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Detection and Prevention of Carbon Monoxide Exposure in General Aviation Aircraft

October 2009

Final Report

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NOTICE

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16. Abstract

Exposure to carbon monoxide (CO), which is formed by the incomplete combustion of carbon-containing materials such as aviation fuels, is associated with headache, dizziness, fatigue, and at elevated doses, death. Exhaust system failures in general aviation (GA) aircraft can result in CO exposure. When this occurs in an aircraft, the end result could be an accident. This research on detection and prevention of CO exposure in GA aircraft addressed the following objectives: (1) to identify protocols to quickly alert users to the presence of excessive CO in the cabin and (2) to evaluate inspection methods and maintenance practices with respect to CO generation. These objectives were accomplished by review of (1) the National Transportation Safety Board database for CO-related incidents/accidents, (2) current CO detector technology, and (3) industry inspection and maintenance practices, Advisory Circulars, and FAA regulations with respect to GA exhaust systems.

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LIST OF ACRONYMS

ac	Alternating current
AC	Advisory Circular
AD	Airworthiness Directive
CFR	Code of Federal Regulations
CO	Carbon monoxide
FAA	Federal Aviation Administration
GA	General aviation
IP	Ingress Protection
IR	Infrared
ISEA	International Safety Equipment Association
NTSB	National Transportation Safety Board
ppm	Parts per million
RF	Radio frequency
RH	Relative humidity
SAE	The Society of Automotive Engineers
SDR	Service Difficulty Reports

EXECUTIVE SUMMARY

Exposure to carbon monoxide (CO), which is formed by the incomplete combustion of carbon-containing materials such as aviation fuels, is associated with headache, dizziness, fatigue, and at elevated doses, death. Exhaust system failures in general aviation (GA) aircraft can result in CO exposure. When this occurs in an aircraft, the end result could be an accident. This research on detection and prevention of CO exposure in GA aircraft addressed the following objectives: (1) to identify exhaust system design issues related to CO exposure, (2) to identify protocols to quickly alert users to the presence of excessive CO in the cabin, and (3) to evaluate inspection methods and maintenance practices with respect to CO generation. These objectives were accomplished by review of (1) the scientific literature on CO incidents/accidents, (2) current CO detector technology and determination of the best placement location for CO detectors in the cabin, (3) industry maintenance practices, Advisory Circulars, and Federal Aviation Administration (FAA) regulations with respect to GA exhaust systems, and (4) current industry inspection practices on exhaust systems in GA aircraft.

A total of 71,712 accident cases between 1962 and 2007 were reviewed from the National Transportation Safety Board (NTSB) accident/incident database. The review of these cases revealed that the CO-related accidents occurred throughout the year; however, the accidents caused by leakage in the muffler or exhaust system were more prevalent in the colder months. Furthermore, it was shown that the majority of the mufflers' CO-related accidents had muffler usage greater than 1000 hours.

The research on the specifications of CO detectors resulted in a list of performance specifications regarding the use of CO detectors in GA. Some of the characteristics that are considered important for GA application include high accuracy, quick response time, inherent immunity to false alarms, and low power consumption. Taking these characteristics into account, it was concluded that among different CO detector technologies, CO detectors using electrochemical sensors may be the most suitable technology for use at this time in a GA environment. Electrochemical CO detectors available on the market that are likely suitable for use in a GA environment range in price from \$175 to \$200, possess good battery life (2000 to 2600 hr), and have quick response times (12s to 35s). A database of available CO detectors on the consumer market was developed, which, along with categorized performance parameters, can help pilots make informed decisions on CO detector selection.

A limited field test using portable electrochemical CO detectors was conducted on two GA aircraft models to determine the best location for a CO detector. The results indicated that the majority of CO detected in the cabin was below 10 parts per million (ppm), well below the FAA standard of 50 ppm. However, a small percentage of CO that was detected in the cabin was above 50 ppm. Based on the analyses of limited collected CO data, the instrument panel appeared to be the best location for the placement of CO detectors. To increase the probability of being able to detect at least 50 ppm anywhere in the cabin and to reduce the occurrence of false alarms, it appears that the CO detector should be set at a lower alarm threshold of 35 ppm.

FAA regulations and guidance documents indicated that the maintenance and inspection of GA aircraft exhaust systems is generally carried out by means of visual inspection. While there is no lifetime limit on mufflers in FAA regulations, the NTSB accident/incident database review showed a strong relationship between the lifespan of a muffler and its failure. Performing a thorough visual inspection and air pressure test with soapy water increased the chance of finding cracks, damage, and developing deterioration in exhaust system components. This maintenance practice, together with an imposed lifetime limit for mufflers (recommended by respective manufacturers), should be considered as a primary prevention method for CO exposure in GA aircraft. Placing a suitable CO detector at the instrument panel would serve as the secondary prevention method to further prevent CO exposure. Familiarity with the signs and causes of exhaust system failures can facilitate the identification and prevention of CO exposure at its sources. This information is summarized in the form of checklists to help pilots and mechanics identify and remedy potential exhaust system failures.

1. INTRODUCTION.

Carbon monoxide (CO) is a byproduct of the combustion of fuel and is emitted in the exhaust of gasoline, propane, or other fuel-powered equipment and engines. It is formed by the incomplete combustion of carbon-containing materials, which are present in aviation fuels. CO is a hidden danger because it is a colorless and odorless gas. Exposure to CO can cause harmful health effects depending on the air concentration and duration of exposure. CO is an asphyxiant in humans, where inhalation causes tissue hypoxia by preventing the blood from carrying sufficient oxygen. Acute CO poisoning is associated with headache, dizziness, fatigue, nausea, and at elevated doses, neurological damage and death. Higher acute exposure or chronic exposures can also affect the heart, particularly in those with cardiovascular disease.

Exposure to CO can result in individuals becoming confused or incapacitated before they are able to leave the contaminated environment. When this occurs in an aircraft, the end result could quite possibly be an accident. Zelnick, et al. [1], reported on studies identifying the contribution of CO poisoning to fatal accidents in aviation, where estimates ranged from 0.5% to 2.0% related to CO. Although the sources of CO generation during flight are known, little is known regarding the exposure to CO during normal flight operations.

Table 1 lists the symptoms that can be expected based on the amount of CO in the area and as a function of duration of exposure [2]. The Federal Aviation Administration (FAA) requires that the amount of CO in the area does not exceed 50 parts per million (ppm) (Title 14 Code of Federal Regulations (CFR) 23.831) [3]. The symptoms of mild headache, nausea, and fatigue can occur at 200 ppm between 2 and 3 hours of exposure, where an increasing magnitude of exposure for shorter periods of time results in similar symptoms. At extreme exposure (12,800 ppm), it only takes 1 to 3 minutes to cause death.

