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Cleveland, Ohio 44135

Technical Support Package

Improved Mufflers for General Aviation

NASA Tech Briefs
LEW-16324

National Aeronautics and
Space Administration

Technical Support Package

for

IMPROVED MUFFLERS FOR GENERAL AVIATION
LEW-16324

NASA Tech Briefs

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Improved Mufflers for General Aviation

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1. INTRODUCTION

This project identified key issues in the silencing of general-aviation aircraft, provided a baseline theoretical approach for the design and optimization of aircraft-engine exhaust systems, evaluated conceptual dissipative, resistive, ant reactive muffler/exhaust system designs, and conducted insertion-loss measurements on prototype designs to demonstrate feasibility. The technical approach was based on the use of a newly available broadband adsorber material, silicon carbide (SIC) foam, in a series of dissipative and resistive muffler designs in combination with reactive elements to maximize noise reduction and minimize engine losses (backpressure). Excerpts of the project are included in this report. A copy of the report in its entirety is available through lerc@cto.nasa.gov.

A theoretical approach and appropriate analysis tools were developed and confirmed through experiments to predict the acoustic properties of the absorber materials, predict engine-noise characteristics and required muffler acoustic performance to meet noise regulations, develop and predict insertion losses for dissipative, resistive, and reactive muffler designs, and finally predict exhaust-system mechanical performance (backpressure). Experimentally, absorber acoustic properties (flow resistance and impedance) were measured as a function of material properties and compared to predicted analytical results to determine empirical parameters (such as structural factor). The noise characteristics of 200-in.^{3} and 320-in.^{3} 4-cylinder general-aviation engines (the Continental 0-200 and Lycoming 0-320 engines, respectively) were characterized and compared to the analytical/predictive results used for muffler system design. Finally, a series of 17 muffler designs were fabricated, installed on McCulloch Autogyro (3 designs) and Cessna 150 aircraft (14 designs), and the muffler insertion-loss characteristics measured.

Because of the backpressure sensitivity of air-cooled aviation engines, as well as muffler size and weight limitations, it was determined that automotive type muffler designs are not applicable to general-aviation engine noise reduction, and that new, innovative muffler designs are required for this application. It was demonstrated that engine noise dominates overall aircraft noise for general-aviation engines under 250 horsepower, and that muffler additions can reduce overall aircraft noise by some 36 dB (to below 100 dB). Due to system complexity and time limitations, a final flightweight design was not constructed during the Phase I project. It was determined, however, that combined dissipative/reactive muffler designs are capable of, and will be required for, meeting the noise, size, weight, and performance requirements of general aviation due to the low frequency of the sound generated and the small muffler size required for engine retrofitting. An additional advantage of these muffler designs is that they are also highly suitable for pollution reduction (catalytic conversion) in addition to noise reduction, a unique feature of the combined dissipative/reactive design.

2. BACKGROUND

2.1 GENERAL-AVIATION AIRCRAFT NOISE REDUCTION

Aircraft noise has been a source of dissatisfaction since airplanes were invented, often pitting the rights of landowners and the general populace against the right of free travel by aircraft. This battle was largely won by the aircraft industry when the Judicial system set an easement for flight above 5,000 feet, but remains a bone of contention in areas around airports under the takeoff and landing paths of aircraft. In addition to presenting a nuisance (and therefore grounds for action) to the property owners around airports, reduction of aircraft noise is also important in terms of passenger comfort (noise, vibration, and harshness) and ground crew safety, as well as compliance with increasingly strict noise standards in and around airports (e.g., FAR Part 36 Stage III regulations).

The noise limits specified in FAR Part 36 are the technologically practicable and economically reasonable limits of aircraft noise-reduction technology at the time of certification. The majority of reciprocating engine aircraft now flying did not require strict adherence to Part 36 because they were certified in the 1950s, 1960s, and 1970s. However, most changes to the original certificate (supplemental type certificate) require adherence to the newer, more stringent requirements.

General-aviation aircraft in Europe are presently taxed based on the noise they generate on takeoff and landing, which has resulted in the virtual grounding of the European general-aviation fleet. Exhaust systems in Europe have evolved into automobile-type systems running the entire length of the fuselage, resulting in excessive cost, weight, and structural requirements. The U.S. certified aircraft exhaust system used today, meanwhile, is the same system as that used on aircraft that were certified in the 1940s, consisting of risers made with stainless steel tubing and mufflers with simple cone diffusers.

The majority of aircraft noise in the general-aviation class arises from the propeller and the engine exhaust, with the relative importance of each source dependent on the engine size (horsepower) and propeller characteristics (number of blades, disk area and disk loading, aerodynamic efficiency, and tip speed). For most aircraft with powerplants less than 250-300 hp, a range which comprises the vast majority of general-aviation aircraft, engine noise is equivalent to or exceeds propeller noise and must be decreased to significantly reduce aircraft noise and come into compliance with current aircraft noise regulations in order to recertify an aircraft.

While the noise problem is not as great for smaller, lighter aircraft (noise levels rise roughly with horsepower squared) as for commuter, business, and commercial aircraft, the number of flights (takeoffs and landings) and the number of aircraft in the general-aviation category are substantially higher than those of all other categories combined. Therefore, while the smaller, lower horsepower general-aviation aircraft may not generate as much noise as larger aircraft, they are generally "heard" more often by the public because of their lower flight altitudes and slower climb speeds, and greater number of takeoffs and landings.

A typical general-aviation aircraft engine generates between 120 and 150 dB of noise through the combination of engine and propeller noise. This level severely exceeds OSHA standards for limited duration exposure and creates a substantial nuisance in and around airports, in addition to presenting a health hazard to pilots, mechanics, and crew working in and around these aircraft. This noise level, which is similar in magnitude to unmuffled automotive and other transportation engines, has required the addition of acoustic filters (mufflers) to reduce noise impact in the community surrounding the airport. This trend is being extended to general-aviation aircraft, to which typical public response has long been to place restrictions (in terms of monetary costs, fines, flight limitations, flight-path restrictions, and even grounding) on the general-aviation community. Tremendous effort, time, and expense have been directed at reducing noise from commercial, business, and short-haul commuter aircraft; however, almost no effort has been expended to reduce noise from the smaller general-aviation aircraft, with the exception of cockpit and cabin noise reduction efforts conducted by the major airframe manufacturers.

Based on current community noise levels and the increasing encroachment of residential areas on airports serving the general-aviation community, aircraft takeoff and landing noise emissions must be reduced. In fact, several locations around large metropolitan areas and heavy-use areas such as the Grand Canyon are imposing local noise standards that are more strict than the federally mandated levels, potentially grounding many general-aviation aircraft and generating increased friction between the public and the aviation community. For many of these aircraft, exhaust-borne engine noise is the dominant contributor to overall aircraft noise, being more significant than other sources including propeller noise and wind noise, especially during takeoff and landing at maximum power.

