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Aircraft Exhaust Systems IV

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The goal of this report is to facilitate the improvement of the power, efficiency and reliability of aircraft exhaust systems. The report summarizes the results of a 16 month long study. Many of the systems tested here are similar to ones popularly used in light aircraft. The tests include 4 into 1 collector systems, 4 into 2 "crossover" systems, "Tri-Y" systems and independent exhaust stacks. Additional aspects of exhaust design in this study are:

Intake waves
Wave speed
Megaphone effects
RPM effects
Exhaust jet thrust
Crossover/Tri-Y reflections
Frequency analysis (FFT's)
Header size
Collector size
Coanda nozzles
Bends in the pipe
EGT and CHT effects
Ball joint effects

Over 350 separate **Exhaust Pressure Graph (EPG)** recordings were made using the Lycoming IO-360 A1B6 engine in the CAFE test-bed Mooney M20E. All of these were made at 125' MSL as static ground engine runs of approximately 15 seconds duration.

CAFE, EAA and the FAA are grateful to the following major contributors to this study: Aerospace Welders of Minneapolis for the high quality exhaust merges and ball joints, George Johnston of EAA Chapter 124 for the lathe-machined model of the Coanda nozzle, Sam Davis at Tube Technologies in Corona, California for the stainless steel exhaust system derived from thes tests, and Bill Cannam, a certified welder from EAA Chapter 124, for the major effort to assemble the stainless steel exhaust system. Curt Leaverton, Jack Norris, Andy Bauer and Steve Williams each contributed professional scientific analysis of the EPG's.

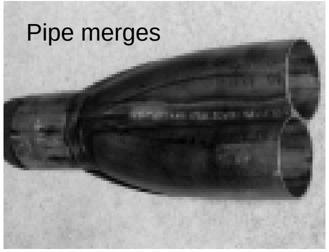
ABBREVIATIONS

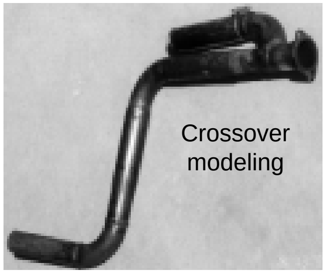
EVO = exhaust valve opening
EVC = exhaust valve closure
IVO = intake valve opening
IVC = intake valve closure
TDC = top dead center
BDC = bottom dead center
W.O.T. = wide open throttle
gph = gallons per hour
dB = decibels, slow A scale
FFT = fast Fourier transform
cyl = cylinder
coll. = collector
msec. = milliseconds
Hz. = Hertz or cycles per sec
"Hg. = inches of Mercury
O.D. = outside diameter

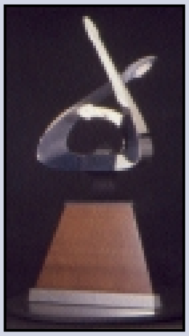

Ball joints

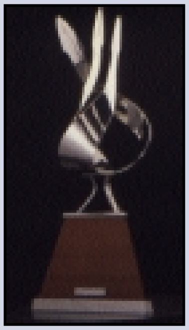

File 411


Coanda nozzle


Pipe merges


Crossover modeling


TRIAVIATHON TROPHY

CHALLENGE TROPHY


THE BASIC EPG
A Review

Figure 1 shows a basic EPG. It was recorded on a well-tuned 4 into 1 collector exhaust system which will be hereafter referred to as "File 411". Figure 1 shows features which are essential for understanding the other graphs in this report. The "X" axis, along the bottom of the graph, shows the degrees of crankshaft rotation beginning at top dead center (TDC) of the firing stroke for cylinder #1. The vertical "Y" axis shows the pressure measured in the pipe in inches of Hg. Since these runs were made at near sea level, the zero pressure level represents ambient pressure of about 30.00" Hg.

The typical EPG shows a steeply rising **"P" wave** of exhaust pressure, shown in red, which starts upward at the point of exhaust valve opening (EVO). The tall P wave typically falls to below zero (ambient) pressure later in the exhaust cycle.

The intake pressure is shown in blue. There is a black vertical dotted line at BDC after the intake stroke, where the piston's descent ceases.

The amount of valve lift of the exhaust and intake valves is shown at the bottom of the graph. At overlap TDC, both valves are open for a brief interval.

The EPG often shows additional waves which come from reflections, turbulence and, in collector-equipped systems, the firings of the other cylinders (cross-talk). These are labeled by their cylinder of origin as the R waves in Figure 1.

The C waves are those measured in the collector, the common pipe into which are merged the individual headers. Each cylinder produces a separate C wave. The time, "**T**", shown in Figure 1 between the rise of the P wave and the rise of the attendant C wave, is very short and can be used to calculate the velocity of the wave.

The "**blowdown**" cycle is defined as the period from EVO to firing BDC, and is labeled "B". It is during this interval that the steep rise of the P wave is seen, as the cylinder discharges or 'blows down' through the exhaust valve and the in-cylinder pressure rapidly falls . Positive in-cylinder pressure during blowdown is still doing some useful work by pushing downward on the piston.

Files 411 Basic EPG: 4 into 1 as 1.75x34.5x2.25x19.5 equal length headers. 29.5" M.P., 2731 RPM 20.4 gph 86°F. 8-18-96. 125' MSL. Lycoming IO-360 A1B6 firing order: 1324
See text for explanation of P, C, S and R waves shown below.

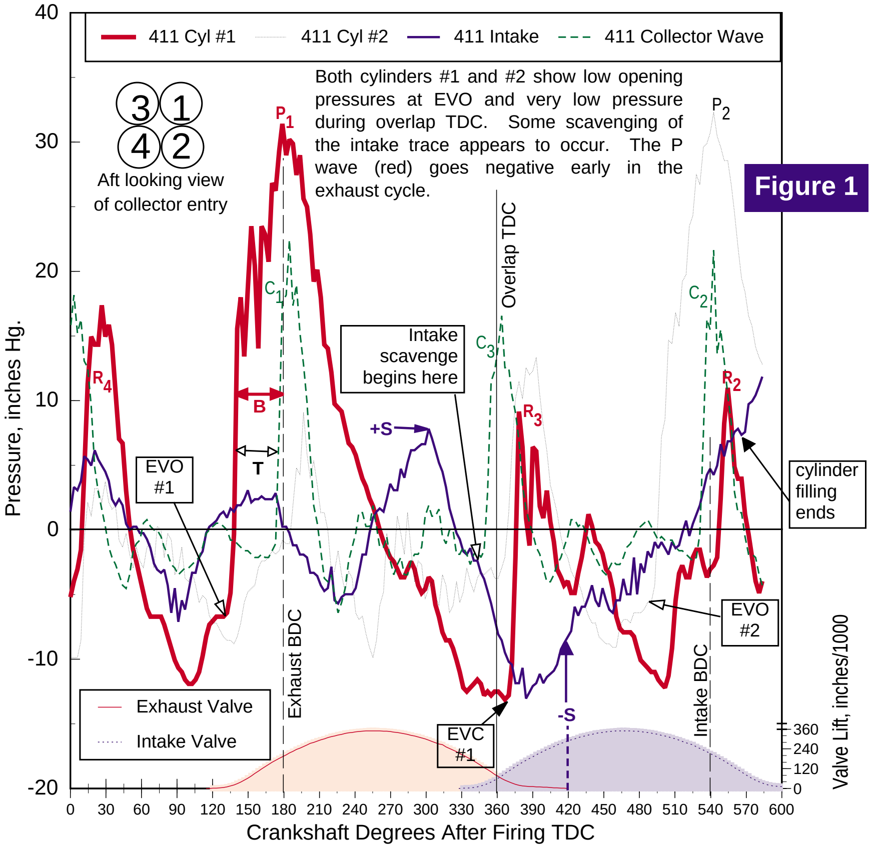


Figure 1

Overlap TDC is a very important interval. When both the exhaust and intake valves are open, the pressures in the exhaust pipe, combustion chamber and intake tract can all influence one another. How much influence depends upon the valve lift during overlap and how long both valves remain open.

During overlap TDC, the suction in a tuned exhaust's header can help empty the combustion chamber of its burnt gas residues. This effect is called "**scavenging**". The exhaust suction may even enhance the combustion chamber's filling from the intake valve, thus improving volumetric efficiency and horsepower. With sufficiently long overlap intervals, it is possible for the suction to pull some cool intake charge across the hot exhaust valve, cooling the valve face, stem, seat and guide. Such cooling comes at a price, which is that raw fuel is being wasted out the exhaust pipe. Higher compression pistons should scavenge better due to their smaller combustion chamber volume.