Table 1. Symptoms Resulting From CO Exposure [2]

ppm CO	Time	Exposure or Symptoms
50	8 hr	Maximum exposure allowed by the Occupational Safety and Health Administration over an 8-hour period [4]
200	2-3 hr	Mild headache, nausea, fatigue
400	1-2 hr	Serious headache, life threatening after 3 hr
800	45 min	Dizziness, nausea, unconscious within 2 hr, death within 2-3 hr
1,600	20 min	Headache, dizziness, nausea, death within 1 hr
3,200	5-10 min	Headache, dizziness, nausea, death within 1 hr
6,400	1-2 min	Headache, dizziness, nausea, death within 25-30 min
12,800	1-3 min	Death

Since the National Transportation Safety Board (NTSB) reports CO exposure in terms of percent of blood, it was of interest to identify typical symptoms as a function of CO concentration in the blood, which is shown in table 2. Slight headaches begin at 10% blood content of CO, drowsiness begins at around 20% blood content of CO, and blurring of vision is present starting around 30% blood content of CO. Unconsciousness and death can occur when the amount of CO is more than 50% in the blood.

Table 2. Percentage of CO in the Blood and Possible Symptoms [2]

Percent CO in Blood	Typical Symptoms
<10	None
10-20	Slight headache
21-30	Headache, slight increase in respirations, drowsiness
31-40	Headache, impaired judgment, shortness of breath, increasing drowsiness, blurring of vision
41-50	Pounding headache, confusion, marked shortness of breath, marked drowsiness, increasing blurred vision
>50	Unconsciousness, eventual death if victim is not removed from the source of CO

In piston engines, proper cooling of the engine cylinder is a major design consideration of general aviation (GA) aircraft. The configuration of modern aircraft piston engines is horizontally opposed so they provide a reasonably good cooling characteristic when ram air is forced into the engine cowling.

To provide cabin heat, a heat exchanger is usually attached to the exhaust system of single-engine aircraft. Figure 1 shows the overall engine in the left-hand diagram, and a breakout of the heat exchanger is shown in the right-hand diagram [5]. Since the exhaust gas and air for the cabin heat move along two independent tubes, the exhaust and cabin air should remain distinctly separate.

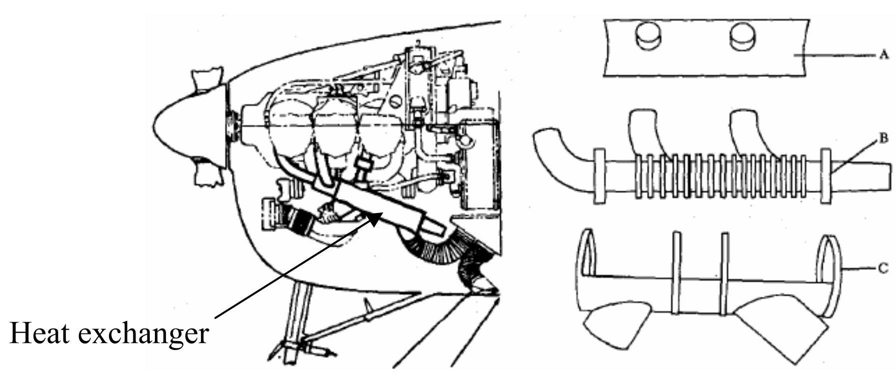

Figure 1. Six-Cylinder, Horizontally Opposed Reciprocating Engine [5]
(Heat Exchanger Upper Sheet Jacket (A), Collector Tube (B), and Lower Sheet Jacket (C))

A significant hazard can result, however, when there is a failure in the piston engine exhaust system. This can come in the form of CO entering the heat exchanger air, which is used to heat the cabin, or through a leak in the firewall between the engine compartment and cabin. An FAA report [6] notes that piston engine exhaust gases typically contain 5% to 7% CO, although an exhaust system failure may result in a smaller concentration of CO due to mixing with other air in the engine compartment. Irrespective of how frequently it occurs, there is a high risk for a hazard whenever there is an exhaust system failure. According to one FAA report [6], 70% of exhaust system failures result in a CO hazard. Thus, proper inspection and maintenance of the exhaust system is extremely important, and textbooks on maintenance procedures [7 and 8] clearly state that aircraft engine exhaust systems must be thoroughly inspected.

The exact design associated with the piston engine exhaust system varies from manufacturer to manufacturer, as well as from aircraft model to model within a given manufacturer. Nevertheless, the common element is the large number of connections that can potentially crack or fail. One representative example of a piston engine exhaust system is shown in figure 2 [5]. There are welds between the end plates and exhaust tubing, and bolts or clamps connect tubes to tubes. Piston engines operate at different rpm, varying from ground idle to maximum takeoff settings that can lead to vibration-type fatigue. At the same time, piston engine exhaust is extremely hot and corrosive, so thermal fatigue or corrosion can result in any part of the exhaust system. Thus, exhaust system deterioration can result from several factors, including:

- Engine vibration, which may eventually cause metal fatigue
- Thermal cycling during engine operation
- High temperature and corrosive effect of engine exhaust

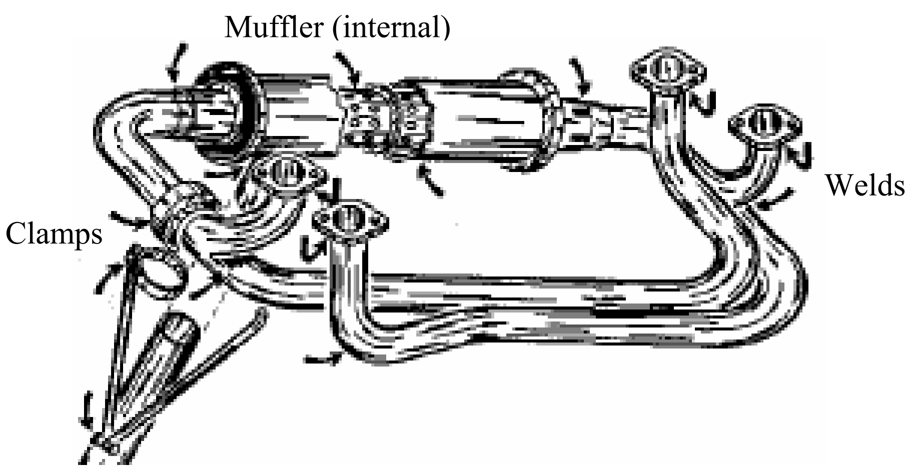

Figure 2. Typical Exhaust System Inspection Areas [5]

These factors can result in fatigue of welded areas and the clamp joints or failure of the muffler and heat exchanger. Failure of the exhaust manifold or joints can result in CO permeation to the cockpit through the engine firewall. Failure of the muffler and heat exchanger can result in CO infiltrating into the cabin through the heater vents. Any type of obstruction in the exhaust system, for example in the inner baffle of the muffler, can lead to local hot spots and burn-through of the tubing walls. Advisory Circular (AC) 91-59A [9] indicates that the most prominent problem area regarding exhaust system failures is the muffler and heat exchanger parts of the exhaust system. Some mufflers have heat transfer pins (figure 3), which are welded to the inner wall to improve heat transfer to the air that flows within the heating system. These pins provide a significant increase in heat transfer capability, but are also additional components that must be periodically inspected and maintained. Figure 4 [10] shows some of the different types of failures found in typical exhaust system mufflers, such as fatigue failure of the exhaust outlet and fatigue failure of the exhaust system wall and inlet.