Engine noise reduction through the use of acoustic filters or mufflers presents an extremely difficult problem, however, that cannot be solved by the simple solution of applying automotive or diesel-type muffler systems due to backpressure, volume, weight, and size constraints that are much more critical for aircraft application. Because of the low frequencies which must be silenced (typically 50-150 Hz primary frequencies), conventional mufflers require extremely large sizes (volumes) or excessive lengths to successfully attenuate the engine noise. For example, at a 42-Hz fundamental frequency, the wavelength of sound in the exhaust is 38 feet, requiring a muffler length of at least 9 feet to attenuate noise using resonant techniques.

Alternately, the muffler volume required using current diesel engine standards (similar in frequency and displacement to aviation engines) would be approximately 6-10 times the total engine displacement, or close to a 3,000-in.^{3} enclosed volume (excluding the tailpipe) for an average-size aviation engine. This is roughly the volume enclosed in a 10-in. diameter pipe almost 4 feet in length (about the size of an exhaust stack on a truck), excluding the volume of a 2-in. diameter internal passage. In fact, the only well-known aircraft muffler system, produced for the Beech Bonanza A36 equipped with a Continental 0-520 engine, runs almost the entire length of the airplane fuselage, changing the structural, drag, and performance characteristics of the entire aircraft. The application of conventional two- and three-pass automotive-type mufflers is unacceptable, meanwhile, due to the 6–15-in.Hg of backpressure that these systems introduce.

Therefore, new and innovative acoustic filter/muffler designs must be developed and introduced into the general-aviation community in order to meet the specific noise-reduction demands of the industry. These muffler designs must be small in volume, low in weight and performance impact (backpressure), relatively low in cost (compared to retrofits/upgrades required for larger aircraft), requiring minimal or no maintenance, and preferably easily retrofittable into the current fleet of private aircraft at minimum cost.

3. Experimental Approach

The overall objective of this project was to demonstrate the use of a high-temperature structural absorber, silicon carbide (SIC) foam, as the basis for a noise attenuation system (muffler) for reciprocating-piston-engine-driven aircraft having low weight, size, and flow resistance compared to conventional automotive-type muffler systems. Specific goals included acoustic characterization of the SiC foam absorber materials, characterization of reciprocating engine noise and airplane noise sources, development of conceptual muffler designs and design methodologies, and fabrication and testing of various muffler designs to demonstrate design feasibility and advantages.

3.1 NOISE MEASUREMENT AND MODELING

The characteristic noise spectra for aircraft and their engines contain two elements: broadband noise and tones. The broadband noise, characterized by random-type time histories, arises from the interaction of the airflow with various stationary and moving parts of the engine, vortex noise from the propeller, and airflow interactions with the airframe. Tones have periodic-type time histories and arise only from the moving components, such as the pistons or propeller. The tone content of the noise is especially significant from a subjective (perceived) standpoint. Proper estimation and/or measurement of these two components of overall aircraft noise is important in designing a noise reduction system.

While propeller noise can be significant for any aircraft, the noise generated by a large percentage of general-aviation aircraft is dominated by the engine contribution. The noise contribution of the propeller is a tone and can be measured easily using commercially available analyzers/filters. An important feature of the measurement equipment is its characteristic bandwidth. While constant bandwidth, proportional bandwidth, one-third octave, and full octave filter systems all reveal the presence of a tone, the overall importance of the broadband noise can be overestimated by up to ≈10-20 dB using full-octave type noise filters.

A decibel is a logarithmic unit representing the smallest perceptible change in the amplitude of sound. A 6-dB change represents a factor of two in sound pressure, or a factor of four in sound power. One subjective measurement of noise that has received wide acceptance is the perceived noise level (PNL). The PNL is a function of the sound-pressure level plus a spectrum shape factor derived from curves such as the “equal noisiness contour,” which provide a weighting factor. The A-weighting noise scale, used for certifying light and primary aircraft for noise, is weighted at each frequency to give the equivalent noise level of a 1,000-Hz noise. Alternately, the C-weighting scale provides constant weighting of all frequencies. A comparison of the A-weighted and C-weighted measurement scales is shown in Figure 1.

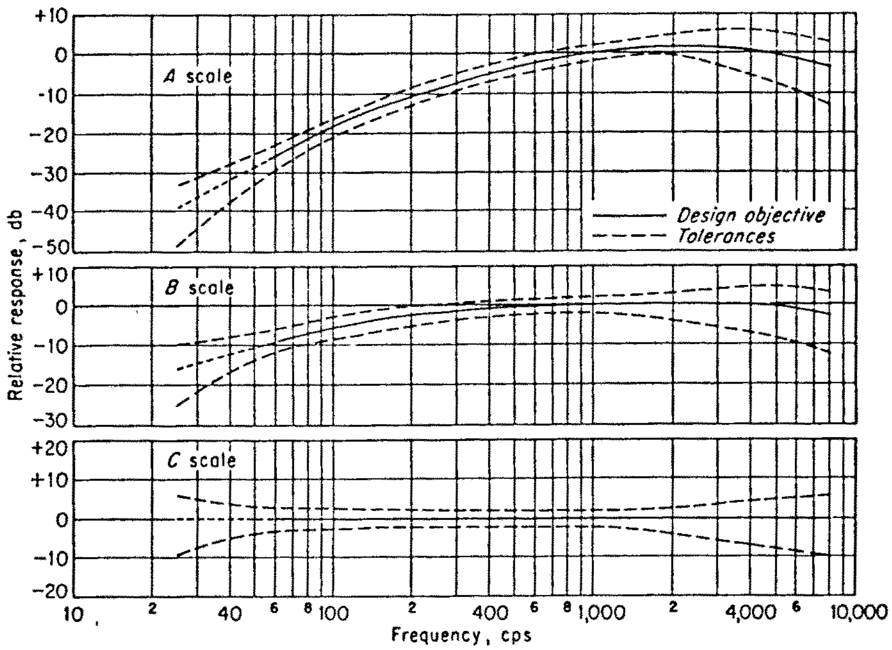


Figure 1

Relative responses of standard (A, B, and C) sound level weighting scales.

Larger aircraft require measurement of the equivalent perceived noise level (EPNL), which includes duration factors and more accurately reflects community impact and annoyance level. However, the FAA declined to adopt the EPNL standards for light and primary aircraft as recommended by the EPA, citing unreasonable economic impact.

In this project, baseline engine noise for the McCulloch Autogyro and Cessna 150 aircraft was characterized using a BBN model 614 portable noise monitor. Measurements were made from a distance of 25 feet at the 0, 90, 135, 225, and 270˚ positions with the engine at maximum power. For insertion-loss measurements of muffler effectiveness, the measurement location was altered to a position 5 feet away at an angle of 60˚ behind the plane of the propeller to minimize wind noise from the propeller wash in a location of maximum directivity for the exhaust noise.