Note that in **Figure 1**, the intake pressure is greater than the exhaust pressure at overlap TDC. Such a pressure gradient will encourage scavenging. At part throttle, the intake pressure would be much lower, and unfavorable reverse flow could occur at overlap. This is one argument for using wide open throttle (W.O.T.) whenever possible in high altitude cruise flight.

PUMPING GAS

Normally, engine designers try to place EVO about 40-75° prior to firing BDC so that the peak of the very high in-cylinder pressure can be dissipated during blowdown, before BDC. A tuned exhaust system, with a very low opening pressure at EVO, can assist in evacuating the cylinder quickly, and can thus allow EVO to be delayed until later in the cycle. The later EVO allows the positive in-cylinder pressure to do more work pushing the piston downward prior to EVO. Thus, a tuned exhaust system works best if the timing of EVO is delayed to take advantage of the tuning.

After blowdown in the exhaust stroke, the piston begins to rise from BDC. A rising piston pushing against a high in-cylinder pressure causes a loss of power known as a "pumping loss". Ideally, the rising piston would be pulled upward by a negative pressure in the cylinder, thus producing a "pumping gain". Suction in a tuned exhaust system can produce such a pumping gain in mid to late exhaust stroke. This is shown in Figure 1 where the exhaust pressure goes negative at 260° of crank angle, which is 80° after BDC. The earlier in the exhaust cycle that the P wave subsides and goes negative or below the ambient (zero) pressure, the more pumping gain can occur, making for greater horsepower.

Thus, an ideal exhaust system should produce a highly negative pressure at the exhaust valve at both EVO and again *as soon as possible* after dissipating the P wave. This negative pressure should be made to persist throughout the overlap stroke so that favorable scavenging can occur.

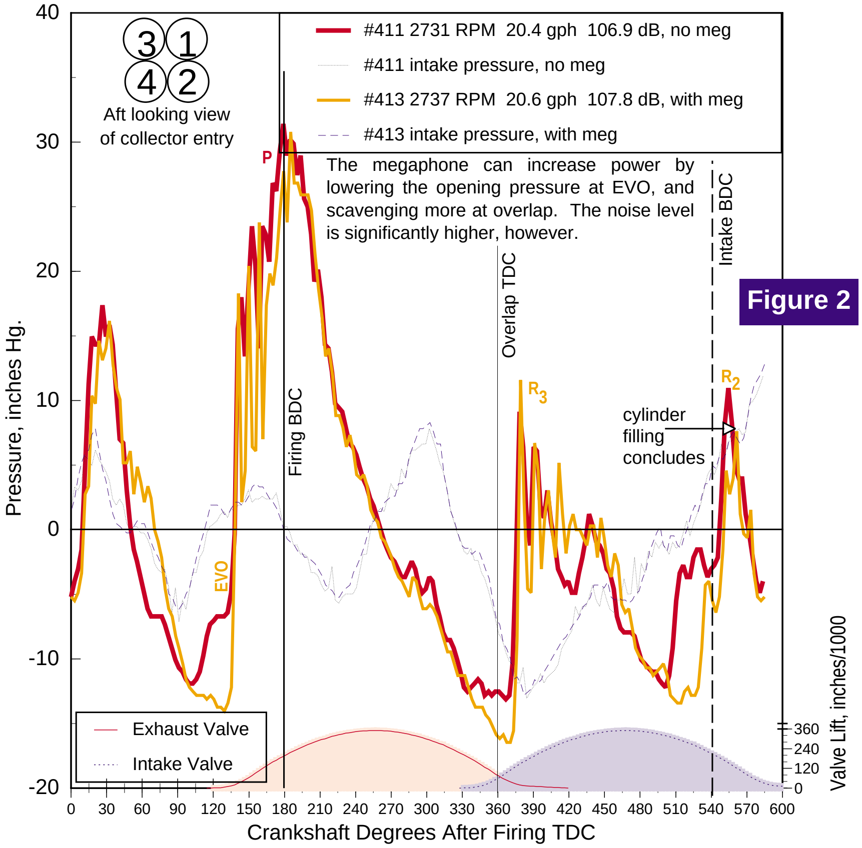
INTAKE PULSATIONS

The piston's descent during each intake stroke exerts strong suction on the intake pipe runner connecting the carburetor to the cylinder. If all of the intake runners attach to a common plenum, as in the Lycoming engines, the suction will affect all of those runners. The suction causes a flow to be initiated in one direction which is abruptly stopped when the intake valve closes. The flow stoppage creates a reflecting wave which again affects all of the runners. This leads to intake pulsations.

The intake pulsations on the Lycoming IO-360 A1B6 engine are sizable and can be seen in **Figure 1.** These pulsations can show how much scavenging effect might be expected, and the character of the cylinder filling. The latter can serve as a guide to the relative volumetric efficiency of the engine.

The W.O.T. intake pulse can reach as high as 6-7" Hg. above atmospheric pressure, as seen at "**+S**" in **Figure 1.** This effect thus gives an instantaneous manifold pressure of about 37" Hg., and, if timed correctly, can act somewhat like supercharging. Ideally, the lowest point in the intake pulsation trough should be timed to occur at "**-S**" or about 60° after overlap TDC. This will tend to assure that the next positive pulse will arrive just prior to IVC, enhancing flow through the intake valve just as cylinder filling ends.

Files 411/413 The effect of a megaphone: 4 into 1 as 1.75x34.5x2.25x19.5 equal length headers. File 413 has a 17Lx2.25x4" megaphone added to 411. Both at 29.5" M.P. (W.O.T.), 86°F. 8-18-96. Lycoming IO-360 A1B6 firing order:1324 Run at 125' MSL.



The megaphone can increase power by lowering the opening pressure at EVO, and scavenging more at overlap. The noise level is significantly higher, however.

Figure 2

Yagi et al[17] have written an excellent paper on using induction system pulsations to force feed the engine's cylinder during the intake stroke.

We did not observe any pressure pulses in the intake waves attributable to the propeller blade sweeping past the air cleaner intake. However, these tests had the air intake located 11-12" aft of the propeller disc. On those cowlings with a very far forward air cleaner intake, the EPG may be able to detect whether the prop is producing a pulse into the air cleaner at just the right moment during the intake cycle.

WAVE SPEED

The EPG can show the *average* speed of a wave traveling through the pipe. The wave speeds observed actually represent the sum of the average sonic wave speed and the average mass flow velocity.

A test using sensors 21.5" apart on a 1.625" primary header showed an average wave speed of 1751 fps.

In **Figure 1**, the time interval "T" represents the time for the 2731 RPM P wave to reach the collector tap from the top of the header, a distance of 47.0". This computes to about 1604 fps average speed. This slower speed suggests that some slowing occurs as the header wave enters the collector.

File 412, at 2507 RPM, showed an average wave speed of 1508 fps, a 7.5% reduction from an 8% reduction in RPM. The reduced speed is due to a lower EGT and the slower average piston speed which gives a slower mass flow.

The exhaust gas expands and cools as it goes down the pipe, and the wave velocity varies directly with the square root of the ratio of the absolute exhaust gas temperatures.

MEGAPHONE EFFECTS

Figure 2 shows that a megaphone added to file 411 produced a lowering of the opening pressure at EVO and better scavenging at the expense of more noise. A megaphone was later added to a Tri-Y system and showed minimal influence on the EPG.

THE EPG TEST METHOD

The EPG pressure sensor was connected to a 9” long copper tube of 0.125” O.D. flush-mounted to the header pipe’s inner wall. The mounting was at a point 1.25” downstream of the cylinder head flange. The signals were processed by the Vetter Sensor Acquisition Module and Digital Acquisition Device. Sensors were calibrated using a water manometer.

A new amplifier was used for this study. Its faster response time and higher resolution provided a much better picture of the EPG relative to those in previous reports.[1,2,3]

The intake pressure recordings were made 1.5” upstream of the intake valve through the fuel injector port in the Lycoming cylinder head.

RPM, noise level, static thrust in pounds, fuel flow, wind incident to the propeller and manifold pressure were recorded manually. Variations in the RPM, EGT, CHT and mixture were used on several runs to study their effects.