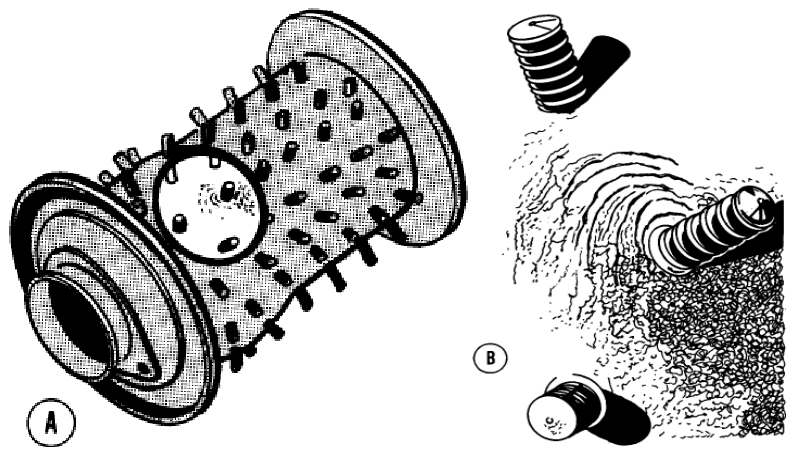

Figure 3. An Exposed Muffler (A) and its Heat Transfer Pins (B) [10]

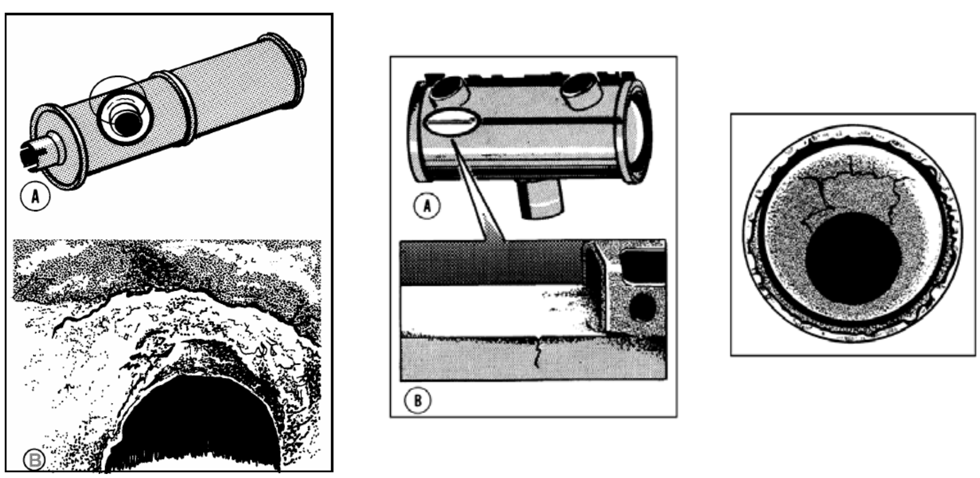

Figure 4. Typical Muffler Failures [10] (Exhaust outlet fatigue (left), wall fatigue (middle), and end plate fatigue at inlet (right))

Besides the thermal and vibration fatigue failures, another type of failure is possible in a turbocharged piston engine. Figure 5 [5] shows how the exhaust gas is routed through the turbocharger to pressurize the intake air when the aircraft is flown at high altitude. At sea-level operation, a waste gate vents a large portion of the exhaust to prevent over-pressurization. Carbon buildup in the waste gate may cause the gate valve to stick, resulting in erratic operation or failure. Thus, periodic inspection and cleaning of carbon buildup is also required in turbocharged piston engines.

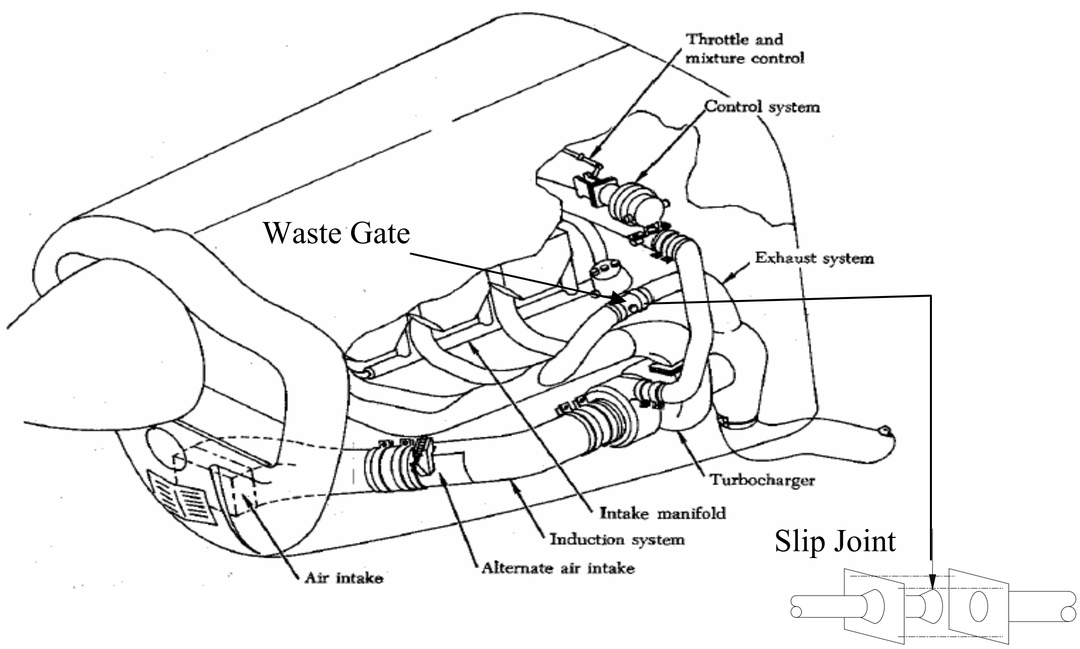

Figure 5. Six-Cylinder, Horizontally Opposed Turbocharged Engine [5]

The right-hand breakout illustration of figure 5 shows another type of exhaust system connection that can lead to potential CO exposure. A slip joint allows two different tubes to rotate and move like a ball joint. In this configuration, there must be a gap between the “mushroom-shaped” tube’s outer wall and the slip joint plate, which is hard-bolted to the opposing tube. By design, the joint allows for a small amount of exhaust gas leakage. If these joints are not inspected and properly maintained, an excessive amount of leakage can occur. This also leads to the need to properly seal the engine-cabin firewall, which must then be periodically inspected and maintained.

Indications of exhaust system failure include smelling smoke in the cockpit, an excessive drop in engine rpm when applying carburetor heat, and sooty-black discoloration on the heat exchanger shroud [9-11]. These indicators of exhaust system deterioration rely on the subjective observation of the pilot or maintenance personnel. The presence of cracks may allow for the infiltration of small amounts of CO into the cockpit.

