

Sponsored and Funded by the Experimental Aircraft Association
and the Federal Aviation Administration

EPG II

BY BRIEN A. SEELEY AND ED VETTER

TRIAVIATHON
TROPHY**CAFE
FOUNDATION**PRESIDENT
Brien SeeleyVICE
PRESIDENT
Larry FordTREASURER
C.J. StephensSECRETARY
Cris HawkinsTEST PILOT
C.J. StephensDIRECTORS
Frank Braal
Crandon Elmer
Otis Holt
Jack Norris
Stephen Williams
Ed Vetter**CHALLENGE
TROPHY**

The method of studying exhaust system design using the EPG (exhaust pressure graph) was described in the January 1996 issue of *Sport Aviation* in the first part of this series of articles. In this Part II report, we will focus on some comparative results obtained from the hundreds of test runs made at the CAFE Foundation test facility. Primary header pipe length and diameter, collector length and diameter, a stock muffled system, a "Tri-Y" crossover system and a look at exhaust wave behavior will be included here.

METHODS

The system used to obtain the data presented here was described in the Part I article. Some of these EPG's were created by combining the data recorded on separate full throttle runs of similar RPM.

To eliminate any fluctuations in static RPM which we thought might be caused by the prop governor, we converted the constant speed propeller on the test engine to a fixed pitch configuration. After doing so, we continued to witness the same fluctuations during full throttle static RPM tests. We then realized that even mildly different wind vectors into the propeller disc area were the source of these fluctuations. We obtained a wind velocity and direction indicator to attempt to control for this variable. The best method, however, is to perform the EPG testing in dead calm air, and the results presented here were selected for such test conditions.

Soft silicone fuel hose of 3/16" diameter O.D. x 4" long attached the pressure transducers to the 1/8" x 18" copper tube sampling ports which are clamped onto the exhaust pipes. These soft tubes probably serve as filtering "balloons," absorbing some resonance and noise in the sampling ports.

To maintain an accurate zero reference, all of these recordings were made by testing the pressure readings from each transducer before starting the engine.

Representative EPG data can be captured in just 10 seconds of run time so that the full power runs can be brief. However, the engine was allowed to warm up before taking the data. The capture is made only after the full, stable static RPM has been reached. This typically requires about 10 seconds and allows the prop to induce its own stable inflow field.

The lengths of pipe cited here are the center-line length of the pipe. Collector lengths cited are the length of the constant diameter portion of the collector, excluding the merge zone. The merge zone was 4"-5" long for most collectors. To afford adequate ground clearance, all collectors used except file 009 included a 90° bend in their constant diameter portion about 2" beyond the end of the merge zone. The sampling port for collector pressure was consistently placed 10.5" downstream from the end of the merge zone.

THEORY

The most important moment for achieving low backpressure is during overlap TDC when both intake and exhaust valves are open. Exhaust systems which achieve this, though they may have high backpressures during other parts of their EPG, can show more horsepower than systems having lower overall average backpressures. In the EPG's presented here, special attention should be given to the P wave amplitude as it crosses the overlap TDC mark.

Also important is the backpressure at the moment the exhaust valve opens, the very beginning of the P wave. The lower this pressure, the more readily the "slug" of exhaust gas jumps out of the combustion chamber.

HEADER LENGTH

Figure 1 shows the results obtained when the length of all 4 header pipes was varied from 36" to 42". Changing the length within this range did not make much difference in backpressure. A more prominent change is observed by holding the header length constant and substantially lengthening the collector pipe. All of the 4 into 1 collector exhaust designs used in Figure 1 consistently produced higher static RPM and fuel flow levels, implying more horsepower, than the independent headers with no collector shown in Figure 2. The systems in Figure 1 showed lower average backpressures than the one in Figure 2.

Note that the R (reflected) waves are prominent in Figure 1 regardless of pipe length. The energy of these waves is the source for some of the backpressure reduction achieved in these systems.

HEADER DIAMETER

Figure 2 shows, as might have been predicted, that the fattest header pipe demonstrates the lowest backpressure.