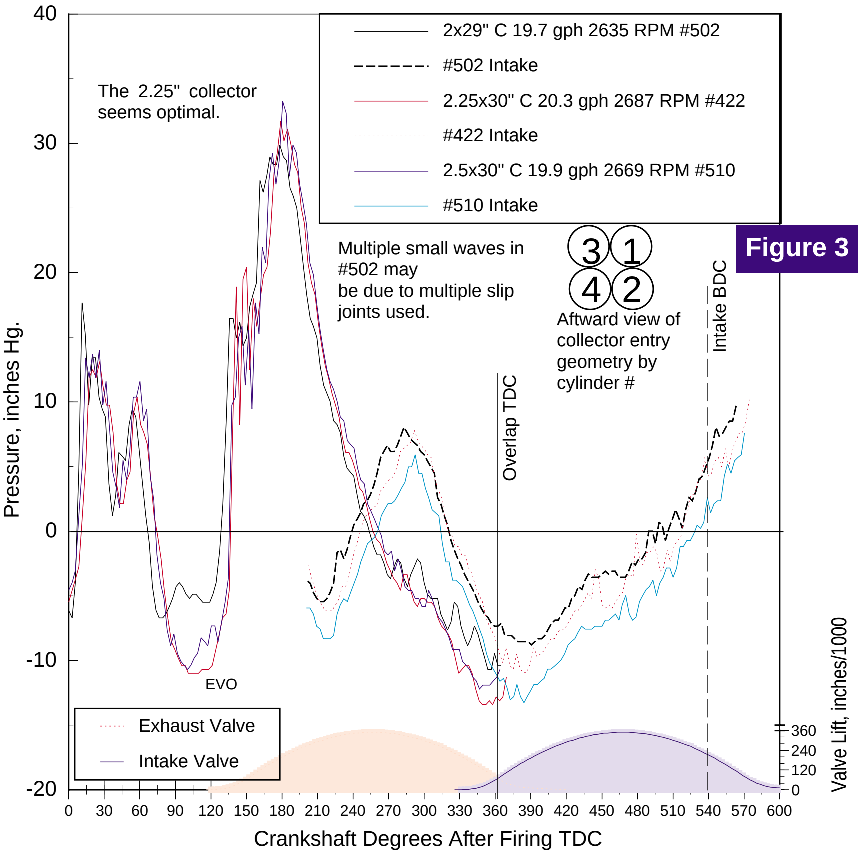
In all of the EPG’s shown here, the timing of the waves with respect to the crankshaft degrees has been shifted to the left (earlier) by 1.25 milliseconds to compensate for a) the 12 inch distance which separates the pressure sensor and the exhaust valve face (1.0 millisecond), b) the electronic rise time of the pressure sensor (0.15 milliseconds) and c) the amplifier delay (0.10 milliseconds). This places the wave timing at its correct phasing with the valve opening cycles.

Fast Fourier transforms (FFT’s) were made on each of the runs to look at the sonic frequencies which had the greatest energy content. Analyzing these transforms exceeds the scope of this report. See the bibliography for several references on wave theory.

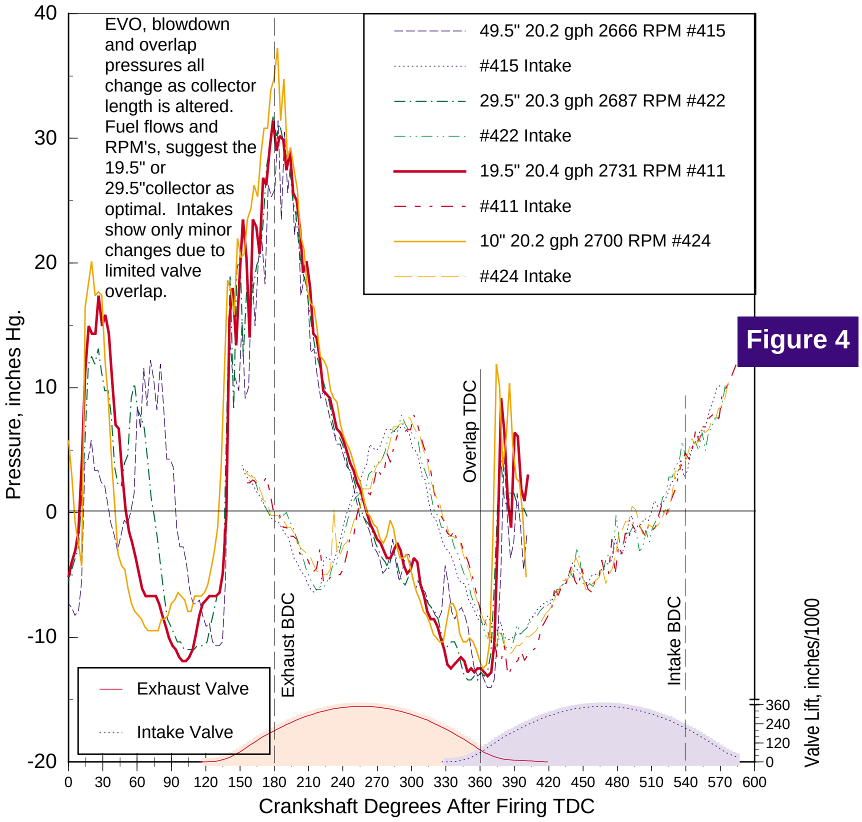
Noise levels were taken from the area between the front seats of the aircraft with the pilot’s side vent window open using the A scale slow setting. Noise was reduced when the tailpipe exit was moved aftward relative to the noise meter, as occurred with the longest tailpipes.

Peak RPM and fuel flow generally correlated with the thrust values and were used as a rough guide to power output. The anemometer showed a change in local wind speed and direction as the propeller’s flow field reached full strength at maximum static RPM. This flow was allowed to equilibrate before the RPM and fuel flow readings were taken.

Files 502/422/510: Varied collector diameters. All use the same 4 nto 1, equal length headers of: 1.75x34.5 with ~30" collector length. 73-82°F. 8-24-96. Lycoming IO-360 A1B6 firing order:1324 Run at 125' MSL.



Files 411, 415, 419, 422, and 424 to compare different collector lengths. All use the same 4 into 1, equal length headers as: 1.75x34.5 with a 2.25" diameter collector. 78-86°F. 8-18-96. Lycoming IO-360 A1B6 firing order:1324 Run at 125' MSL.



BENDS IN THE PIPE

File 411's header pipe bends were as follows:

Cyl #1: 25° + 90° + 170° = 285°
Cyl #2: 85° + 90° + 90° = 265°
Cyl #3: 35° + 170° + 180° = 385°
Cyl #4: 80° + 70° + 20° = 170°

Individual testing of these separate cylinders did not show any significant changes in their EPG waveforms. See **Figure 1**, cylinders #1 and #2.

Many aircraft use a downward bend in the tailpipe to keep exhaust soot off the aircraft's belly. Keeping collector length constant, files 502 (a straight 2x29" collector), 503 (2x29" with a 90° bend at the exit), and 504 (1.5" nozzle on a straight 2x29" collector) were tested at W.O.T. The results were EVO opening pressures of -5.0, -4.0 and +3.0, respectively with overlap pressures of -10.0, -10.0, and -4.0, respectively. The P wave width remained the same.

File 503, with a 90° downward bend of the collector at the exit, caused an insignificant increase in backpressure. The nozzle did impose a significant backpressure penalty.