In addition to baseline noise measurement, noise modeling procedures were used to predict propeller and engine noise levels and their first eight-tone harmonics for the Cessna 150 using the Continental 0-200 engine, with the modeling results compared to the measured noise levels and frequency distributions.

3.2 NOISE REDUCTION CONCEPTS

The basic noise reduction concepts investigated in this project were based on the use of an acoustic liner to muffle sound emanating from reciprocating-engine exhausts. The two basic muffler concepts are illustrated in Figure 2: a lined expansion chamber with a small open area, and an expansion chamber with perforated flow-through baffles placed in the exhaust flow. These concepts differ considerably from the originally proposed concept of a simple lined duct due to the low frequencies observed; the simple lined duct is applicable to 500 Hz and above, while the primary frequencies observed were below 100 Hz.

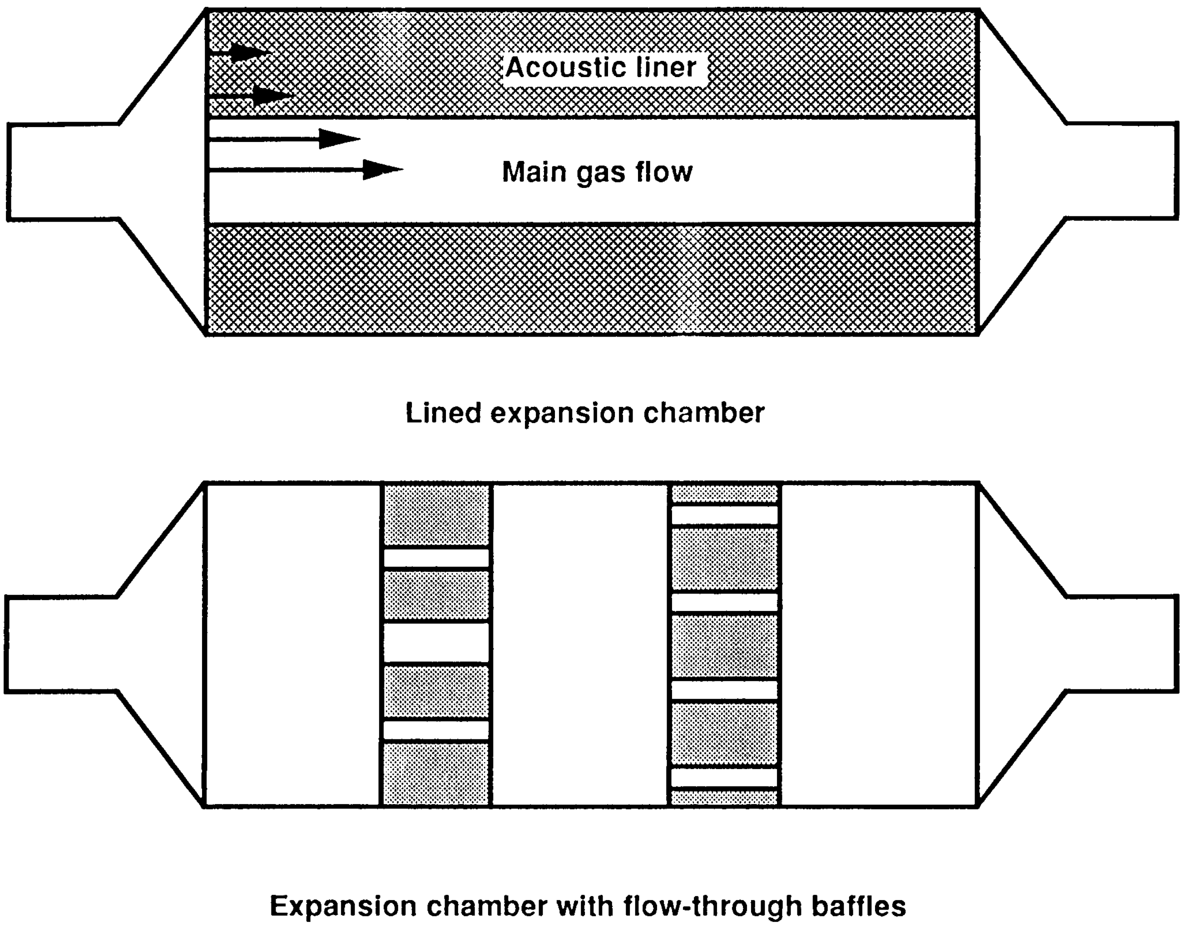


Figure 2
Schematic of basic muffler concepts.

The lined expansion chamber and the chamber with flow-through baffles were identified as having the best potential for optimal performance over the 50–1,000–Hz frequency range identified as being important for light aircraft utilizing constant-speed propellers. Typical acoustic responses for conventional lined duct and expansion chamber muffler designs are shown in Figure 3, while the lined expansion chamber (which combines both features) response is shown in Figure 4. The requirement for small open area (a design feature of both concepts) arises from the plane-wave nature of low-frequency waves, for which a quarter wavelength is much longer than the muffler dimensions, thereby requiring a substantial portion of the flow to travel through the absorber/baffle material to filter out noise.