FAA Special Airworthiness Information Bulletin (SAIB)-CE-03-52 [12] notes that in the year 2000, the average age of the nation's 150,000 single-engine aircraft was over 30 years old. Although CO hazard is not limited to aging aircraft alone, the risk of exhaust system failure naturally increases with older aircraft. FAA AC 43.13-1B [10] notes that half of the (piston engine) exhaust system failures occur within 400 hours of operation. One recent concern expressed by the NTSB is the incidence of CO exposure leading to a fatal accident soon after the aircraft completes its annual or 100-hour inspection [13]. Part of the reason for these accidents soon after inspection may be due to the fact that a crack is difficult to see in a simple visual inspection. The densely packed engine compartment makes it difficult to perform a thorough inspection unless some parts are disassembled and removed. Even if the exhaust system is intact without leaks during an inspection, it is possible that a crack or failure simply occurs soon after inspection. Indeed, the recent NTSB Safety Recommendation cites a number of Service Difficulty Reports (SDR) where exhaust system failures were found only after disassembly and pressure testing, even though the exhaust system had passed its annual inspection just a short time earlier [13]. Incidents such as these suggest that CO exposure is a serious hazard that can suddenly occur at any time.

2. RESEARCH OBJECTIVES.

This research on CO exposure in GA addresses the following objectives: (1) to identify exhaust system design issues related to CO exposure, (2) to evaluate inspection methods and maintenance practices with respect to CO generation, and (3) to identify protocols to quickly alert users to the presence of excessive CO in the cockpit and cabin.

To accomplish the objectives of this research, the work was divided into four major phases. Some of the studies in these phases were carried out in parallel.

- In Phase 1, the NTSB database was reviewed in detail to determine the sources of CO exposure and its effect on GA incidents/accidents. This information and the corresponding analysis formed the basis for much of the remaining research activities.

- In Phase 2, the most current CO detection technologies and those most suitable for the GA applications were studied. Also, in this phase, potential locations within GA aircraft for the placement of CO detectors to alert users to the presence of excessive CO in the cockpit and cabin were identified.

- In Phase 3, in parallel with the review of the NTSB database, the industry inspection and maintenance practices and FAA regulations and guidance materials on inspection and maintenance of GA aircraft exhaust systems were reviewed to assist in the development of methods and practices that could be used to determine the integrity of the exhaust systems.

- In Phase 4, in collaboration with some of the GA aircraft maintenance and inspection stations through an FAA regional office, best practices for the maintenance and inspection of exhaust systems were gathered and recommendations were made to ensure proper maintenance and inspection of GA aircraft.

In the following sections, the processes to achieve the objectives of each phase of the project are discussed.

3. CHARACTERISTICS OF CO-RELATED GA ACCIDENTS.

The objective of this part of the research was to determine the sources of CO exposure and the causes of CO-related accidents/incidents in GA aircraft through the analysis of historical data from databases containing information on GA accidents and maintenance-related issues.

Two databases were evaluated for GA accidents and CO-related incidents: the NTSB database on accidents and incidents [14] and SDRs [15]. The NTSB accident database contains information from 1962 to the present about civil aviation accidents and selected incidents within the United States, its territories and possessions, and in international waters. Generally, a preliminary report is available online within a few days of an accident. Factual information is added when available, and when the investigation is completed, the preliminary report is replaced with a final description of the accident and its probable cause. The SDR database contains maintenance records of aircraft being serviced from 1995 to the present and separates the GA from the commercial airliners and other non-GA aircraft.

A total of 71,712 cases between 1962 and 2007 were reviewed from the NTSB database. These were categorized into the following three groups:

- CO-related cases: This group includes accidents that were clearly related to CO exposure. Accident reports clearly stated that the probable cause of the accident was related to CO exposure. Some of these reports also indicated a root cause, such as muffler failure, exhaust system failure, cracks in exhaust stacks, as well as the percentage of CO present in the blood.

- Potential CO-related cases: This group included accidents that may be related to CO exposure. This category was investigated because discussions with FAA personnel suggested that there were more CO-related cases than those identified by the NTSB accident/incident database. Thus, it was of interest to identify cases that may be consistent with definite CO cases and would require further investigation. Accident reports for this group indicated that the probable cause of the accident involved engine failure, engine power loss, defective valves, etc. This group was initially considered for further analysis, but ultimately, the lack of full reports made it difficult to accomplish further in-depth analysis. Thus, the subsequent analysis was performed on characteristics identified from CO-related cases only.

- Non-CO-related cases: This group included accidents and incidents that were not related to CO exposure.

Of the 71,712 cases in the NTSB accident/incident database, 62 cases were directly related to CO exposure (CO-related cases). The SDR database was searched using keywords related to exhaust systems such as "muffler," "heat exchanger," and "heater shroud," which resulted in approximately 400 reported cases. Among the approximately 400 cases identified, no general trends could be observed. A detailed analysis of the reviewed databases is presented in appendix A.

4. CARBON MONOXIDE DETECTOR EVALUATION.

The FAA standard for CO in an aircraft cabin is no more than 50 ppm [3]; however, there is currently no requirement to monitor for CO in the cabin. Due to the colorless and odorless characteristics of CO, it is extremely difficult to determine if hazardous levels of CO are in the cabin without some type of CO detector technology. However, little guidance exists regarding suitable CO detector technology for use in GA aircraft. Additionally, if CO detectors are used in the cabin of GA aircraft, no guidance exists to recommend the best placement to detect CO quickly and accurately. Therefore, the major objectives of this part of the research were to (1) review and summarize CO detector technology and performance characteristics to assist in identifying CO detectors that may be suitable for use in GA aircraft and (2) determine the optimal placement of the CO detector inside the cabin. The following sections discuss the process that was followed to achieve these objectives. Appendix B provides a detailed discussion of the evaluation of CO detection technologies as well as identifying the best-suited locations for the CO detectors.

4.1 THE CO DETECTOR TECHNOLOGY EVALUATION.

An extensive review of the literature and the vendors of portable CO detector technology that may be suitable for GA aircraft was conducted. However, this review did not consider the design and approval process that may be required for permanently installed CO detectors. The process to gather the information included reviewing the relevant scientific research literature regarding CO-related aviation incidents and detector technology. The research team reviewed related FAA regulations and guidance and consulted vendors and manufacturers on the potential use of CO detector technology in GA aircraft. The most common types of consumer-based CO sensors are biomimetic, semiconductor, and electrochemical, whereas infrared sensors are used primarily for research purposes [16]. Resolution and accuracy refer to the detection limits and how close the measured value is relative to the true CO level. Analysis was mostly based upon the sensor properties, including lifetime, resolution and accuracy, immunity to poisoning, false alarms and false negatives, battery life, and selectivity. False alarms are instances where the detector alarms even though CO levels are low; false negatives refer to instances where the detector fails to alarm when CO levels are high; selectivity is the detector's ability to distinguish between CO and other gases; and immunity to poisoning refers to the detector's resistance to interference from other substances or pollutants in indoor air.