COLLECTOR SIZE

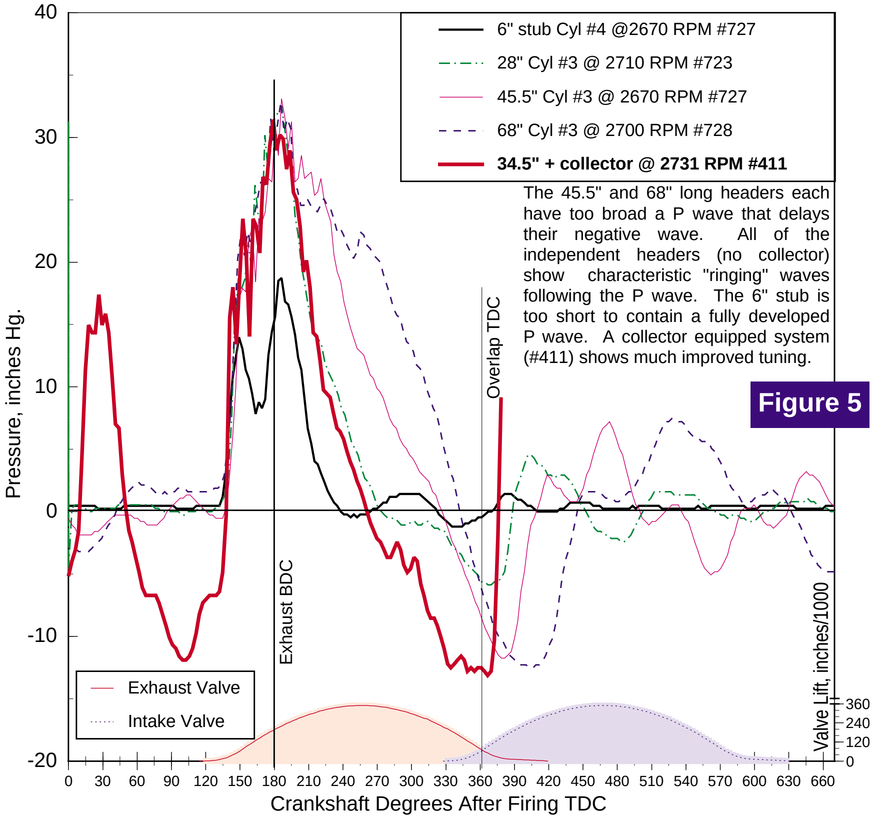
See **Figure 3.** These tests repeatedly showed that, for this particular engine, the 2.25" diameter collector was best for optimizing exhaust backpressure at sea level. A 2.125" diameter collector would probably give a good compromise between climb power and high altitude jet thrust.

See **Figure 4 and 6**. Collector length appeared to optimize at 20-30". It must be long enough to develop some continuum of flow and fully contain each pulse.

COLLECTOR EFFECTS

See **Figure 5**. The addition of a collector to 4 separate independent pipes consistently caused the entire EPG to shift to lower, more negative pressures. Some suspect that this effect may be caused by the more continuous mass flow in the collector exerting a prolonged vacuum effect upon all of the headers. A suitable collector was one with about 50-90% greater cross sectional area than each individual header and with a length of

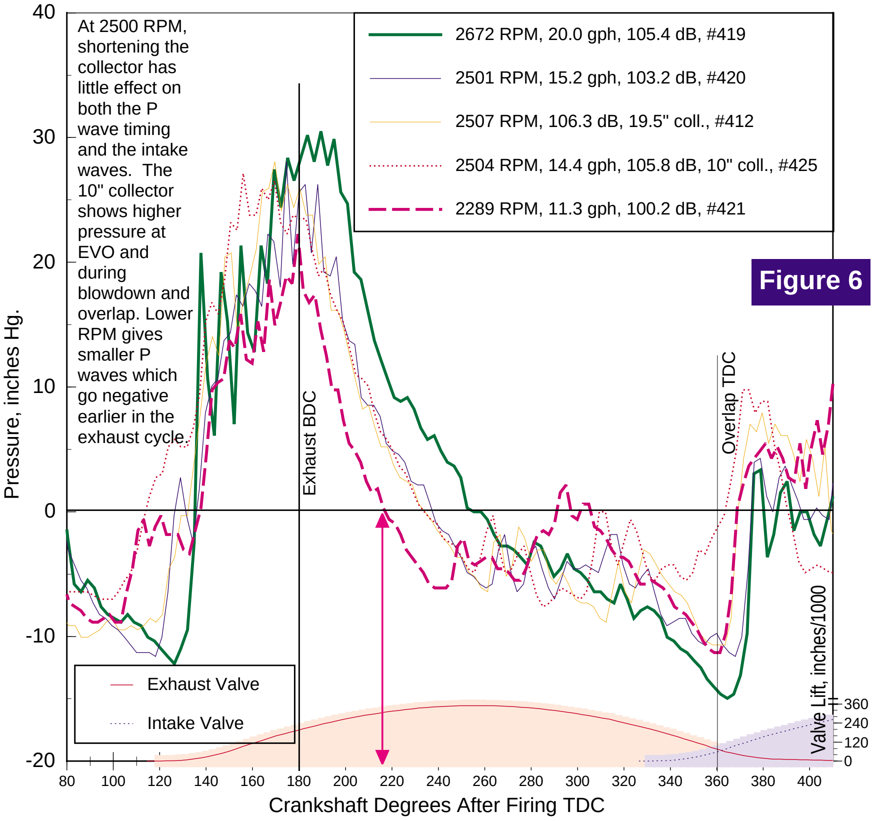
Files 723/724/725 RPM effects: All of these headers are 1.625x28" with no collector except file 411 which is 1.75x34.5x2.25x19.5. All at 97°F except 411 at 86°F. Lycoming IO-360 A1B6 firing order:1324 at 125' MSL..



The 45.5" and 68" long headers each have too broad a P wave that delays their negative wave. All of the independent headers (no collector) show characteristic "ringing" waves following the P wave. The 6" stub is too short to contain a fully developed P wave. A collector equipped system (#411) shows much improved tuning.

Figure 5

Files 419/420/421/412/425 RPM and collector length effects: All headers are 1.75x34.5". Files 419, 420, and 421 used a 2.25x40" collector. File 412 used a 2.25x19.5" and file 425 used a 2.25x10" collector. All at 78-86°F. Lycoming IO-360 A1B6 firing order: 1324 at 125' MSL..

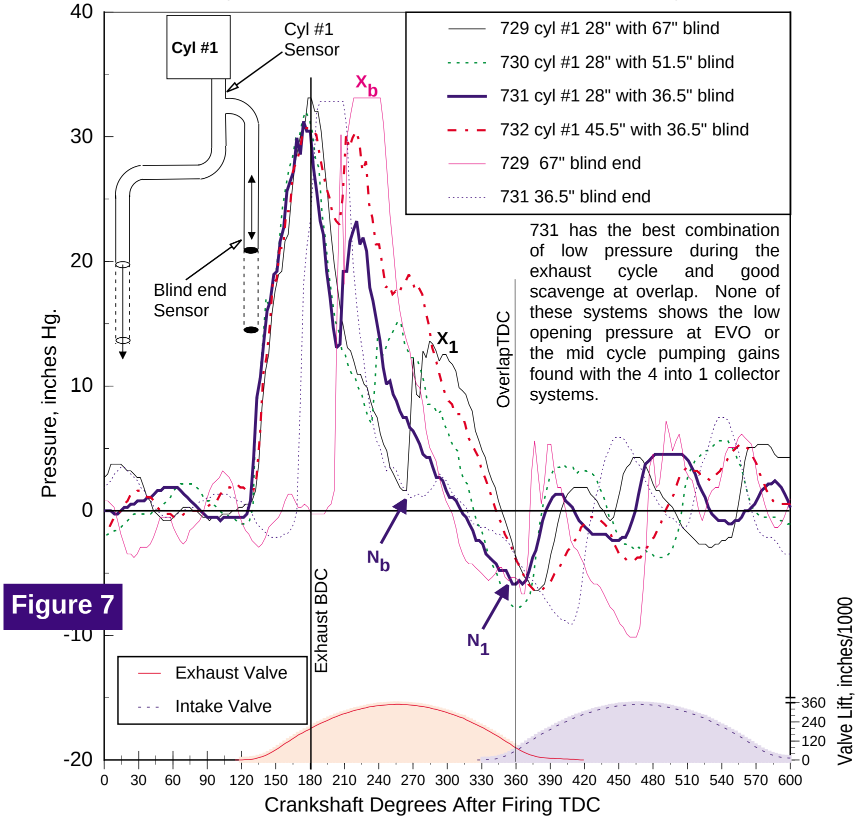


At 2500 RPM, shortening the collector has little effect on both the P wave timing and the intake waves. The 10" collector shows higher pressure at EVO and during blowdown and overlap. Lower RPM gives smaller P waves which go negative earlier in the exhaust cycle.

Figure 6

Files 729/730/731/732 Crossover systems of various blind leg lengths. Cyl #1 has a 1.625x28" primary header except in 732 where it is 45.5" long. The blind offtake is 2.5" downstream of #1 cyl head. 97°F Lycoming IO-360 A1B6 firing order:1324 at 125' MSL. Note how blind end pressures are reflected back into the header to alter timing.