Figure 2 also shows very small R waves, seen on each trace's down-slope. These represent the return waves from the open end of the pipe, unamplified by the other cylinder exhaust pulses. The lack of energy in these R waves casts some doubt on whether adjusting the lengths of independent pipes can produce enough wave tuning to lower the backpressure. It may be that much longer lengths are needed than those tested here, but such long pipes become unworkable in aircraft applications.

None of the independent pipes in Figure 2 ever achieves a sub-zero or negative backpressure. In many other EPGs, the addition of a collector to independent pipes was repeatedly found to lower the backpressure. The addition of a collector also tends to reduce noise compared to independent header pipe systems. However, collectors create problems in bulk, weight and space requirements. They also must be carefully suspended and vibration-isolated from the engine.

A comparison of the climb and cruise performance of an aircraft using independent pipes versus one with

Files 125, 127, 129, 131. 1.625" diameter equal length headers. Lengths as shown. 2.5" x 13.25" collector unless otherwise specified. All traces from cylinder # 1's transducer. 2664-2680 RPM/29.0" M.P./19.6-19.9 gph/87°F. Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

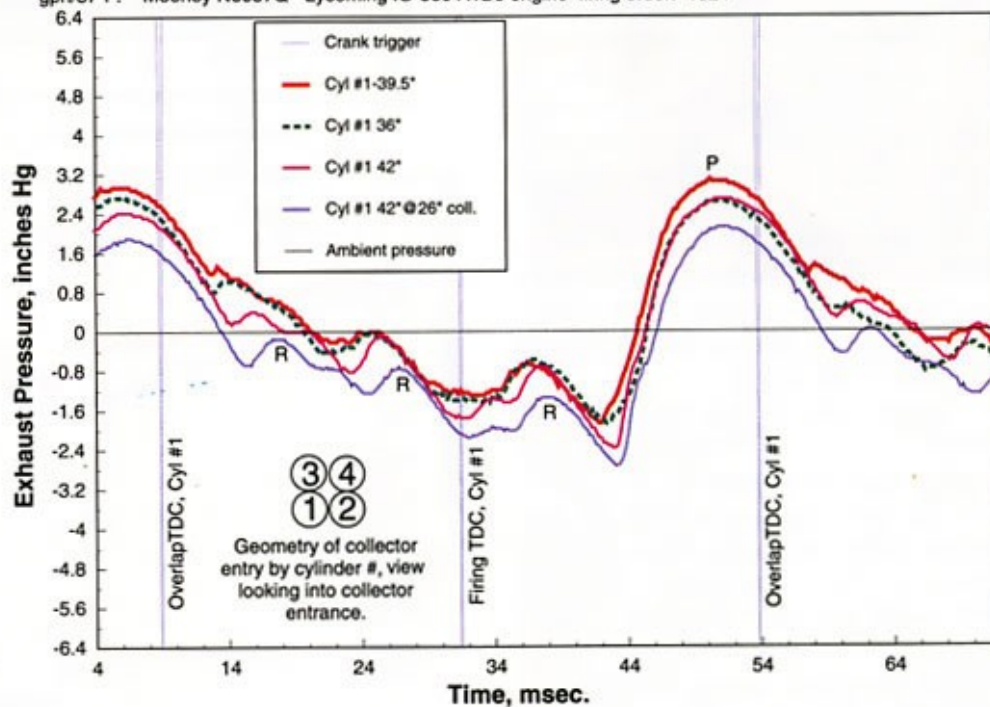


Figure 1.

those same pipes coupled to a collector is planned for a future study by the CAFE Foundation.

R waves in the top trace is unusual and indicates some interference.