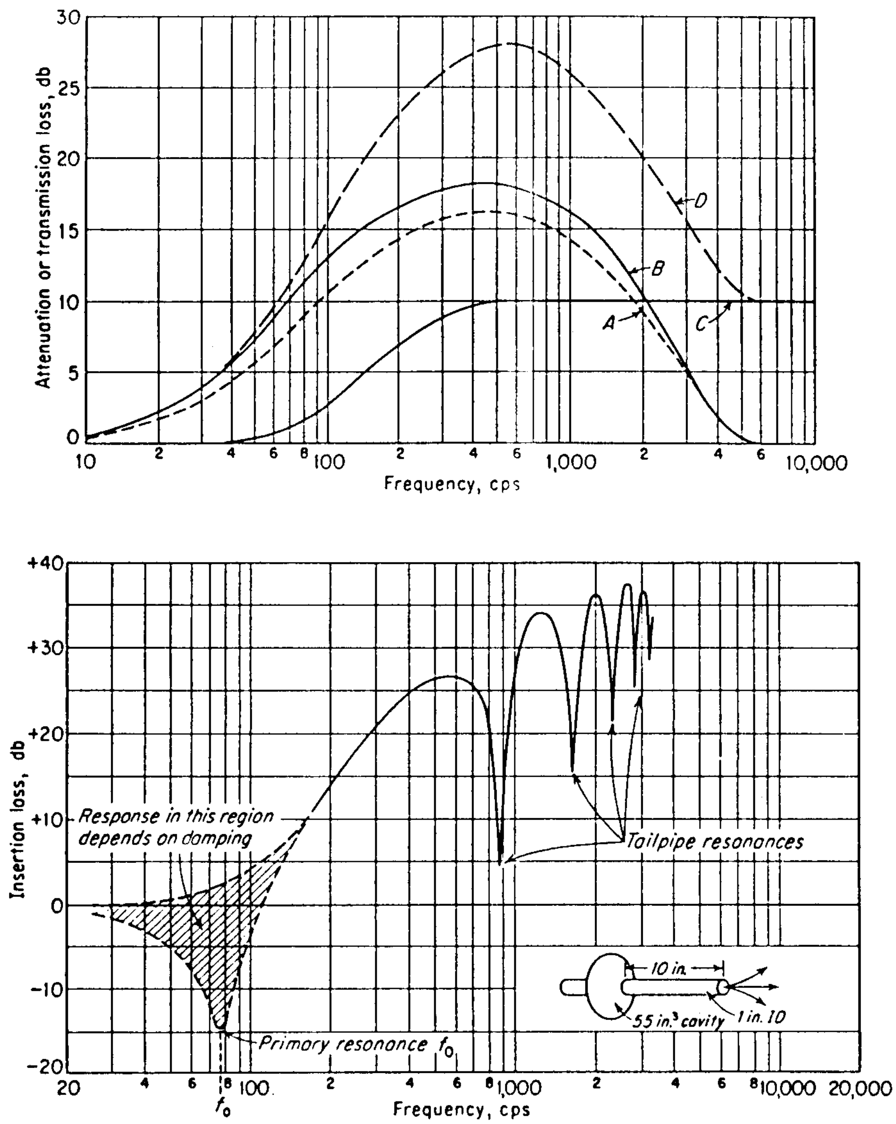


Figure 3

Typical acoustic responses for conventional lined duct (top) and expansion chamber (bottom) muffler designs.

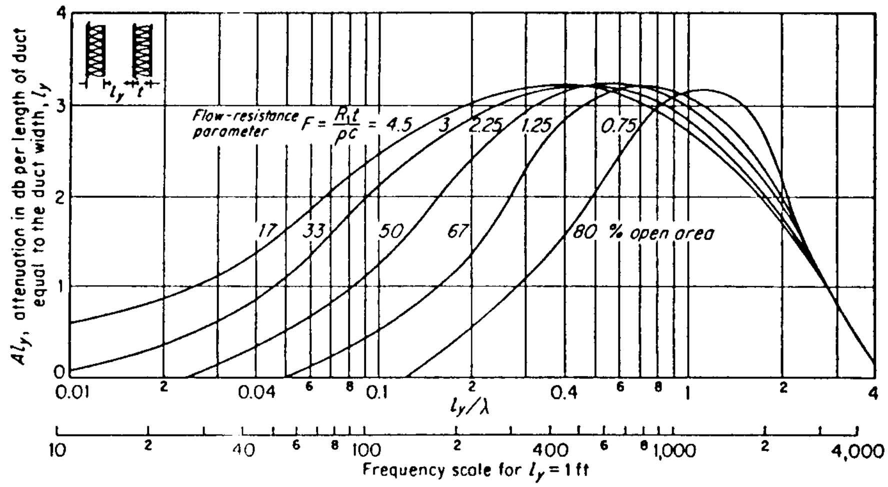


Figure 4

Typical acoustic response for lined expansion chamber muffler design.

3.3 Ceramic Foam Broadband Adsorbers

Previous materials were not capable of being used as a homogeneous absorber when placed directly in the gas-flow path in an engine exhaust environment due to their tendency to adsorb liquids and/or solids and their fragility when exposed to the gas flow and high sound-pressure and vibration levels. Combinations of glasspacks or fibrous materials contained within a perforated metal structure have been developed, but are rather expensive to manufacture and have limited life in the high sound-pressure environments encountered in aeropropulsion engines, and would present excessive flow resistance when placed directly in the exhaust gas flow.

Ultramet has developed a new class of reticulated (porous) open-cell foam materials fabricated by the replication of polyurethane foams using engineering ceramic and metallic materials. These materials offer the process control and mechanical, physical, and acoustic properties required for adsorbers/filters in high-temperature, high-vibration environments. Unlike previous felts, glasspacks, and sintered metals, these materials have extremely high strength (1,000–6,000-psi), low density, and high temperature stability, far in excess of previous acoustic materials, making them adaptable to the challenge of compact, lightweight aircraft muffler systems.

The ceramic foams used as homogeneous broadband adsorbers are fabricated using a replication/coating process. An ester-type polyurethane foam having the desired pore size [available from 10–100 pores per linear inch (ppi)] is first impregnated with a phenolic resin, which will form a carbon residue on subsequent pyrolysis. If even higher porosity is desired, the foam structure may then be compressed in one, two, or three dimensions to maximize the desired properties and directionality (in this case, noise attenuation). Heat treatment is then applied to transform the phenolic-impregnated polyurethane foam into a vitreous carbon foam skeleton. The carbon skeleton is then coated with the desired material (in this case, SiC) using chemical vapor deposition (CVD)/infiltration (CVI) techniques to bring the strength, temperature, and environmental resistance up to desired levels. In this manner, the precise properties of the foam can be controlled during the manufacturing process, and repeatably and reliably produced. All materials used in the process are inexpensive, and sizable manufacturing capacity exists once the designated foam properties are determined. Figure 5 shows the strength of SiC foam as a function of density, while flow resistance (pressure drop) is shown as a function of density in Figure 6.

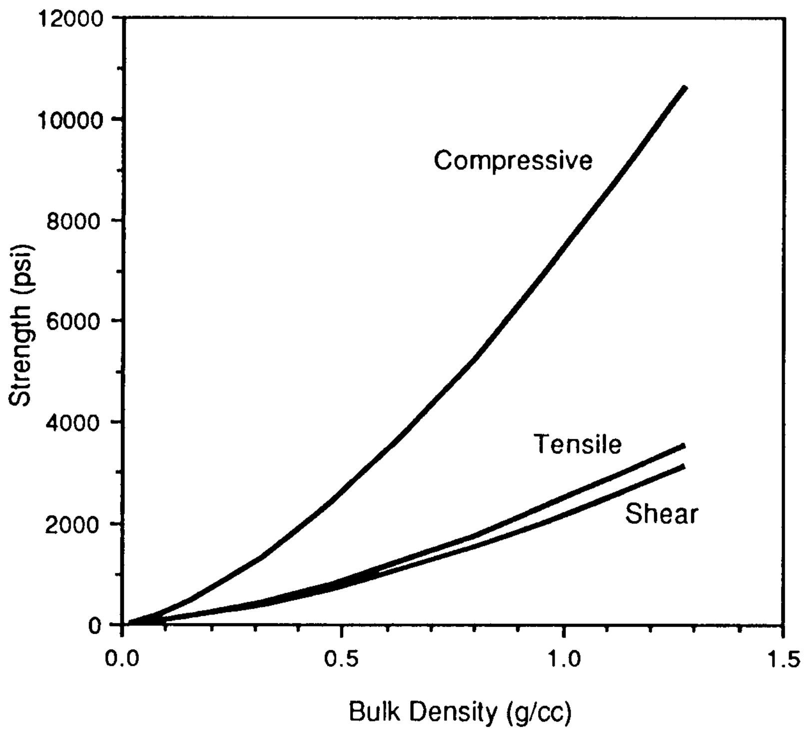


Figure 5

SiC foam strength as a function of density.