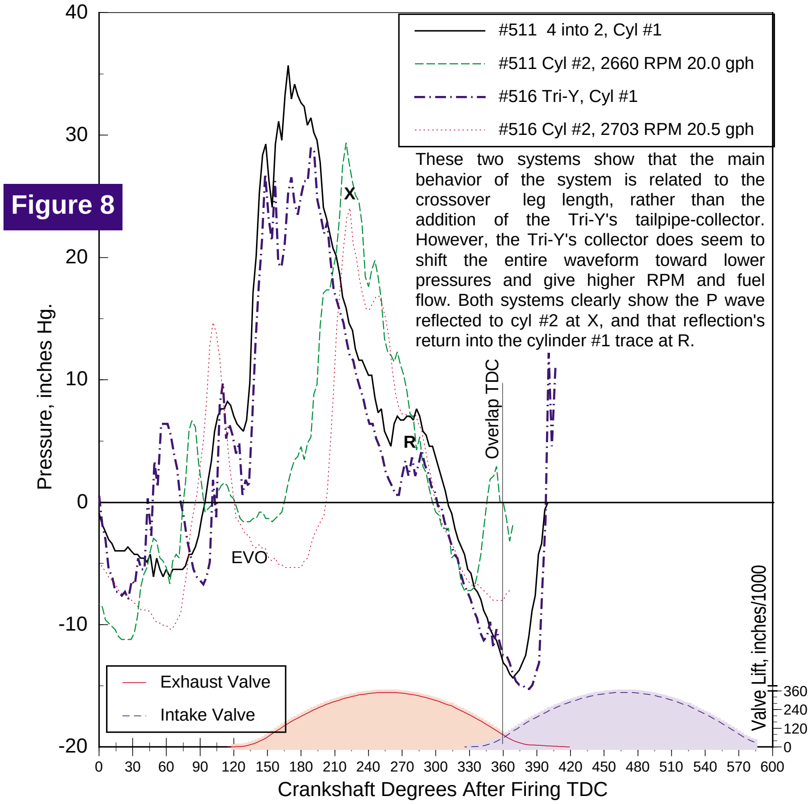
Figure 7



731 has the best combination of low pressure during the exhaust cycle and good scavenge at overlap. None of these systems shows the low opening pressure at EVO or the mid cycle pumping gains found with the 4 into 1 collector systems.

Files 511/516 to compare crossover 4 into 2 versus a Tri-Y system. All use the same equal length headers as: 1.75x34.5 with 511 having 2 each 1.875"x18" tailpipes and the Tri-Y having a merging of those 2 tailpipes into a single 18.5x2" outlet. 77-78°F. 8-24-96. Lycoming IO-360 A1B6 firing order:1324 Run at 125' MSL. Both at W.O.T.

Figure 8



These two systems show that the main behavior of the system is related to the crossover leg length, rather than the addition of the Tri-Y's tailpipe-collector. However, the Tri-Y's collector does seem to shift the entire waveform toward lower pressures and give higher RPM and fuel flow. Both systems clearly show the P wave reflected to cyl #2 at X, and that reflection's return into the cylinder #1 trace at R.

at least 18" or so. See "length formulae" below.

In **Figure 5**, the small waves which occur after the P wave in the independent pipes are called 'rings', as in a doorbell ringing. The negative portions of these rings are of such short duration that they require the pipe designer to choose between positioning them early in the cycle to obtain pumping gains or late in the cycle to scavenge at overlap. The collector system has such a long duration negative wave after the P wave, that it serves both purposes, i.e., gives pumping gain as well as scavenging at overlap.

CROSSOVERS AND TRI-Y

A crossover exhaust joins the headers of cylinders whose firings occur 180 crankshaft degrees apart. The P wave of one cylinder will then travel upstream to the other cylinder where it will bounce off of a closed exhaust valve and return. Pipe lengths in the crossover can be chosen so that the returning wave will produce a negative pressure for scavenging.

See **Figure 7 and 8.** Two different crossover systems were tested. One was a simulation model in which an independent header on cylinder #1 had an offshoot pipe welded on about 2.5" downstream from the cylinder flange. The offshoot pipe was a blind leg whose length could be adjusted and on the end of which a pressure sensor was attached, as shown in Figure 7.

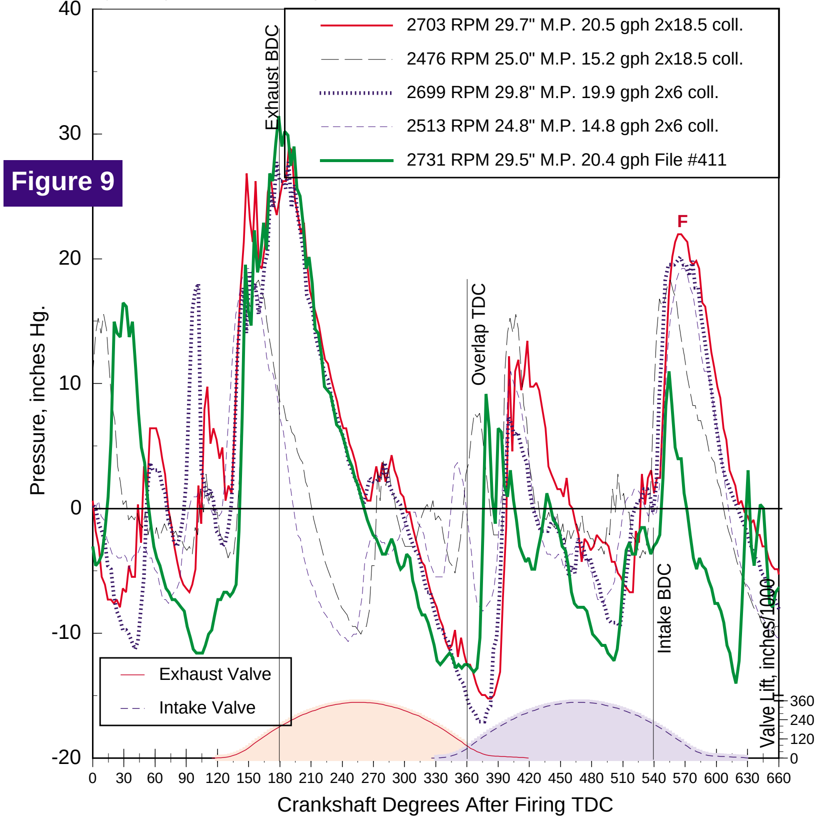
The other crossover system (File 511) was 1.75x34.5" headers pairing cylinder 1 with 2, and 3 with 4. Each of these pairs of cylinders fire 180° apart. See **Figure 8.**

The reflected waves from the blind leg are powerful and their effect on the P wave can be clearly seen here. In Figure 7, X_b marks the peak of the P wave's arrival in the 67" blind leg of file 729 in the simulation model. X_1 marks the ill-timed return point of that peak into the cylinder # 1 pressure trace. This ruins the tuning. N_b marks the trough in the 36.5" blind leg of file 731. N_1 shows this trough's return to the cylinder to help it develop a negative scavenging wave. This simulator lacks the influence of cyl #2's firings.

The crossover system showed better performance if the length from cylinder flange to tailpipe exit was 28" rather than 45".

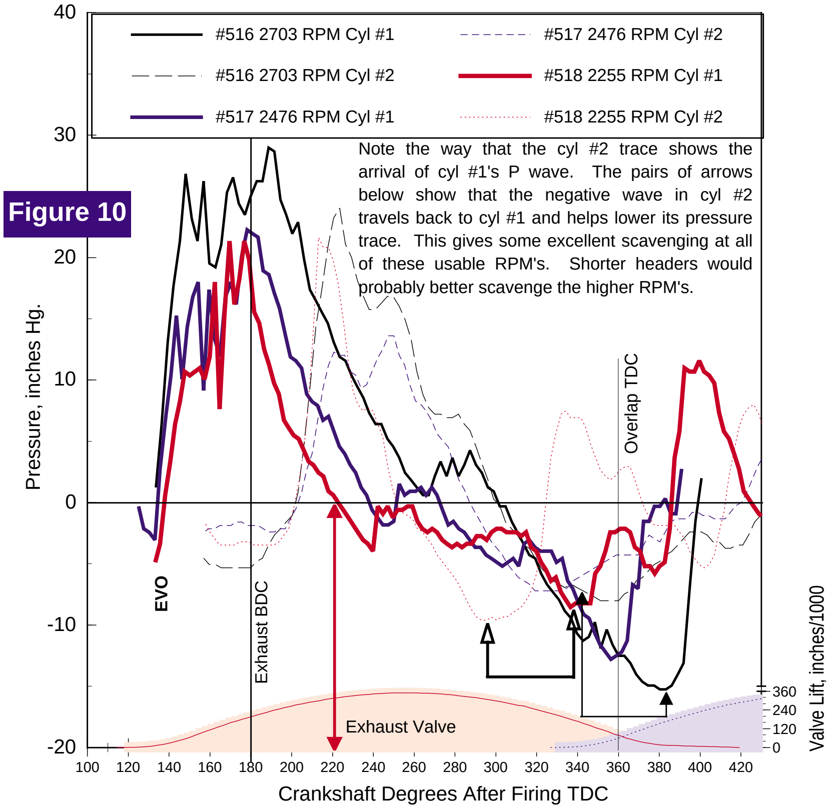
Files 516/517/601/603/411: Tri-Y system at differing RPM's. Headers are 1.75x34.5" into two separate 1.875"x18" intermediates which then merge into a single 2x18.5" collector for files 516/517 but into a 2x6" collector for files 601/603. Cylinders #1 and #2 are merged together as are cylinders #3 and #4. File #411 is a 4 into 1 collector system. 78°F. 8-24-96. Lycoming IO-360 A1B6 firing order: 1324 Run at 125' MSL.