COLLECTOR DIAMETER

Figure 3 shows that the effect of substituting a larger diameter collector is to lower the backpressure and to increase the power produced. The presence of four rather than the usual three separate

COLLECTOR LENGTH

Figure 4 shows a the EPG's obtained from collectors of different lengths (see photo). All collectors were of 2.5" diameter and had a 5" long parallel merge zone. A pyramid shaped "goilet" spike¹ was present inside the

File 166. Varied header diameters, each header 36" long with 2 ea. 90° bends of 2.5" radius except cyl. # 3 with 2 ea. 90° bends of 3.0" radius; no collector. 2624 RPM/18.9 gph/59°F. Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

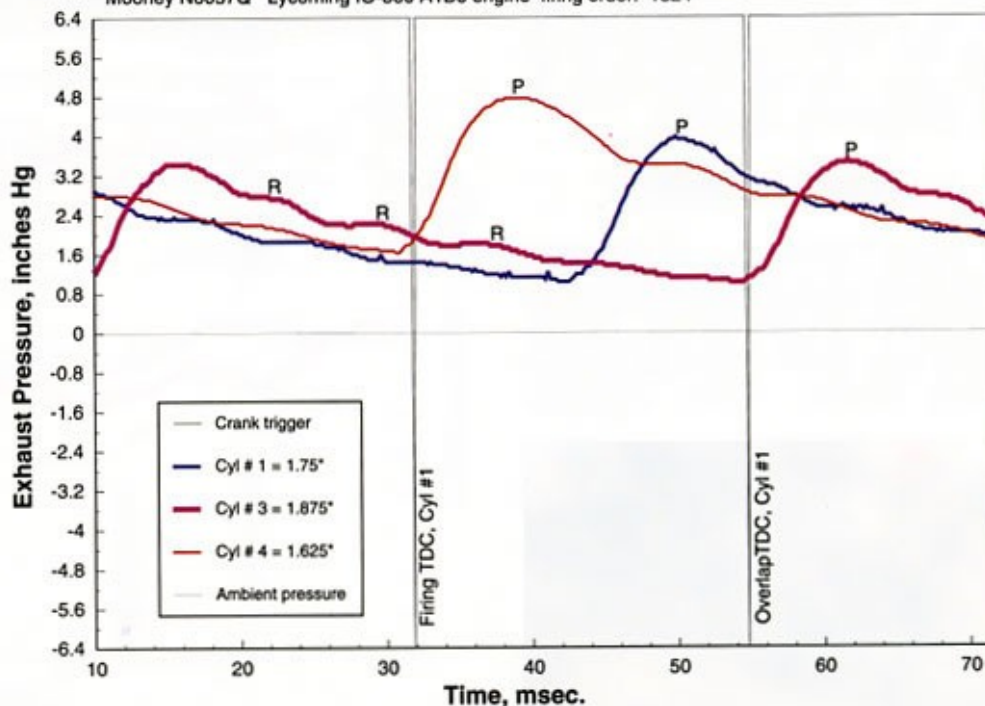


Figure 2.

merge zone to smooth the transition from header to collector. The CAFE Foundation has learned that the internal details of the collector merge are very important in the performance of the system.² The goal here is to avoid any abrupt increase in cross-sectional area as the header transitions into the collector.

In most cases, the change in collector length was accomplished by simply hacksawing off a portion of the collector, making no change in the detailed anatomy of the merge.

Figure 4 shows that the 26.5" collector gave lower backpressure and higher static RPM than the 14" collector. The pressure traces from the collector sampling ports show that the shorter collector has exhaust pulses of low amplitude, approximating ambient pressure. The longer collector's trace shows repeating waves, labeled "C", indicating the preservation of the energy of each cylinder's exhaust pulse. These C waves are reflected into the header to produce the R waves shown.

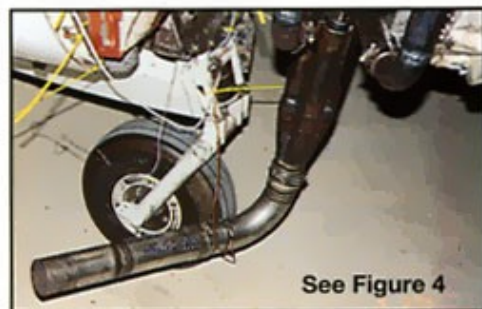
In our tests, increasing the collector length beyond about 36" only seemed to increase the backpressure.