3.4 Foam Absorber Acoustic Characterization

Figure 7 shows a schematic of the apparatus used to measure the flow resistance properties of the SiC foam materials. The acoustic flow resistance *R* is calculated as follows:

$$R = \frac{\Delta P}{V} \quad (1)$$

where ΔP is the pressure drop across the sample and V is the airflow velocity. This flow resistance is related to the acoustic resistance of the foam when it is used as a duct lining, by relating the flow velocity to the rms particle velocity over a range of frequencies, and is related mechanistically to the viscous damping of sound waves due to air friction.

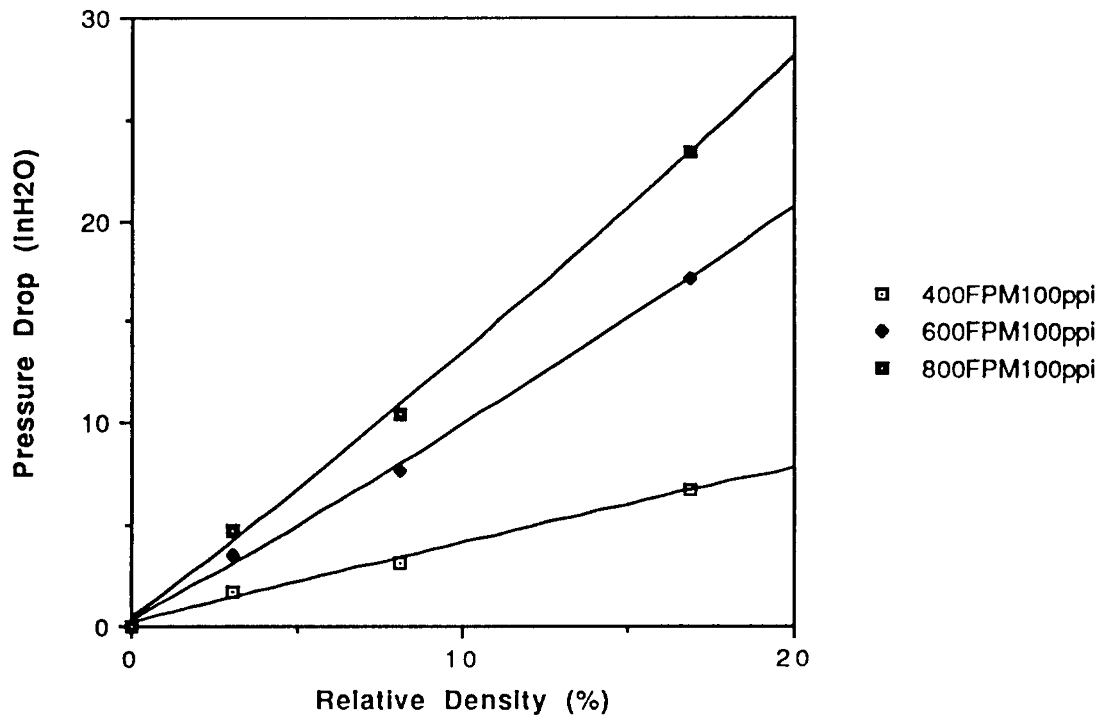


Figure 6

SiC foam flow resistance (pressure drop) as a function of density.

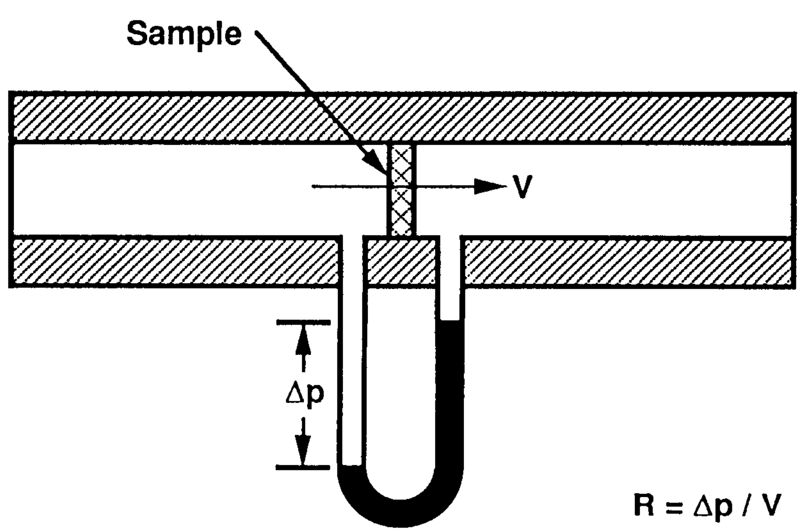


Figure 7

Schematic of flow resistance measurement apparatus.

After flow resistance testing was conducted, the apparatus illustrated schematically in Figure 8 was used to measure the normal-incidence acoustic impedance of the foam materials. The normal-incidence impedance Z is defined as the complex ratio of the rms acoustic pressure p at the surface of the sample to the rms acoustic particle velocity u at the same surface:

$$Z = \frac{P}{u} \tag{2}$$

The acoustic impedance has a resistive component Re(Z) that is analogous to the flow resistance of the material, and a reactive component Im(Z) that is dependent on the resonance of air in the lining and any cavity behind the lining.

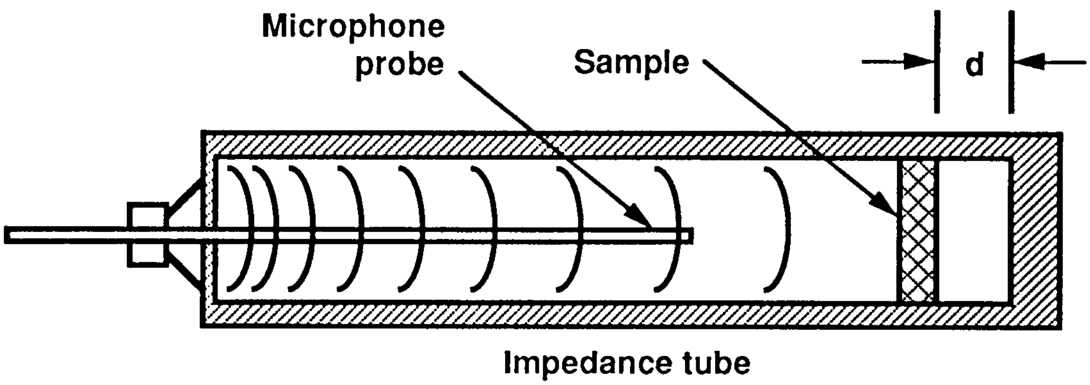


Figure 8

Schematic of impedance measurement apparatus.