Figure 9



Files 516/517/518 to compare a Tri-Y system at differing RPM's. All use the same equal length headers as: 1.75x34.5 with 1.875"x18" intermediates merging into a single 18.5x2" outlet. 78-79°F. 8-24-96. Lycoming IO-360 A1B6 firing order:1324 Run at 125' MSL.

Figure 10



Note the way that the cyl #2 trace shows the arrival of cyl #1's P wave. The pairs of arrows below show that the negative wave in cyl #2 travels back to cyl #1 and helps lower its pressure trace. This gives some excellent scavenging at all of these usable RPM's. Shorter headers would probably better scavenge the higher RPM's.

A commonly used, 'off-the-shelf' Lycoming crossover system has 1.75" O.D. headers wherein cylinders 1 and 2 are joined about 11" downstream of cylinder 2 and 33" downstream of cylinder 1. This makes a 44" "blind leg" or crossover length between those two cylinders. Cylinders 3 and 4 are similarly joined. These joined pipes then each exit through a 2.125"x16" long tailpipe.

The Tri-Y system in Figure 8 was 1.75x34.5" equal length headers which merged cylinders 1 with 2 and 3 with 4 into 1.875x18" intermediate pipes. The intermediates merged into a 2x18.5" collector.

In **Figure 9**, the Tri-Y showed a large amount (-15.0" Hg.) of suction during overlap, but this came at the sacrifice of both opening pressure and pumping gain relative to the green trace of file 411's 4 into 1 collector. At lower RPM, a large pumping gain appears but the scavenge is lost. At "F" on the graph, a large pressure trace arrives from cylinder # 2's P wave influence. It is the reflection of such large pressure waves that make the negative pressures so dramatic in the Tri-Y and crossover systems.

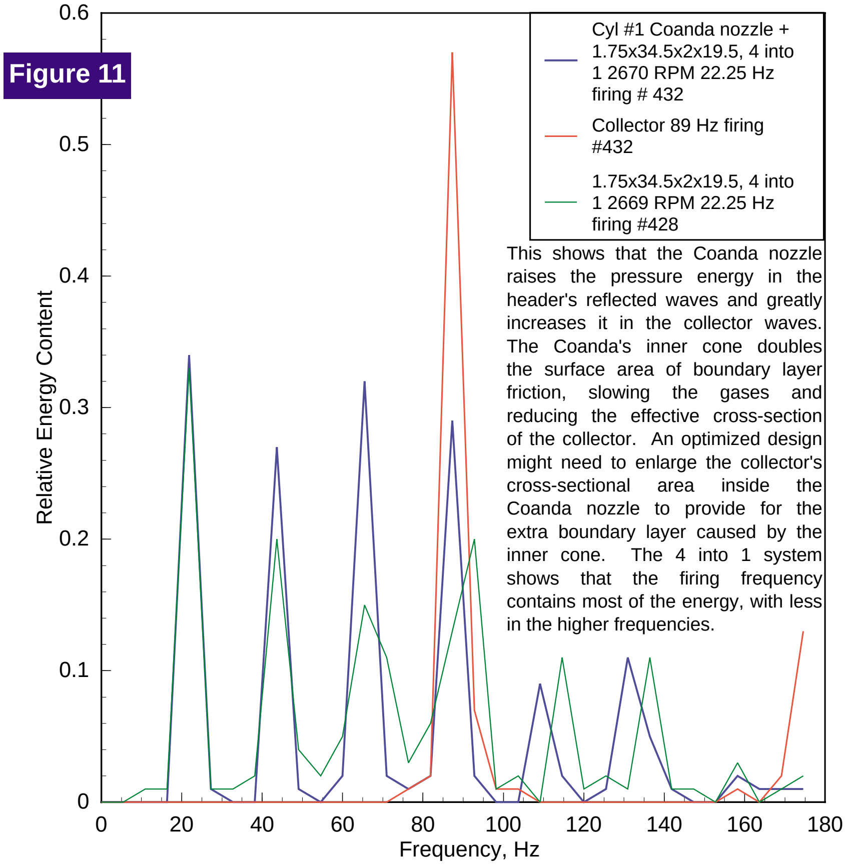
See **Figure 10.** This expanded scale graph shows how the negative waves in the blind leg of cylinder #2 return and reduce the pressure in cylinder #1's header. See the paired arrows. The red double-ended arrow shows the remarkably early onset of negative pressure at low RPM in this system. These primary header lengths (34.5") seem to be optimal for about 2500 RPM, judging by good pumping gain and scavenge of the blue trace on the graph.

The Tri-Y's wave timing is primarily controlled by the primary header length. The diameter and length of the common tailpipe seem to shift the entire pressure trace up or down as a unit. In other studies, increasing the length of the intermediate pipes beyond 18" seemed to raise the backpressure.

Crossover systems and Tri-Y systems are, in some ways, halfway between the independent pipe system and the collector system. They still exhibit higher opening pressures than the 4 into 1 collector systems, but they enjoy larger, longer duration negative waves after their P wave than do independent pipes. Tri-Y tuning is more critical than the 4 into 1 system as to

Figure 11

Files 432/428. Fast Fourier transform. (FFT) Interference seems to cause the higher frequencies to diverge even though the RPM's and firing frequencies were nearly identical.



This shows that the Coanda nozzle raises the pressure energy in the header's reflected waves and greatly increases it in the collector waves. The Coanda's inner cone doubles the surface area of boundary layer friction, slowing the gases and reducing the effective cross-section of the collector. An optimized design might need to enlarge the collector's cross-sectional area inside the Coanda nozzle to provide for the extra boundary layer caused by the inner cone. The 4 into 1 system shows that the firing frequency contains most of the energy, with less in the higher frequencies.

RPM .

FREQUENCY ANALYSIS

The fast Fourier transform shown in **Figure 11** is a way to depict the sound frequencies most prevalent in a given EPG. The 4 into 1 system shows the firing frequency. Interestingly, some of the systems peak at multiples of the firing frequency of the cylinder. A special type of loudspeaker might theoretically be used with a noise cancelling program (destructive interference) to nearly eliminate the exhaust noise by countering each of the main frequencies shown on the FFT.

COANDA NOZZLES

The Coanda nozzle is shown in the photo on the cover page. It consists of a megaphone inside which is placed a solid cone whose taper ratio produces no net change in cross-sectional area throughout the megaphone. The outlet of the Coanda nozzle has a sharply tapered trailing cone intended to produce a low pressure vortex. Theory has it that this vortex will reduce backpressure and give more horsepower.

The Coanda nozzle was added to both the 4 into 1 exhaust system and the Tri-Y system. See **Figure 12.** In both cases, no power gain was evident and the EPG did not show any striking change. The Coanda nozzle did seem to give some noise reduction and mellowing of the exhaust sound.

HEADER SIZE

See **Figure 13.** The optimum header size for this engine at 2500 to 2700 RPM, at sea level appears to be 1.75” diameter. The length of the headers in a 4 into 1 system seems optimized at about 28-36”. Longer length probably raises backpressure and delays onset of scavenging while shorter lengths reduce the ability to contain a fully developed, powerful wave.

LEAN vs RICH EPG’s

A richer mixture produces a lower EGT and thus a slower wave speed than does a lean mixture. Two EPG’s were run using 25” of manifold pressure and 2500 RPM wherein one used 15 gph and the other 11 gph. The P waves and scavenging were nearly identical but the opening pressure at EVO was lower for the rich mixture case. The FFT’s for these runs do show frequency changes, but the EPG’s look remarkably similar.