Collectively considering the advantages and limitations of the various CO detector technologies, electrochemical sensors appear to be the most suitable for a GA environment due to their relatively high accuracy, quick response time, inherent immunity to false alarms, and low power consumption. Similar conclusions have been presented by other research regarding electrochemical sensors with respect to cost and performance [17].

4.2 THE CO DETECTOR LOCATION.

If a portable CO detector is to be used in GA aircraft, it is essential that it be positioned in a location in the cabin that ensures early and consistent detection of the CO when it enters the cabin. Additionally, the CO detector should be placed in a location where the pilot can be sufficiently alerted to the warning signals of the CO detector should it alarm. Thus, the major objective of this portion of the research was to identify the best location to position a portable CO detector in the cabin of a GA aircraft. A secondary objective was to determine ambient levels of CO in the cabin under normal operating conditions.

Multiple portable, battery-operated, single-gas CO detectors with datalogging capability (GasBadge® Pro, Industrial Scientific, Oakdale, PA, USA) were placed in multiple locations in the aircraft cabin. The locations of the CO detectors were based upon potential pathways of CO into the cabin, which were determined from maintenance manual schematics, as well as from results of the NTSB's determination of potential sources of CO exposure in CO-related accidents. Potential pathways of CO into the cabin for many aircraft types included the heater vents, unsealed holes in the firewall, as well as fresh air vents. Thus, the following locations were selected to meet the above-mentioned objectives: visor above the pilot (clearly visible and accessible), lower panel of right and left doors (near heater vents and visible), the instrument panel (close to the firewall, visible and accessible), and the back-seat area (near fresh air vent).

CO was monitored over a 12-month period from several single-engine GA aircraft during student flights of the Aviation Department of the Kansas State University at Salina. For the first 8 months, different aircraft (high-wing model) were monitored each week using five CO detectors at the designated locations in the cabin. The last 4 months included monitoring a low-wing GA model in addition to the high-wing models. At the beginning of each week, the CO detectors were installed in the cabin by a technician and were turned on. The detectors remained on the particular aircraft for the whole week, continuously monitoring CO (at a sampling rate of one sample every 10 seconds, or 0.167 Hz). At the end of each week, all CO detectors were removed from the aircraft, the data were downloaded, and the detectors were recalibrated. The calibrated CO detectors were then placed on a different aircraft for the next week of CO monitoring. The CO detectors sampled CO continuously, which included when the aircraft was taxiing, in flight, and when it was parked and not in use. Therefore, to ensure proper analysis, it was necessary to correlate the detected CO level to the status of the airplane. Two different methods were used. First, a battery-operated GPS device (GPSTrackStick, RE Williams, Inc., Valencia, CA, USA) sampling at a rate of one sample per minute (0.017 Hz) was placed in the cabin. The GPS was used to identify the altitude, location, and time of takeoff and landing of the aircraft. Second, a questionnaire was prepared that included a time log for flight events, such as engine startup, takeoff, landing, and engine shutdown, as shown in figure 6. The questionnaire was completed by the pilot for each flight. From the GPS device and the questionnaire time log, the relevant operation time between engine startup and engine shutdown could be determined for each flight. Ambient levels of CO were determined as a function of aircraft model (high-wing, low-wing), and where the aircraft was on the ground or in the air. The results of this study were gathered and analyzed and are provided in appendix B.

GENERAL AVIATION PILOT QUESTIONNAIRE

Aircraft's Type/Model: __________ Tail Number: _________ Flight date: ____/____/____

- **Type of Flight**: ○Touch and Go's ○Cross-Country ○ Other
- **Altitude range during the flight**:

___ Below 2,000 ft. ___ 2,000 to 4,000 ft. ___ 4,000 to 6,000 ft. ___ 6,000 to 8,000 ft.

- **Flight time**: Start: _____ hr _____ min Temp/DP: ______ Altimeter: ______

End: _____ hr _____ min Temp/DP: _______Altimeter: ______

■ Heating system during the flight was (Specify time):___ On___ Off ___ Sometimes on

From Until	From Until	From Until	From Until	From Until

■ Fresh air vents during the flights were: ___ Open ___ Closed ___ Sometimes open

■ Which windows were open during the flight (specify time):

Right window	From Until	From Until	From Until	From Until
Left window				

■ Comments:

Turn On: Press and hold for **5** seconds **Turn Off**: Press and hold for **5** seconds

Figure 6. The GA Pilot Questionnaire

Flight Procedure	Time
Engine start at 1000 RPM	
Taxi to run-up area	
Arrive run-up area	
Increase engine power to 1800 RPM	
Decrease engine power to idle at 650 RPM	
Taxi to runway	
Arrive at runway hold short line	
Cleared for take-off	
Take-off full engine power 2150 RPM	
Landing	
Engine shutdown	

Comments:--

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Figure 6. The GA Pilot Questionnaire (Continued)

5. EXHAUST SYSTEM MAINTENANCE AND INSPECTION.

This section focuses on maintenance and inspection issues related to CO exposure in GA aircraft. The objectives were to determine what the possible sources of CO are, the pathways for infiltration of CO into the cockpits, and the procedures for maintenance and inspection of GA aircraft exhaust and heater systems. This is an important objective because exhaust and heater system maintenance is the primary mechanism for preventing CO exposure in GA aircraft. Three major sources of information were used to achieve these objectives: (1) maintenance- and inspection-related information retrieved from CO-related accident/incident reports in the NTSB database, (2) existing regulations pertaining to GA aircraft maintenance and inspection in

AD 90-06-03 [18], and (3) GA aircraft service manuals [19 and 20]. The NTSB accident/incident database was reviewed to determine the potential sources of CO and their relationship to maintenance and inspection practices. Analysis of the NTSB accident/incident database revealed that two particular aircraft models were prominent in terms of the number of CO incidents. However, this may be due to the large number of these particular aircraft models in the GA fleet and not to an increased rate of CO incidence. Nevertheless, these two models were selected for further study due to their prevalence in the GA fleet. Aircraft industry maintenance practices and FAA regulations and guidelines were also studied to identify practices that may lead to poor maintenance and inspection of exhaust and heater systems. Furthermore, pathways for the infiltration of CO into GA aircraft cockpits were determined. This step provided information about potential placement locations for monitoring CO exposure through CO detectors. The results of this study are presented in appendix C.