The addition of a megaphone to the collector was more beneficial in reducing backpressure than was a change within collector length alone. This has been a consistent finding in our tests of the 4 into 1 exhaust systems.

The relative trend of increased noise as the collector length was shortened was not surprising. The noise quality was markedly changed by the addition of the megaphone to the collector, being more objectionable even though the sound meter indicated relatively little change in the noise level.

WAVE VELOCITY

Figure 5 shows the very high velocity of the pressure wave traveling down the header into the collector. The collector trace shows a pulse for each and every cylinder's firing, and those



See Figure 4

Files 242, 143, 228. Varied collector diameter, 1.625"x 34-36" headers, all traces from cyl #1. 1 ea. 90° bend of 2.5" radius in collector and 2 ea. 90° bends in each header. All runs at full throttle with RPM, fuel flow, and noise levels as shown. 120° elevation/75-84°F. Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

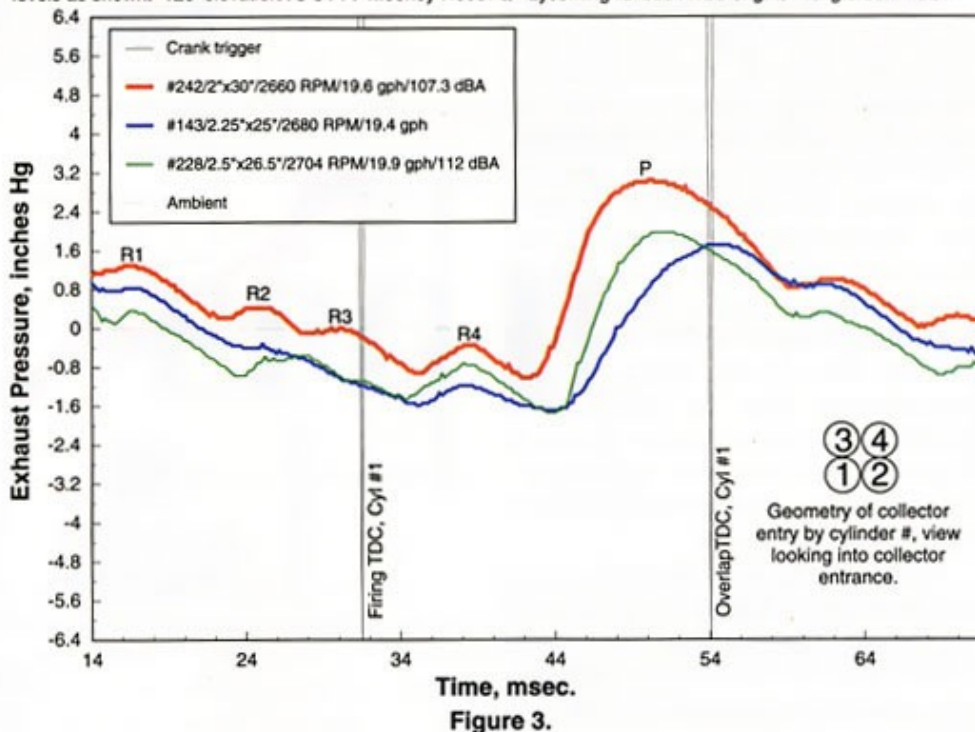


Figure 3.

pulses can be seen to quickly reflect back up into the header trace. The wave velocity measured here traveled 24.6" in 1.43 msec. This would be 1433 fps in the header primary. If we use the collector arrival time, the computation is 49.4" in 3.04 msec giving a speed of 1354 fps. The wave velocity slows as the gas cools enroute, so that the speed measured would be reduced by longer headers, a fatter collector or

a sampling port further downstream on the collector.