BALL JOINT EFFECTS

In the 2” collector tests (506,507) there was a very slight increase in backpressure when a ball joint was used, but no change in fuel flow, RPM or thrust was observed.

The P wave of the EPG was also unaffected by the addition of a 2.25” diameter ball joint 22” downstream of the collector merge when the total collector length was 43.75”. Two different ball joints were used. One (715) had a smooth internal wall and the other (717) had the more common internal concave chamber. The collector wave, recorded at a point 4” downstream of the ball joint, also showed essentially no change from either of the ball joints. When a megaphone was added to the straight collector, it showed a marked negative wave after the collector wave peak . Ball joints can probably be used for vibration isolation of the collector without detuning of the exhaust.

COLD VS. HOT

Two runs (701,703) were made with identical pipes (1.625x28x2.25x21.75) except that one was at 67° F OAT and the other at 80° F OAT. The RPM’s, fuel flows and P wave shape were nearly identical. The 80° F run showed slightly lower pressure at EVO (-9” Hg. vs. -6.5” Hg.) and overlap (-10” Hg. vs. -7” Hg.).

Two other runs (500,501) were made with identical pipes (1.75x34.5x2x20), one with 200° F CHT and the other with 400° F CHT. These showed no significant difference in the EPG.

MORE HORSEPOWER

Bruce Arrigoni, who has extensive experience in dyno race tuning of the Subaru engines with Formula Power in Concord, California, states that the single most effective way to increase the Subaru horsepower output was to smooth the sharp-edged transition of the exhaust valve's seat bevel cut where it blends into the valve's tulip portion. This apparently greatly improves the flow past the valve both at initial opening and during the small valve openings at overlap.

LENGTH FORMULAE

Most simple mathematical formulae for calculating the ideal length for exhaust pipes fail to recognize that there is a Doppler phenomenon occurring in an exhaust pipe because the sonic exhaust wave is riding on the "wind" of the streaming mass flow of fuel and air. The sonic wave moves at 1500-1800 fps while the mass flow moves at 200-400 fps. The sonic wave thus travels faster to the tailpipe than does the returning reflected sonic wave which must "swim upstream" to reach the exhaust valve.

Computer programs can address these complexities using what is called the "method of characteristics". One such program is Curt Leaverton's "Dynomation", available from V.P. Engineering, 5261 NW 114th St., Suite J, Grimes, IA. 50111. Ph. 515-276-0701

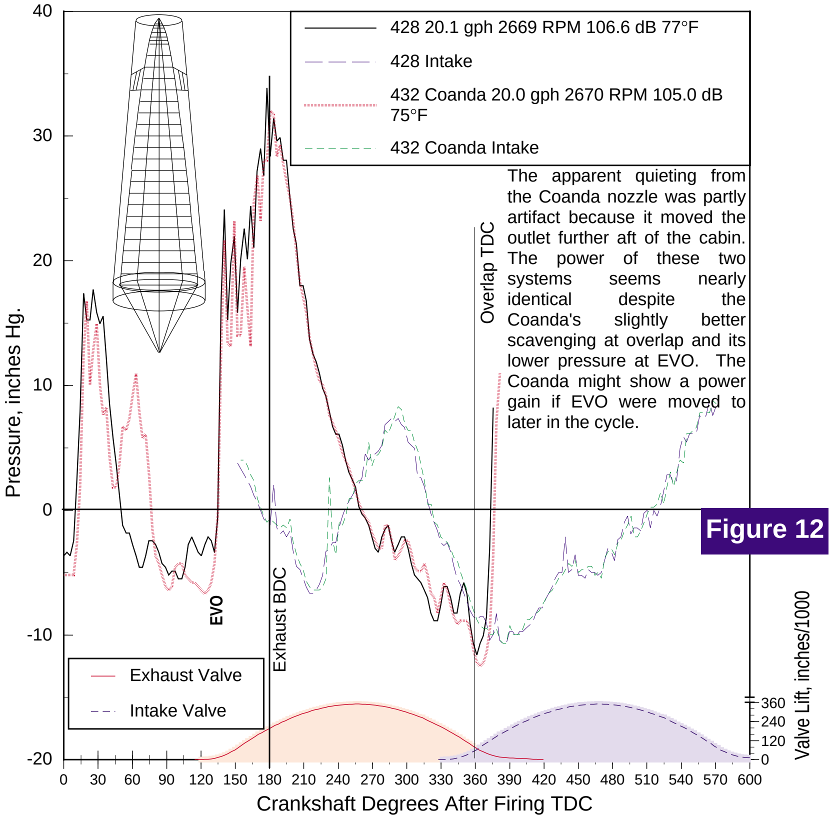
SIZING THE PIPES

It must be remembered that the 200 HP engine becomes a 130 HP engine at cruise altitudes of 8000-12,000 ft. Optimization of exhaust tuning at these altitudes, with the attendant reduced air density, will call for the use of smaller diameter headers and collectors. A compromise must be found to not rob the engine of its sea level climb power. A stainless steel multisegmented jet nozzle/megaphone whose outlet area could be adjusted for altitude could be worthwhile for optimizing both low and high altitude performance.

RECOMMENDATIONS

The 4 into 1 exhaust system (File 411) used on the CAFE testbed Mooney can be reproduced by Sam Davis at Tube Technologies in Corona, California as mandrel bent pipes requiring TIG welding to their exhaust flanges. Alternative designs can be made in mild steel from "U" bends and then sent to Sam for duplicating in 321 stainless steel. Aerospace Welders in Minneapolis, Minnesota can provide very high quality stainless steel collec-

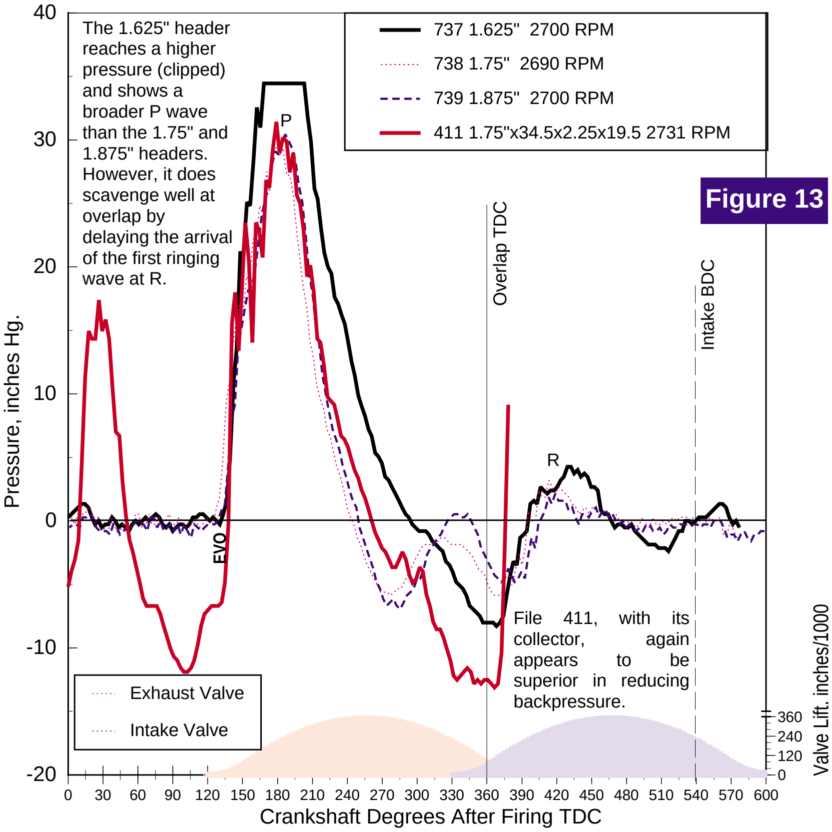
Files 428/432: 428 = 1.75x34.5x2x19.5. File 432 has a Coanda megaphone of 2x11x4 as drawn below added onto the 19.5" collector of file 428. Wind 3 mph in both runs. 8-18-96. Lycoming IO-360 A1B6 firing order:1324 Run at 125' MSL.



The apparent quieting from the Coanda nozzle was partly artifact because it moved the outlet further aft of the cabin. The power of these two systems seems nearly identical despite the Coanda's slightly better scavenging at overlap and its lower pressure at EVO. The Coanda might show a power gain if EVO were moved to later in the cycle.

Figure 12

Files 737/738/739/411 Comparing straight stacks of 35.25" using various header diameters to the collector equipped system #411. 96°F Lycoming IO-360 A1B6 firing order: 1324 at 125' MSL.