6. BEST PRACTICES IN MAINTENANCE AND INSPECTION OF GA AIRCRAFT EXHAUST SYSTEM.

The objective of this part of the research was to ascertain best practices in maintenance and inspection of GA aircraft exhaust systems. To realize this objective, a review of current industry exhaust system inspection procedures from FAA regulations as well as maintenance manuals from several types of GA aircraft was conducted. Also, several FAA-certified GA repair stations were contacted to document the current inspection practices. A total of seven interviews were conducted. A questionnaire was prepared (as shown in figure 7) for the review and interview process. The questionnaire addressed the following areas:

- Events that trigger inspections of exhaust systems and mufflers
- Procedures and steps that are followed during an inspection of exhaust systems and mufflers
- Findings during inspections that may be related to CO exposure within the aircraft cabin
- Use of and familiarity with CO detector equipment during inspections
- Determining factors for the replacement of exhaust systems or mufflers
- Suggestions for inspection process improvements or design improvements of exhaust systems and mufflers

General Aviation Exhaust System Best Practices Questionnaire

- What triggers an inspection of a GA aircraft exhaust system? (e.g., sooty-black material on the exhaust system, exhaust smell in the cockpit, annual/100 hr inspection, etc.)
- What steps/procedures are followed for a GA aircraft exhaust system inspection?
- What indicators trigger a more detailed inspection of the exhaust system?
- What steps/procedures are followed in this more detailed inspection of the exhaust system?
- Based on your experience what indications have you found during inspections of exhaust systems or engine firewalls that have been a contributing factor to carbon monoxide problems within the aircraft cabin?
- During an exhaust system inspection and/or maintenance, is it common practice to conduct testing for carbon monoxide in the aircraft cabin?
- What types of carbon monoxide test equipment are you familiar with or have used during inspection/maintenance of exhaust systems? Which do you feel are the most effective?
- What factors determine when the exhaust system/muffler needs to be replaced or repaired?
- What suggestions do you have to improve the inspection process or improved exhaust system/muffler design?

Figure 7. Best Practices Questionnaire

This review assisted in the development of methods and practices that could be used to determine the integrity of exhaust systems. The review also provided familiarity with the signs and causes of exhaust system failures, which can facilitate the identification and prevention of exhaust system failures that may result in CO exposure. As such, two checklists were developed to assist in this process. One checklist was developed for pilots of GA aircraft to convey information to inspection stations that may be related to potential CO leakage. Another checklist was developed to assist mechanics in identifying potential signs related to faulty exhaust systems that may result in CO leakage. The results of this study and the checklists for the pilots and mechanics are presented in appendix D.

7. RESULTS.

The review of the NTSB accident/incident database revealed that CO-related accidents happened throughout the year, although accidents caused by a leakage from the muffler or exhaust system were more prevalent in the colder months. Inadequate maintenance and inspection (e.g., poor welds, unapproved modifications, missed holes or cracks in the muffler) was implicated in a large number of CO-related accidents. This supports the notion that inspecting mufflers and the exhaust system, especially by visual means alone, may be difficult. The review of the NTSB accident/incident database also indicates a strong relationship between the hours of muffler use and its failure. When the muffler was implicated as the cause of a CO-related accident, the vast majority had muffler usage greater than 1000 hours.

Each of the five prominent CO detector technologies (i.e., electrochemical, spot, biomimetic, infrared, and semiconductor) has advantages and limitations when compared to each other. Regarding the use of CO detectors in GA, some specifications like detector accuracy, quick response time, low false alarms, and low power consumption are important. Taking these characteristics into account, the electrochemical, sensor-based CO detectors may be the most suitable for use in a GA environment. The research on the specifications of CO detectors resulted in an exhaustive list of performance specifications categorized by different tiers regarding their usage in GA aircraft. Tier 1 is composed of imperative performance parameters within a GA environment while Tier 2 includes useful performance parameters and specifications for detector selection in a GA environment. Other helpful specifications are categorized in Tier 3 and Tier 4. These categorized performance parameters can help pilots make informed decisions on CO detector selection.

Monitoring ambient levels of CO during flights of GA aircraft indicated the presence of CO in the cabin when the aircraft was on the ground as well as in the air. Examining the procedures carried out before aircraft takeoff showed that most of the ground CO exposure events happened during taxiing before takeoff and after landing, particularly when the windows were open. Although the majority of CO detected in the cabin was below 10 ppm, there were a few cases in which the CO was detected above 50 ppm, the level above which the CO exposure is prohibited by FAA standards. In almost all of the cases during flight tests, this level of exposure occurred for very short durations (less than 1 minute). The analyses showed that none of the detectors placed in potential locations inside the cabin detected all the nonstandard CO exposure cases. However, further analyses revealed that setting the alarm threshold on the CO detector located at the instrument panel below the FAA standard (50 ppm) increased the chance of detecting the above 50-ppm CO exposure cases anywhere in the cabin.

The review of FAA regulations and guidance documents indicated that maintenance and inspection of GA aircraft exhaust systems is generally carried out by means of visual inspection. GA manufacturer service manuals, however, reveal that the complexity of the muffler makes it extremely difficult to visually inspect the interior of the muffler for internal corrosion and cracks, which increases the chance of missing developing or possibly even severe damage. In such a case, using remote visual inspection aids such as a mirror with a ball joint, magnifiers, and/or a borescope has been recommended to be included in maintenance and inspection programs to determine airworthiness of difficult-to-reach component.

The GA aircraft service manuals recommend replacement of mufflers after 1000 hours of use and are supported by the analysis of CO-related accidents caused by leaks in mufflers. However, the FAA regulations have no restriction on the lifetime limit of mufflers. As the GA aircraft fleet continues to age, this concern becomes an important issue.

Accompanied by a thorough visual inspection, an air pressure test with soapy water can increase the chance of identifying cracks, damage, and developing deterioration. Familiarity with the signs and causes of exhaust system failures can facilitate the identification and prevention of exhaust system failures that may result in CO exposure. The prepared checklists available in appendix D summarize this information for pilots and mechanics. Performing a thorough visual inspection and an air pressure test and determining an appropriate muffler lifetime before replacement are the primary prevention methods for CO exposure in GA aircraft. Placing a CO detector inside the GA aircraft cabin to alert the pilot of the presence of hazardous CO levels is a secondary prevention method. Regarding the different pathways of CO infiltration into the cabin and the large number of CO-related accident/incidents for which the cause of CO leakage was undetermined, this secondary prevention method can further improve the chance of preventing CO-related accidents in GA aircraft.

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APPENDIX A—CHARACTERISTICS OF CARBON MONOXIDE-RELATED GENERAL AVIATION ACCIDENTS

A.1 INTRODUCTION.

Carbon monoxide (CO), a byproduct of the combustion of fuel, is emitted in the exhaust of fuel-powered equipment and engines and is formed by the incomplete combustion of carbon-containing materials that are present in aviation fuels. CO is a hidden danger because it is a colorless and odorless gas. Exposure to CO can cause harmful health effects depending on the concentration and duration of exposure. Acute CO poisoning is associated with headache, dizziness, fatigue, nausea, and at elevated doses, neurological damage and death. Exposure to CO can result in individuals becoming confused or incapacitated before being able to leave the contaminated environment. When this occurs in an aircraft, the end result could quite possibly be an accident. To prevent accidents involving general aviation (GA) aircraft related to CO exposure, it is necessary to determine the causes of CO exposure when operating a GA aircraft. Therefore, the objective of this research was to determine the sources of CO exposure and causes of CO-related accidents/incidents in GA aircraft through the analysis of historical data from databases containing information on GA accidents and maintenance-related issues.