A STOCK MUFFLER

Figure 6 shows the EPG's of an all stainless steel system of the type commonly used in production aircraft. It incorporates four 1.75" diameter x .035" wall header pipes of 22.5"-23.5" length converging into a 5"

Files 228, 232, 236. Varied collector length, 1.625"x 36" headers, 2.5" diameter collectors. Meg = 7.75" x 3.75" outlet. Probes in both cyl #1 and collector. 1 ea. 90° bend of 3.0" radius in collector and 2 ea. 90° bends in each header. Full throttle/72-67°F. Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

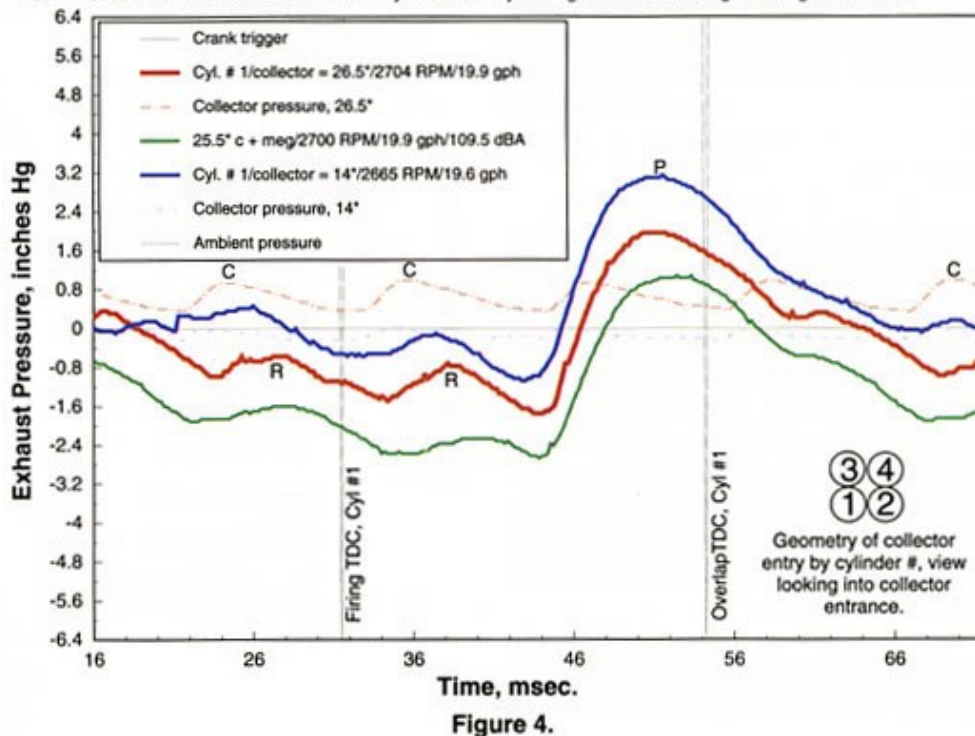


Figure 4.

File 009. 2" x 33" collector with 5.5"L parallel merge (38.5" total) with 1.75" x 43.75" equal length tortuous headers. No megaphone. 3 separate probes spaced as shown. 2704 RPM/29.3" M.P./19.2 gph/76°F. Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