The 1.625" header reaches a higher pressure (clipped) and shows a broader P wave than the 1.75" and 1.875" headers. However, it does scavenge well at overlap by delaying the arrival of the first ringing wave at R.

File 411, with its collector, again appears to be superior in reducing backpressure.

Figure 13

EXHAUST JET THRUST

Figure 14 shows the results of measuring the pressure at the tailpipe exit with a pitot tube (total pressure). The pressure measured this way can be used to compute the jet thrust available from the exhaust. Several formulae can be used for this, however, they require several assumptions, which are listed in bold below:

$\rho_e = P/gRT_{abs}$

$\underline{\mathbf{M}} = (C/1728) \times (RPM/60) \times \rho_{sl} \times \eta_v$

$V = M/\rho_e A = (2q/\rho_e)^{1/2}$ where

V = ave. gas velocity at exit, ft/sec
$\underline{\mathbf{M}}$ = mass flow rate in slugs/sec
$A = (\pi(\text{tailpipe diameter}-2(w))^2/4)/144$
w = wall thickness

$q = 1/2 \times \rho_e \times V_p{}^2$ = pitot pressure at the tailpipe exit.

V_p = peak velocity derived from q.
$V = V_p \times .817$**
Thrust in pounds $= (\underline{\mathbf{W}} \times V)/g = \underline{\mathbf{M}} \times V$

A rough check can be made using the gph and air fuel ratio:

$\underline{\mathbf{W}}$ = lb/sec = (gphx6x**12**)/3600

**See reference 19. The .817 is derived from a complex analysis of these pipes' Reynold's numbers and boundary layer thickness.

ρ_{sl} = 0.0023769
ρ_e = exhaust gas density
q = dynamic pressure, psf
η_v = 0.95 = volumetric efficiency
A = pipe exit area, sq ft, excluding b.l.
b.l. = boundary layer
R = 54.0 = exhaust gas constant[8]
g = accel of gravity = 32.174 ft/sec^2
T_{abs} = 1760° R = exit temperature
P = 2116 psf = sea level pressure
6 = pounds per gallon of avgas
12 = 1 + air fuel ratio of 11 to 1 (rich)
3600 = seconds per hour
1728 = cubic inches per cubic foot
C = 180 cubic inches = effective full time engine displacement

Using these formulae and 20.2 gph at 2685 RPM with 2.25 psi outlet pressure, (**Figure 14**), a peak exhaust jet thrust of about 10-12 pounds is found at wide open throttle with a 2" tailpipe. The 1.5" tailpipe nozzle gives 17-21 pounds of thrust. Simultaneous solution of these equations can be used to find the unknown values.

The ambient pressure will determine the exhaust gas density upon exit and thus the exit velocity. The low ambient pressure at 10,000-14,000' would give an increase in exhaust thrust, especially with turbocharging, which maintains a higher exhaust mass flow at those altitudes.[6]

Files 438/439/440/505 Average exhaust jet thrust variation with RPM and fuel flow. All are the same 4 into 1, equal length headers: 1.75x34.5 with 2x19.5" collector, except 505 which uses a 1.5" nozzle outlet on a 2x29" collector. 72-74°F. 8-18-96. Lycoming IO-360 A1B6 firing order: 1324 Run at 125' MSL. A collector exit pitot probe was used here.

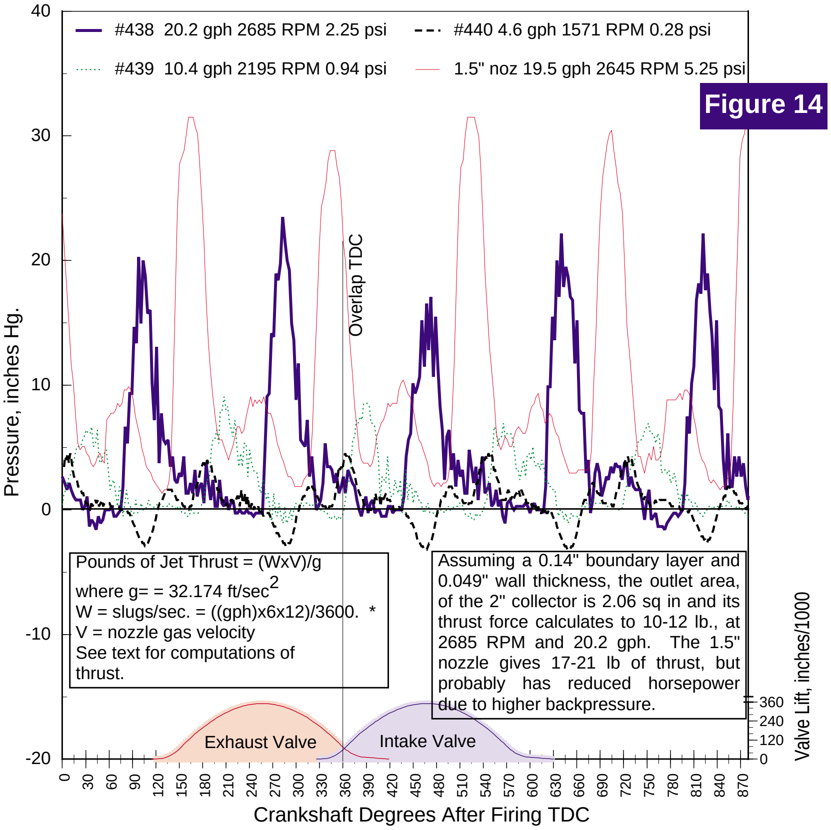


Figure 14

Pounds of Jet Thrust = (WxV)/g
where g= = 32.174 ft/sec^2
W = slugs/sec. = ((gph)x6x12)/3600. *
V = nozzle gas velocity
See text for computations of thrust.

Assuming a 0.14" boundary layer and 0.049" wall thickness, the outlet area, of the 2" collector is 2.06 sq in and its thrust force calculates to 10-12 lb., at 2685 RPM and 20.2 gph. The 1.5" nozzle gives 17-21 lb of thrust, but probably has reduced horsepower due to higher backpressure.

*Fuel = 6 lb/gal and air/fuel ratio is 11, giving the 6 and 12 above.

tors and merges for any desired system. All systems must include slip joints or ball joints for strain relief placed both at the mouth of the collector entry as well as about half way down the headers The joints must always be secured with redundant spanning bolts, compression springs and cotter pinned castle nuts.

CONCLUSIONS

1. Substantial negative pressure waves can be generated in tuned aircraft exhaust systems and the timing of their suction can be arranged so as to improve engine power. Such improvement should produce more power, better efficiency and a cleaner combustion chamber.

2. The 4 into 1 collector exhaust systems appear to offer the best combination of low opening pressure, some pumping gain and good scavenging, though the crossover and Tri-Y systems can also obtain good scavenging during the overlap stroke.

3. The addition of a suitable megaphone to the collector of a 4 into 1 exhaust system usually produces an increase in the negative pressure achieved at the exhaust valve, but at a substantial penalty in noise.

4. The use of swiveling ball joints on the collector of a 4 into 1 exhaust system has a neglible effect on the EPG and provides an important vibration-isolation benefit to the system.

5. The optimization of pipe geometry for the crossover, Tri-Y and 4 into 1 exhaust systems can be found by study of the EPG.

6. Fast Fourier transforms, derived from the EPG, could facilitate the development of an electronic, active noise-cancelling muffler. Aircraft exhaust systems, by their limited RPM range, are particularly well-suited to such a muffler.

7. The Coanda nozzle did not produce a noticeable increase in power. Fabrication and durability problems make this nozzle of limited attractiveness.[11]

8. Exhaust jet thrust was measured and calculated for several exit sizes, RPM's and fuel flows. It can produce significant thrust at high power settings, especially at cruising altitudes.[6]

9. The stock camshaft used in an aircraft engine is typically optimized for reliability and tractability and is not optimized for the tuned exhaust systems tested here. To fully realize the potential benefits of a tuned exhaust system, the camshaft timing must be suitably altered by making exhaust valve closure occur later and the overlap period of longer duration and higher lift.[12] Many of the scavenging systems here do not exhibit as much effect upon the intake manifold pressure during the overlap as might occur if the camshaft had greater valve overlap.

10. Further study should include the correlation of climb and cruise airspeeds with EPG's taken in flights which are controlled for power setting and aircraft weight. These should be performed using exhaust jet nozzles, megaphones, altered ignition timing, higher compression pistons, and, if possible, altered valve timing.◆

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IMPORTANT NOTICE

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