Two databases were evaluated for GA CO-related accidents and CO-related incidents: the National Transportation Safety Board (NTSB) database on accidents and incidents [A-1] and Service Difficulty Reports (SDR) [A-2]. The NTSB accident database contains information from 1962 to the present about civil aviation accidents and selected incidents within the United States, its territories and possessions, and in international waters. Generally, a preliminary report is available online within a few days of an accident. Factual information is added when available, and when the investigation is completed, the preliminary report is replaced with a final description of the accident and its probable cause. The SDR database contains maintenance records of aircraft being serviced from 1995 to the present, and separates the GA aircraft from the commercial airliners and other non-GA aircraft.

A.2 REVIEW OF NTSB AND SDR DATABASES.

A total of 71,712 accident cases between 1962 and 2007 were reviewed from the NTSB database. These cases were categorized into the following three groups:

- CO-related cases: This group includes accidents that were clearly related to CO exposure. Accident reports clearly stated that the probable cause of the accident was related to CO exposure. Some reports also indicated the root cause such as muffler failure, exhaust system failure, cracks in exhaust stacks, as well as the percentage of CO present in the blood.

- Potential CO-related cases: This group included accidents that may be related to CO exposure. Accident reports for this group indicated that the probable cause of the accident involved factors such as engine failure, engine power loss, and defective valves, among others that may have resulted in CO exposure. This group was initially considered for further analysis, but ultimately the lack of full reports made it difficult to accomplish further in-depth analysis. Thus, the cases in this group were not analyzed further for CO exposure characteristics.

- Non-CO-related cases: This group included accidents and incidents that were not related to CO exposure.

Of the 71,712 cases in the NTSB accident/incident database, 62 cases were directly related to CO exposure (CO-related cases). Figure A-1 depicts the total number of GA CO-related accidents as a function of aircraft manufacturers. As this figure shows, Piper and Cessna models constitute the majority of accidents among GA aircraft from 1962 to 2007.

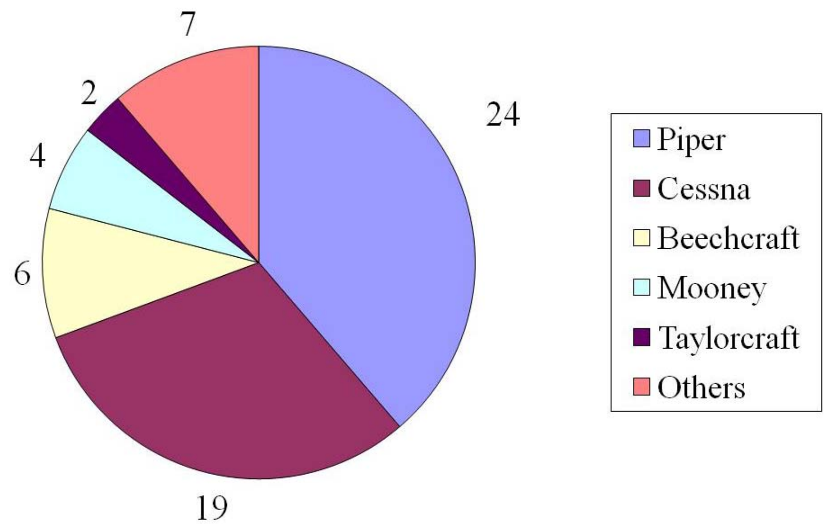

Figure A-1. Total Number of CO-Related Accidents as a Function of Aircraft Manufacturer

Figures A-2 and A-3 show the distribution of CO-related accidents for Piper and Cessna aircraft, respectively. The 62 CO-related cases from the NTSB accident/incident database were also sorted according to aircraft manufacturer and models. Figures A-2 and A-3 show that Piper models 28 and 22 and Cessna models 150 and 172 were found to have the highest "raw" number of accidents/incidents. This number, however, must be kept in perspective because these aircraft models are also the most prevalent aircraft models in service (numbering in the tens of thousands). Thus, these aircraft may not necessarily have any higher rate of incidence for CO-related accidents than other aircraft models.

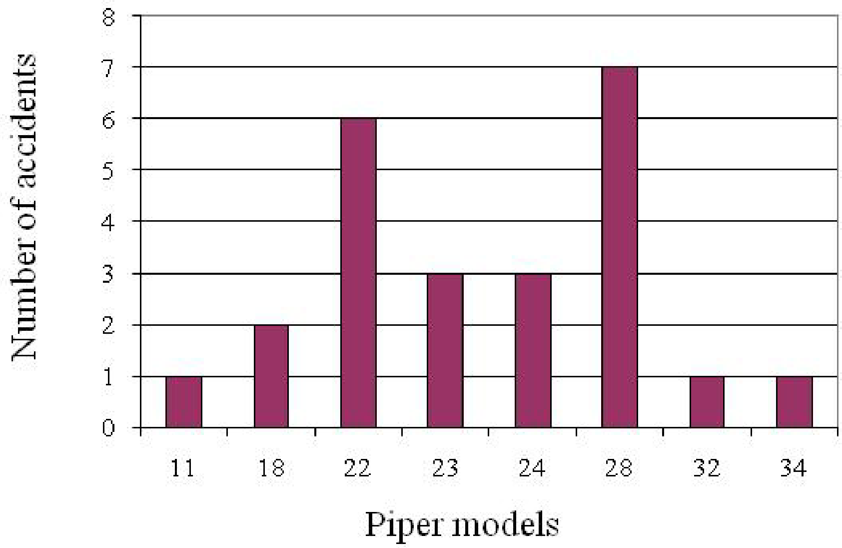

Figure A-2. Piper Aircraft Models Involved in CO-Related Accidents/Incidents

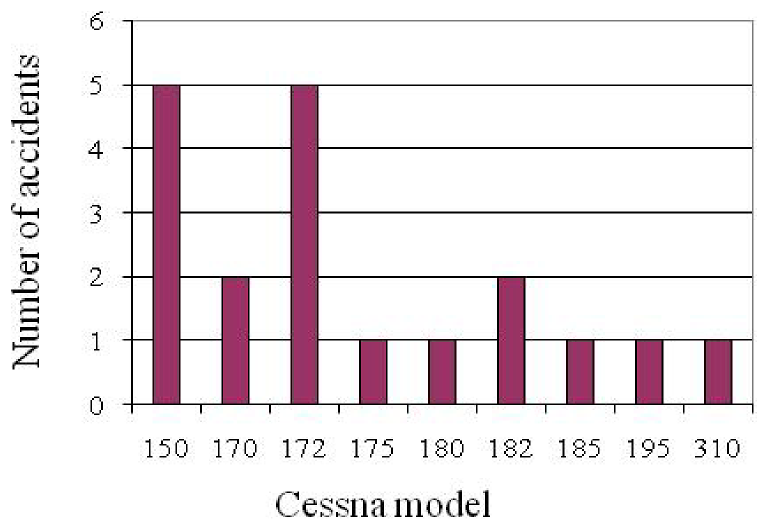

Figure A-3. Cessna Aircraft Models Involved in CO-Related Accidents/Incidents

The 62 CO-related cases were also categorized by the source of the CO leakage. As shown in figure A-4, the muffler system was the top source of CO leakage in the CO-related accidents, totaling 22 cases.