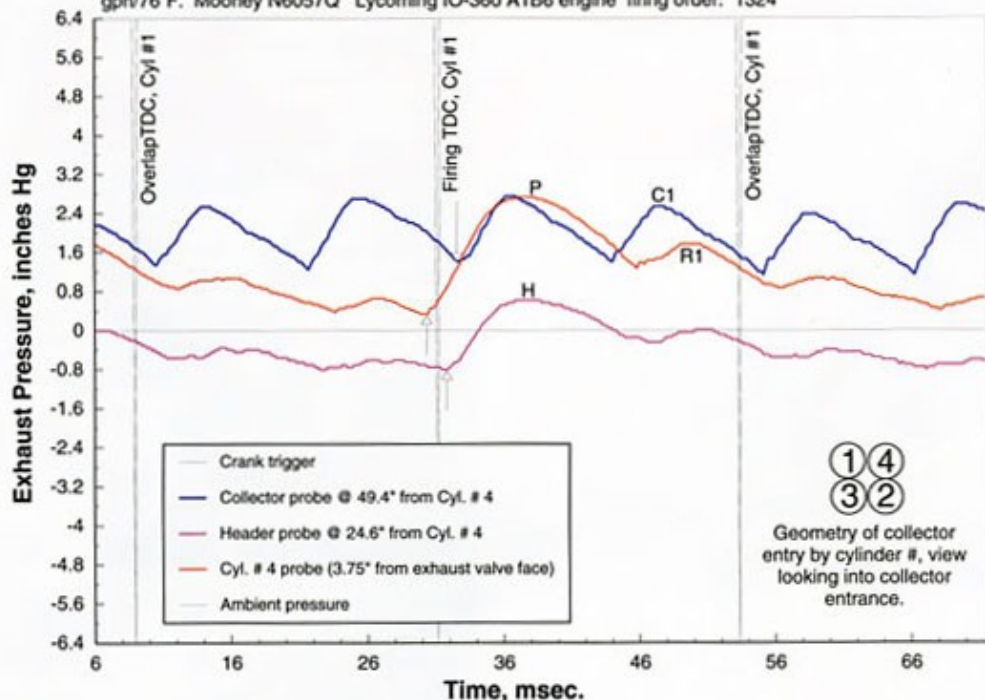


Figure 5.

diameter by 10" long cylindrical muffler can. The 3" diameter tailpipe exits the can at an approximately 30° angle and includes one 70° bend along its 24" length. (see the adjacent photo). The two most striking findings in Figure 6 were the consistently high backpressure and the large amount of "cross-talk" detected in each pipe. The small muffler can's lack of plenum effect probably accounts for

the high level of cross-talk observed. It is presumed that the cross-talk produces chaotic destructive interference in the wave energy and this would be expected to quiet the exhaust. However, this interference also robs wave energy which could be used to reduce back pressure.

There was a significant reduction in full throttle static RPM and fuel flow with this muffler. Most surprising of

all was the relatively loud 110.6 dBA cabin noise level recorded during this run, which is not significantly quieter than systems where a non-muffled collector was used.

This stock muffler system appears to actually exceed the 2" Hg. average backpressure required by the FAA certification standard. One SAE study³ states: "There is a 1% power loss for each 1" Hg increase in exhaust backpressure." If this holds true, then about 7% more horsepower can be obtained over the stock muffler system by using the best tuned system thus far tested here. That equates to 14 bhp.

TRI-Y SYSTEM

The "Tri-Y" exhaust system is one in which the four individual primary header pipes merge into two secondary pipes which, in turn, merge into one tertiary common collector. It has been postulated that this system can produce a substantial reduction in backpressure if the 4 into 2 merge is made by joining headers from cylinders whose firings occur 360 crank degrees apart. The exhaust pulse or "P" wave in one header would presumably "crossover" and travel up the paired header pipe and reflect off of the closed exhaust valve of that cylinder. The resulting reflected negative wave would then, presumably, travel back upstream to the original cylinder and deliver suction to that cylinder at just the right time during its overlap stroke. This theory is the basis of the commonly used "crossover exhaust

File 163. Stock Mooney Muffler: 4 ea. 1.75" x 23" x .035" wall ss headers into a muffler can of 5" diameter x 10" L, with a 3" x 24" tailpipe with 1 ea. 70° bend of 4.0" radius. Approx. 2620 RPM/29.2" M.P./18.7 gph/59°F. Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