3.5 Insertion-Loss Modeling

Muffler insertion-loss estimates were generated at the fundamental engine harmonic (firing frequency) based on duct lining and expansion chamber theory and the foam absorber complex propagation constant. Because the muffler response and propagation constant are different for each frequency, performance estimations were made only at the fundamental engine harmonic, which dominates the engine acoustic power output and is the most difficult (lowest) harmonic to reduce.

3.6 Muffler Design and Fabrication

Seventeen variations on the two basic muffler design concepts were designed, fabricated, and tested on the McCulloch Autogyro (three variations) and Cessna 150 (fourteen variations) for insertion loss. The Cessna variations are shown schematically in Figure 9, with the McCulloch designs, described below, being variants of these. The basic designs were based on achieving a 10-dB noise reduction of the fundamental engine harmonic, and modifications were incorporated to create sound reflections and thereby increase noise reduction, reduce higher frequency noise, and reduce backpressure.

The prototype mufflers/tailpipes were constructed using industry standard 321 CRES steel. Stamped endcaps were attached to the exhaust system and tailpipe, and 0.005-in. 321 CRES was rolled around the muffler inserts and clamped using hose clamps and the muffler end expansions for ease of modification.

3.7 Insertion-Loss Measurement

Initial insertion-loss measurement was conducted on a McCulloch Autogyro with sound measuring equipment located at a distance of 25 feet at the 0, 90, 135, 225, and 270˚ positions, 4 feet off the ground. The unlined multiple-baffle (spaced foam disks with 0.625-in. center holes), 0.5-in.-thick 65-ppi liner, and 1-in.-thick 100-ppi liner designs were tested in this manner. Following an accident involving the Autogyro on June 11, all subsequent testing was conducted on a Cessna 150L, at these five points as well as at a distance of 5 feet and a 60˚ angle behind the plane of the propeller.

A new stock exhaust system was used for all testing, with the test mufflers attached to the stock tailpipe fitting. The air temperature ranged from 75–92˚ F, and wind was on the aircraft nose at 6-7 mph. Sound measurements were made using three dB meters. One meter, C-weighted, supplied data which, using Fourier transform analysis, was reduced to specific dB vs. frequency information. A BBN model 614 portable noise monitor was installed in the aircraft with a microphone attached to the test stand outside. This monitor averaged a 10-second sound wave output at maximum power and produced A-weighted sound levels corrected for nighttime community noise levels. Finally, a digital sound meter was used to provide real-time confirmation of computed noise results. In all cases, the microphones were placed 5 feet behind and at a 60˚

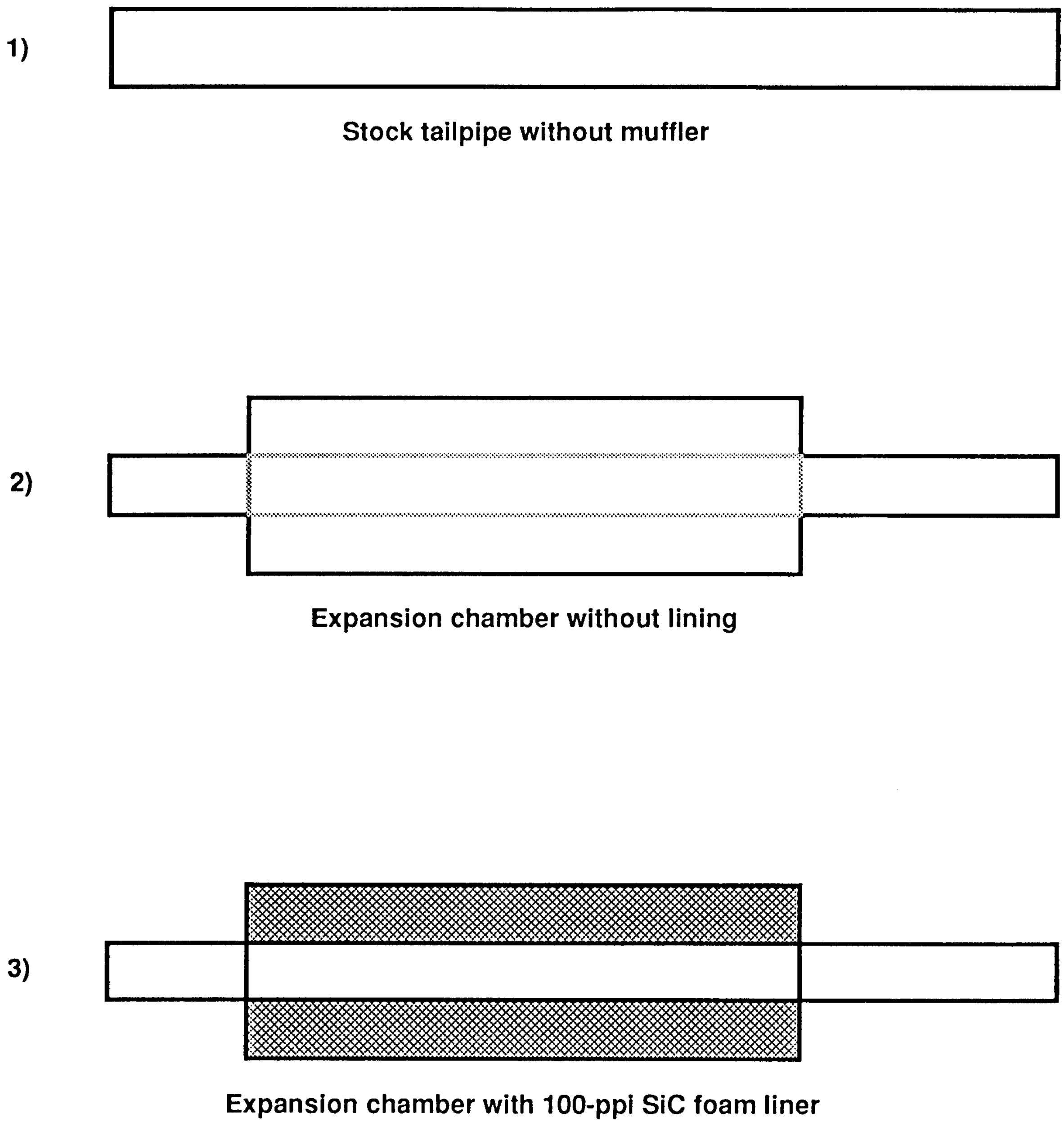
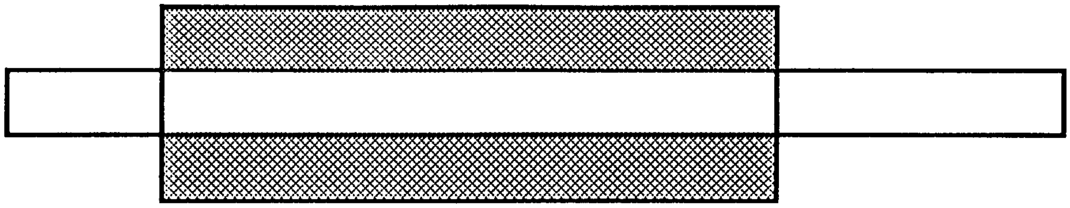


