divider.

Since the flow divider must evenly divide the fuel between the cylinders, this is precisely what is tested. The tests are performed at both low and high pressures to simulate all operating scenarios. A slow increase in the fuel flow confirms that the valve is seating, and that it opens as the pressure increases. Then as pressure comes up, the individual indicators on the low-volume fuel meters should all dance in harmony. During the test, we can watch the meters rise and fall in unison, each hitting the calibrated marks at exactly the same moment. This confirms that the flow divider is doing its job of making sure no cylinder is shortchanged.

One of the real eye-openers was seeing exactly how much fuel comes out at different flow rates. At idle there is truly only a trickle of fuel coming out of each port. It was visibly clear that even at that low a rate of flow, the fuel was being divided evenly between all ports. I also got to see what the flow looked like at full throttle. A small fountain of fuel came out of each port but wasn't nearly as much as I might have guessed!

With this complete, a bracket

is added to the assembly, which holds the flow divider and purge valve rigidly in relationship with each other. A mounting bracket is added and the whole flow divider assembly, except for applying lock-wire, is complete.

HOSE ASSEMBLY

It was then time for something entirely different: making fuel line hoses. These are stainless steel—jacketed Teflon hoses with Aeroquip-style fittings on the ends. Two of them go into the system as shipped from Airflow Performance. Don demonstrated the operations on a set of hoses he was assembling, and then I got to replicate the same steps on mine. After all the stories I've heard about how hard it can be to make these hoses (and, without a doubt, care and correct procedures must be taken), I found it surprisingly manageable to achieve a good result. The hoses were taken into the pump-flow bench and pressure-tested. I was thrilled to find I had no leaks!

Fire sleeve was the next step. It was much easier to install than the actual making of the hoses. The material was cut to length and slipped onto the straight fitting to start the installation. Then with a gentle (too much and you risk shooting your assembly across the room!) puff of compressed air in the end of the fire sleeve, you "inflate" it and slip it up the hose. Done right, it goes on like a charm. A careful application of the locking bands and a little high temperature RTV on the ends to seal the fire sleeve, and they are done.

FUEL DISTRIBUTION LINES

The next process I got to experience was fabricating my fuel distribution lines. These narrow lines run from the flow divider to the injector nozzles on each cylinder. These are critical assemblies, since breakage in one of these lines would mean raw fuel being dumped on hot cylinders! None of us knew how this would come out, since it required silver-soldering the ends on the stainless steel lines, and I had never done any silver-soldering before. It takes judgment and a good hand on the torch to make acceptable assemblies. However, I was game to try, never wanting to pass up the chance to learn something new from someone experienced.

I have to say that without Don carefully watching my work (and even pulling the torch back when I was about to overheat the assembly a few times), I would not have ended up with usable lines. It is a touchy operation that requires some practice. I got eight shots at it (two ends per line, and four lines). I think I could achieve an adequate level of skill with enough practice, but with only a few lines to be fabricated, I achieved "acceptable" but not "pretty." Don did have to fix up a few mistakes, but the real test was pressure testing. As it turned out, they all pressure-tested fine, and after careful inspection Don pronounced them "flyable"!

NOZZLE TESTING

When the fuel lines were done, we pulled all the other parts that make up the kit I ordered for my XP-360. This included mounting hardware, adapter plates, filtered airbox mounting plates, the injector nozzles, the flow restrictors for the nozzles, and a handful of other small parts. Then we had to do one last set of tests on the nozzles. Anything that fuel can flow through gets flow-tested and pressure-tested. The nozzles were no exception.

This test was simple. The restrictor (the standard size for the XP-360 is 0.028 size restrictor) was dropped into each nozzle. The nozzle was installed into the fuel-flow bench and hit with 12 PSI of fuel pressure. The test was to make sure that the stream of fuel coming out of the nozzle was a clean fine line and that the flow rate was very close to 32 PPH. These nozzles and restrictors are machined to fine tolerances, but this last check is mandatory to ensure they are on the money just before they go into the customer's box.

The first three were perfect, but the last one had a "sloppy" stream of fuel coming out and a lower-than-allowed flow rate. We disassembled the unit and used some compressed air to blow out the restrictor in case there was a little trash in the way. When it was reassembled and back on the flow bench, we got perfect results. We capped the four assemblies, ensuring that no other trash would get into the injector and keeping the restrictors in place in the nozzles, and were done.

FINISHING UP

All the parts were bagged, tagged, and packed in a shipping box. A current installation manual was included, and my unit was ready to go out the door! I'll catch up with it again in a few months at Superior Air Parts when I go to build my engine. I'll install it on my new engine with a real sense of pride, but also with a sense of confidence. I'll know I saw it working myself, having tested it with my own hands.

By having stepped through the process of building it, I know what each part is, what it does, and how it works. I feel extraordinarily fortunate to have been in the right place at the right time, and I thank Don and the rest of the gang at Airflow for being such generous hosts! They have also not seen the last of me. After I'm flying, I'll be heading back down to Airflow to have my injectors flow-balanced. I wonder what they'll let me do on that visit!

Dwight Frye is a software engineer who co-owns a 1967 Citabria 7ECA and is very slowly building a Van's RV-7.

GO DIRECT

AIRFLOW PERFORMANCE INC.
111 Airflow Drive
Spartanburg, SC 29306
864-576-4512
airflow2@bellsouth.net
www.AirflowPerformance.com