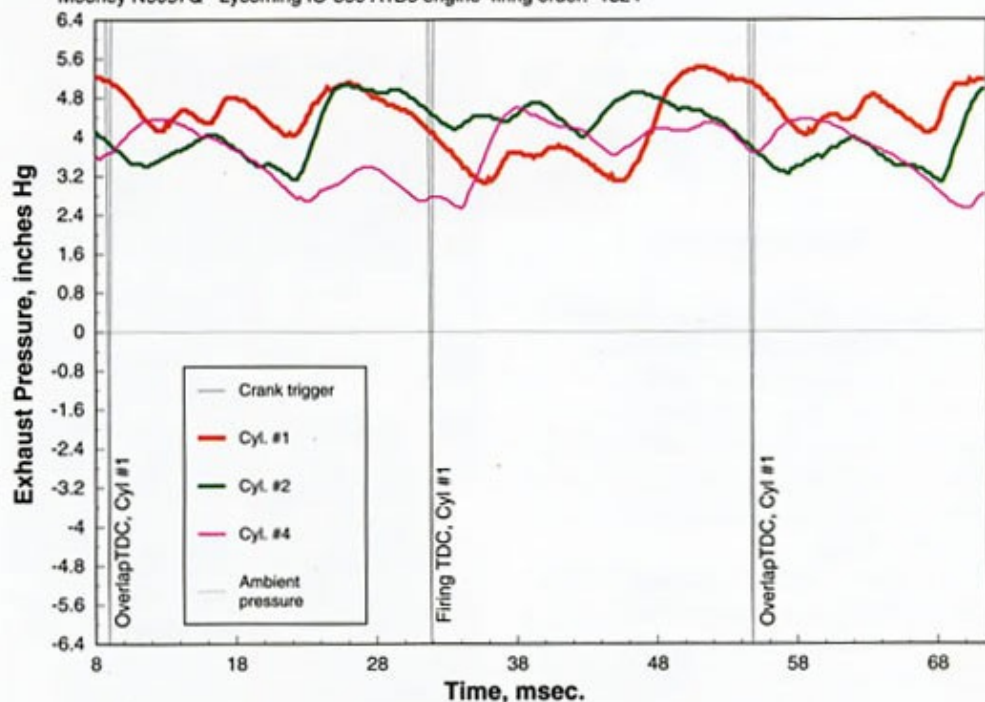


Figure 6.



Files 256, 258. Tri-Y system: 4 equal length primaries of 1.625" x 34-37" into 2 secondaries of 1.75" x 24", then into 1 tertiary of 2.25" x 12.5". Megaphone is 10"L x 4" outlet. Cyl # 1 and 2 are paired, as are 3 and 4. All traces from cyl # 1. 84°F. Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

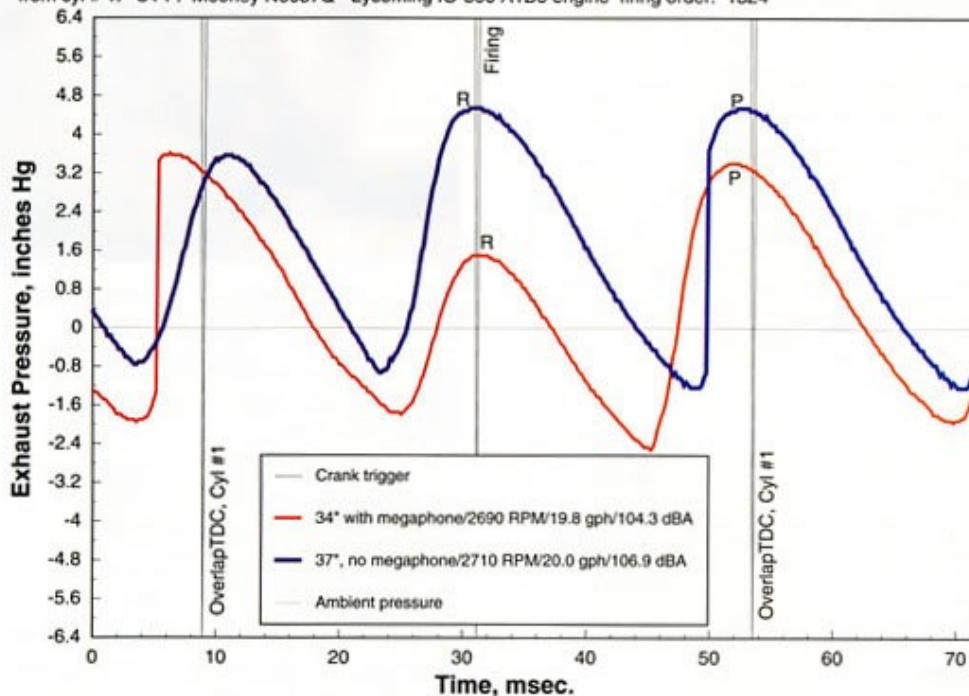


Figure 7.

system" popular on many homebuilt aircraft and is heavily based upon the "sonic" or wave theory of exhaust system behavior.