Figure 9

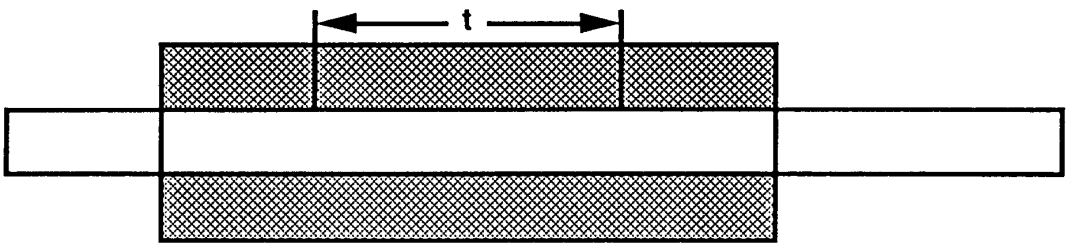
Schematics of muffler design variations.

4A)



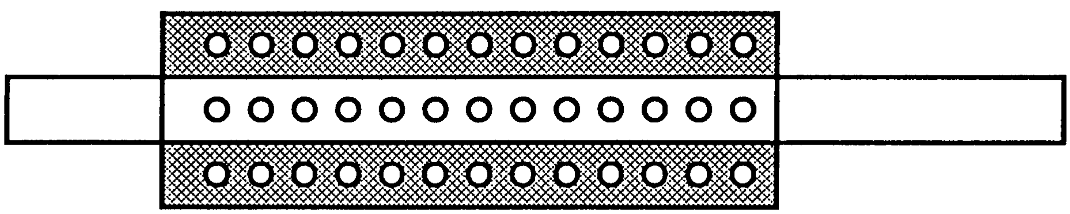
Expansion chamber with 100-ppi SiC foam liner
and full-length high-rayl insert

4B-4D)



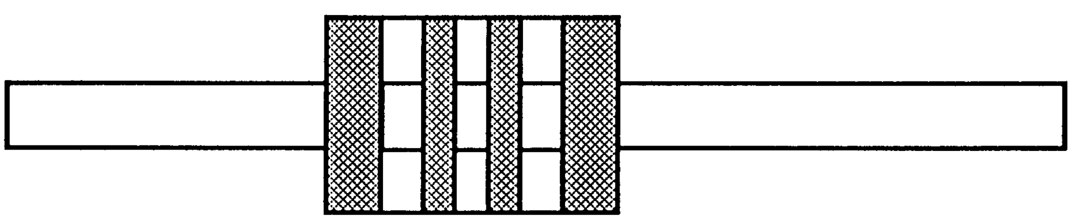
Expansion chamber with 100-ppi SiC foam liner
and 1.0", 3.0", and 6.0" high-rayl inserts

5)



Expansion chamber with 100-ppi SiC foam liner
and open side-branch resonator perforations

6)

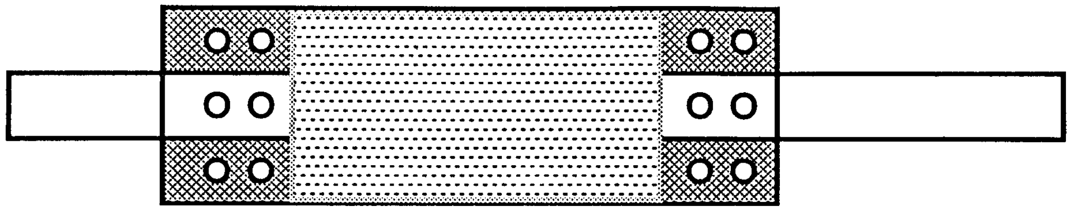


Expansion chamber with 65-ppi SiC foam baffles at ends
and two 100-ppi SiC foam baffles in middle

Figure 9

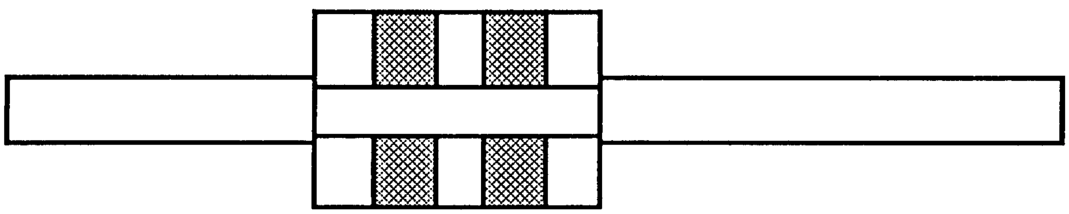
Schematics of muffler design variations (continued).

7)



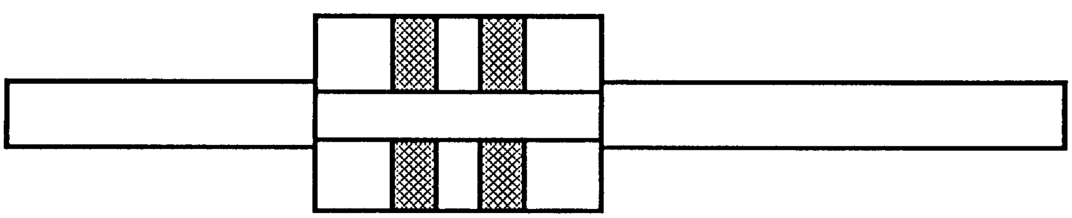
Expansion chamber with SiC foam liner and Inconel outer skin covering all but two rows of open side-branch resonator perforations at either end

8)



Expansion chamber with two 1.0" thick, 65-ppi SiC foam flow-through baffles

9)

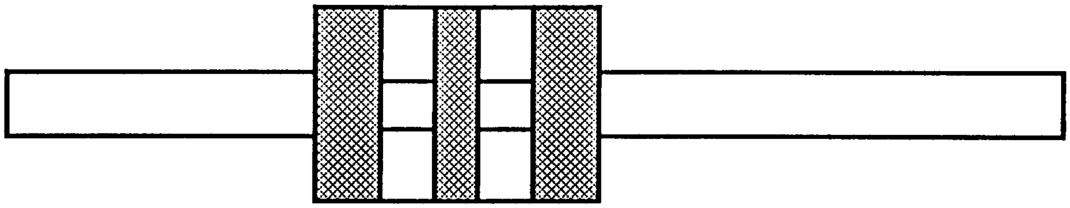


Expansion chamber with two 0.5" thick, 100-ppi SiC foam flow-through baffles

Figure 9

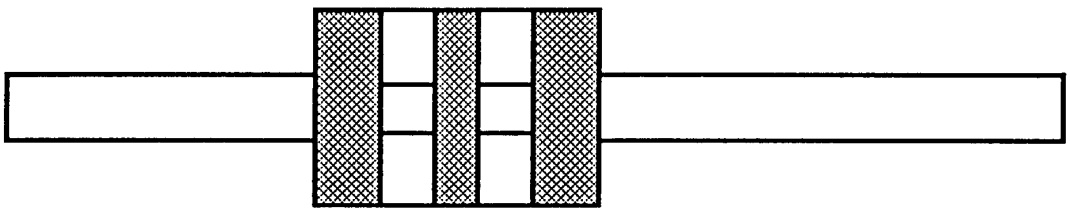
Schematics of muffler design variations (continued).