The Tri-Y system shown in the adjacent photo produced the EPG shown in Figure 7. There is some negative back pressure occurring during the early part of the exhaust stroke. The very large R waves come mainly from the exhaust of the paired cylinder. At the header wave velocity derived from Figure 5, and the Tri-Y's 37" primaries, calculation predicts that cylinder #1's P wave would bounce off of cylinder #2's closed exhaust valve and return in 8.6 milliseconds. At 2700 RPM, the IO-360 exhaust valve stays open for 15 milliseconds. A key unknown is the duration of the negative wave influence at the valve, i.e., its wave length.

Because the RPM and fuel flow level of the Tri-Y system shows some promise for improved horsepower, the CAFE Foundation plans extensive further EPG testing to find the optimum combination of diameters, and lengths for primary, secondary and tertiary pipes in the Tri-Y system.

SHARE YOUR IDEAS

A number of very knowledgeable EAAs have written and emailed further information to the CAFE Foundation

about exhaust systems. We welcome this input and look forward to much more in the future.

A word about noise: the CAFE Foundation EPG study is focusing on reductions in backpressure as the main goal, since this is the path to the highest efficiency.³ We feel that once we have matured our understanding of how to reduce backpressure, then we can "trade away" some backpressure by adding noise reducing components to the exhaust.

In our Part I article, the EPG in Figure 2 showed a persistently sub-zero backpressure, causing some readers to question whether that is possible. We are investigating this promising finding and will attempt to include those results in our Part III article.

Bibliography

1. Seeley, Brien, Tuned Aircraft Exhaust Systems, *Sport Aviation*, Vol. 39, No. 11, November, 1980.
2. Schalk, Paul, personal communication. Ricardo North America. Engineer experienced in OEM automotive exhaust design by flow bench. Phone 313-397-6666.
3. Adams, Tim G., Effect of Exhaust System Design on Engine Performance. SAE Technical Paper Series. Paper #800319, presented at Cobo Hall, Detroit, February 25-29, 1980. ♦

IMPORTANT NOTICE

Every effort has been made to obtain the most accurate information possible. The data are presented as measured and are subject to errors from a variety of sources. Any reproduction, sale, republication, or other use of the whole or any part of this report without the express written consent of the Experimental Aircraft Association and the CAFE Foundation is strictly prohibited. Reprints of this report may be obtained by writing to: EAA, *Sport Aviation*, P.O. Box 3086, Oshkosh, WI, 54903-3086.

ACKNOWLEDGEMENTS

This work was supported in part by FAA Research Grant Number 95-G-037. The CAFE Foundation gratefully acknowledges the assistance of Anne Seeley, Mary Vetter, EAA Chapter 124, the Sonoma County Airport FAA Control Tower Staff, and several helpful people in the engineering department at Avco-Lycoming, Hartzell Propellers, and John Schwaner at Sacramento Sky Ranch.

SPONSORS

Experimental Aircraft Association
Federal Aviation Administration
Aircraft Spruce & Specialty Co.
Fluke Corporation
B & C Specialty Company
Engineered Software "PowerDraw"
Bourns & Son Signs
Johnny Franklin's Muffler Shop
Sam Davis at Tube Technologies
Sani-Fit
Factory Pipes

COMPARATIVE AIRCRAFT FLIGHT EFFICIENCY, INC.

The CAFE Foundation:
A Non Profit, All Volunteer,
Tax-exempt Educational
Foundation
4370 Raymonde Way, Santa
Rosa, CA 95404.
707-526-3925 FAX 544-2734
Aircraft Performance Evaluation
Center: 707-545-CAFE
(hangar, message)
America Online:
CAFE400@aol.com
Internet: CAFE400@sonic.net