10A)



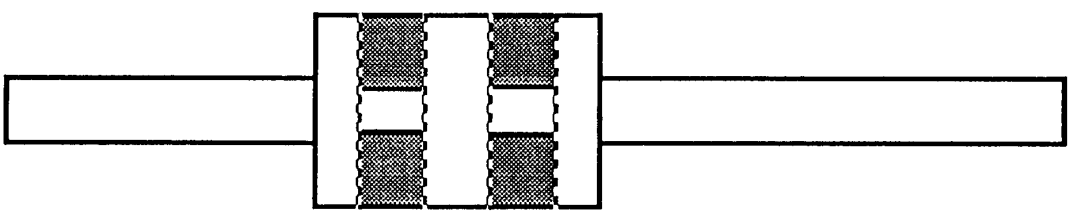
Expansion chamber with 65-ppi SiC foam baffles at ends
and 100-ppi SiC foam baffle in middle

10B)



Expansion chamber with 65-ppi SiC foam flow-through
baffles at ends and 100-ppi SiC foam flow-through baffle
in middle, with high-rayl inserts inside baffles

11)



Expansion chamber with two 100-ppi SiC
foam flow-through baffles covered with
perforated steel sheets

Figure 9

Schematics of muffler design variations (continued).

angle to the plane of the propeller, 12 in. off the ground and 14 in. apart. The exhaust manifold was equipped with a digital pressure gauge to record backpressure, and thermocouples were inserted at the beginning and end of the exhaust system.

5. Conclusions and Recommendations

The following conclusions may be drawn from the results of the completed project:

- For light aircraft (less than 150-200 hp), engine noise dominates overall aircraft noise.

- Adequate predictive methods exist for estimating engine and propeller noise and their spectral distribution.

- No currently available muffler design is optimal for reducing size, weight, induced backpressure, and noise for application to general-aviation aircraft engines.

- The combined dissipative/reactive muffler design developed in this effort is capable of meeting noise reduction, backpressure, weight, and size requirements for general-aviation aircraft.

- Tuning of the combined dissipative/reactive muffler system is a highly complex and difficult task, and the required analytical tools do not exist for this type of design.

- Aircraft noise reduction continues to be a solvable problem, even with light aircraft, for both community and pilot comfort. When economically viable technology becomes available, the lower EPA noise recommendations will most likely be adopted by the FAA, and a large number of private aircraft do not comply even with current FAA noise limits.

Based on the perforated baffle design results on the McCulloch Autogyro and the predicted and experimentally confirmed noise estimates for the Cessna 150, it is clear that, at least for engine sizes up to 150 hp, engine noise dominates total aircraft noise as expected. It is also clear that reducing this noise level with small lightweight muffler systems inducing less than 0.5-1.0 in.Hg backpressure is an extremely difficult task, since even adding expansion chambers suitable for a 15-20 dB noise reduction (approximately 16:1 expansion ratio or 8–10-in. diameter) will exceed this backpressure level. A side-branch resonator design should be capable of just barely meeting the backpressure and noise reduction requirements, although the size and weight of such a system would make necessary significant modifications to the aircraft, such as a new engine cowl and other aerodynamic and acoustic changes. The combined dissipative/reactive muffler system approach taken during this project, however, demonstrated good potential and appears to be the optimal solution to the general-aviation aircraft engine noise problem.

Because of the nature of the A-weighting measurement scale, most noise generated by the engine in the 50–1,000-Hz range contributes to the total equivalent noise. The A-weighting technique acts almost as a correction factor for the measured noise distribution, with lower frequencies discounted in proportion to their contribution such that the entire observed frequency range contributes to the overall engine noise level. This implies that a multiple-chamber tuned resonant duct design or the use of a dissipative material with tuned ducts is required to solve the engine noise problem.

The measured noise reduction at the engine fundamental frequency, combined with the actual backpressure reduction obtained, indicates that the combined dissipative/reactive muffler system is capable of meeting noise, backpressure, and geometry (size and weight) requirements for a general-aviation aircraft-engine noise-reduction system. However, the results also indicated that tuning of such a system is a daunting task that will require significant further effort to develop a workable, salable exhaust system that is easily retrofittable to the current aircraft fleet.

Existing engine and propeller noise-prediction techniques were found adequate to predict aircraft noise magnitude and spectral distribution. However, muffler design and performance prediction tools do not presently exist that are capable of handling combined dissipative/reactive muffler designs. Although the basic analytical tools are available, they require iterations at each frequency, and hand calculation is exceedingly time-consuming.

Based on the program results, it is clear that additional efforts are warranted for general-aviation aircraft noise reduction (primarily engine noise reduction for smaller aircraft) using the combined reactive/dissipative muffler system:

- Automated analytical design tools covering both dissipative element (absorber) properties and the acoustic and mechanical performance of the total exhaust system must be developed, and such tools should be capable of tuning the exhaust system based on A-weighted (equivalent noisiness) or EPNL (equivalent annoyance value) procedures.

- Analytical tools and flight testing should be applied, at a minimum, to aircraft powered by the < 200-hp engine class, including the Continental 0-200 and 0-360 and the Lycoming 0-320 and 0-360 engines, leading to a supplemental type certificate.

- FAR Part 36, Part 23, and Part 21 compliance must be demonstrated on an acceptable exhaust system, leading to a Product Manufacturing Authority (PMA) and the introduction of low-noise exhaust systems into the field.

- The availability of smaller, multibladed propellers should be increased for the intermediate and larger (200-350 hp) light-aircraft classes, for which propeller rather than engine noise dominates the overall aircraft noise level.

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This work is dedicated to the memory of Gerald Redman, a true champion and enthusiast of general aviation, who died as a result of injuries sustained in an accident involving his McCulloch Autogyro during the testing segment of the project. He will be dearly missed by his family, friends, and the general-aviation community he loved so well.

7. REFERENCES

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