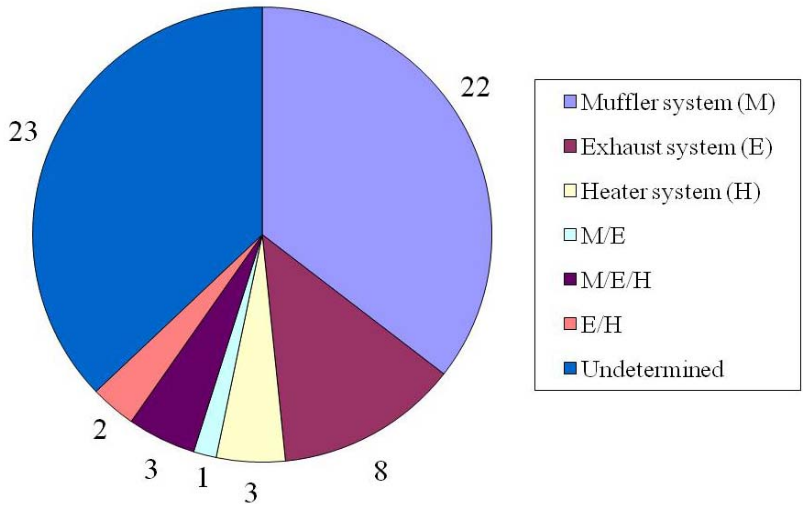

Figure A-4. The CO-Related Accidents Based on the Source of CO Leakage

The CO-related cases were further categorized based on season, with December, January, and February as the winter months, March, April, and May as spring, June, July, and August as summer, and September, October, and November as fall. Each season and month was also subdivided by source of CO leakage, as shown in figures A-5 and A-6. It was observed that muffler and heater system cases were more prevalent in the colder seasons, such as fall, winter, and spring. It was also observed that more cases in the summer were of undetermined causes. While most cases with an undetermined source were clustered in the summer, roughly the same number of CO-related accidents/incidents occurred in every season.

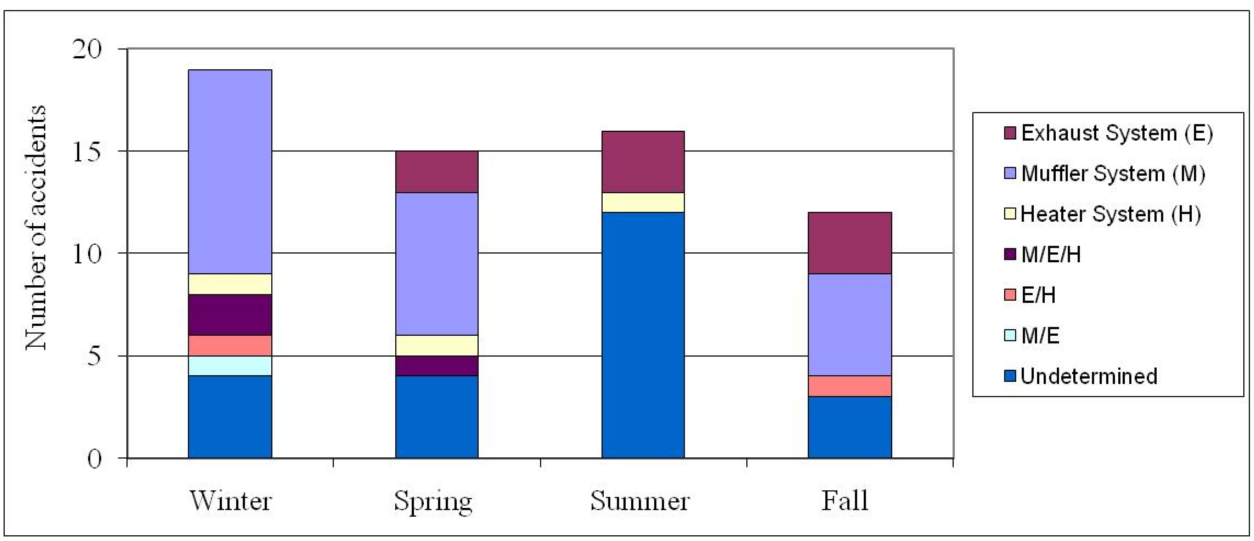

Figure A-5. Seasonal Distribution of CO-Related Accidents and Their Source of CO Leakage

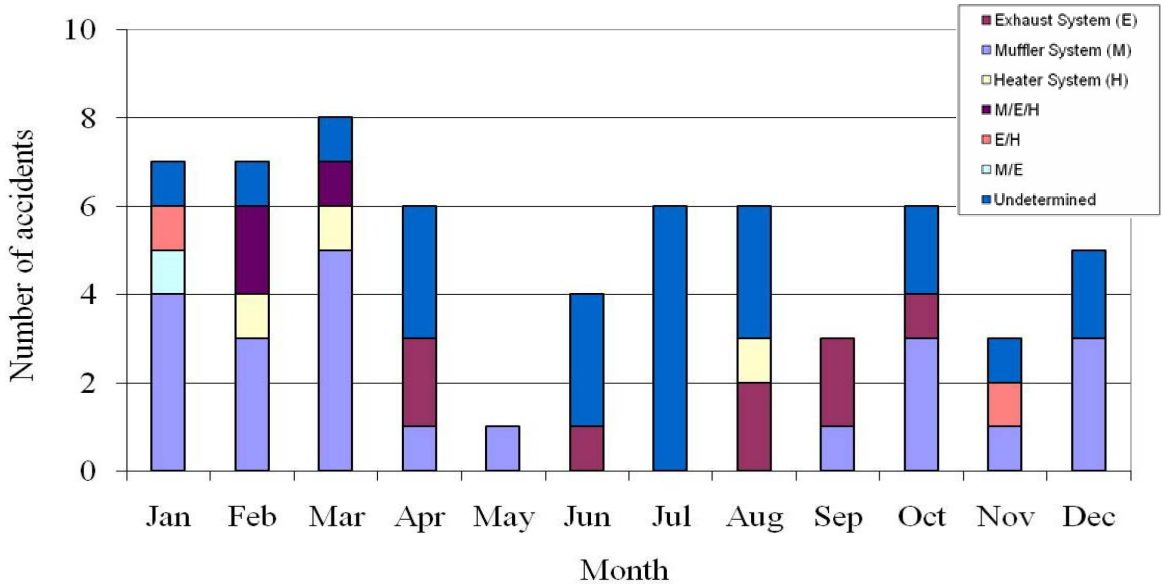

Figure A-6. Monthly Distribution of CO-Related Accidents and Their Source of CO Leakage

Figure A-7 shows the average percentage of carboxyhemoglobin in the blood with respect to the different sources of CO leakage. Where data were available in the NTSB accident reports, most sources of CO exposure related to the accident resulted in average CO in the blood of at least 20 percent, which, as shown in table A-1 [A-3], is consistent with headache and drowsiness.

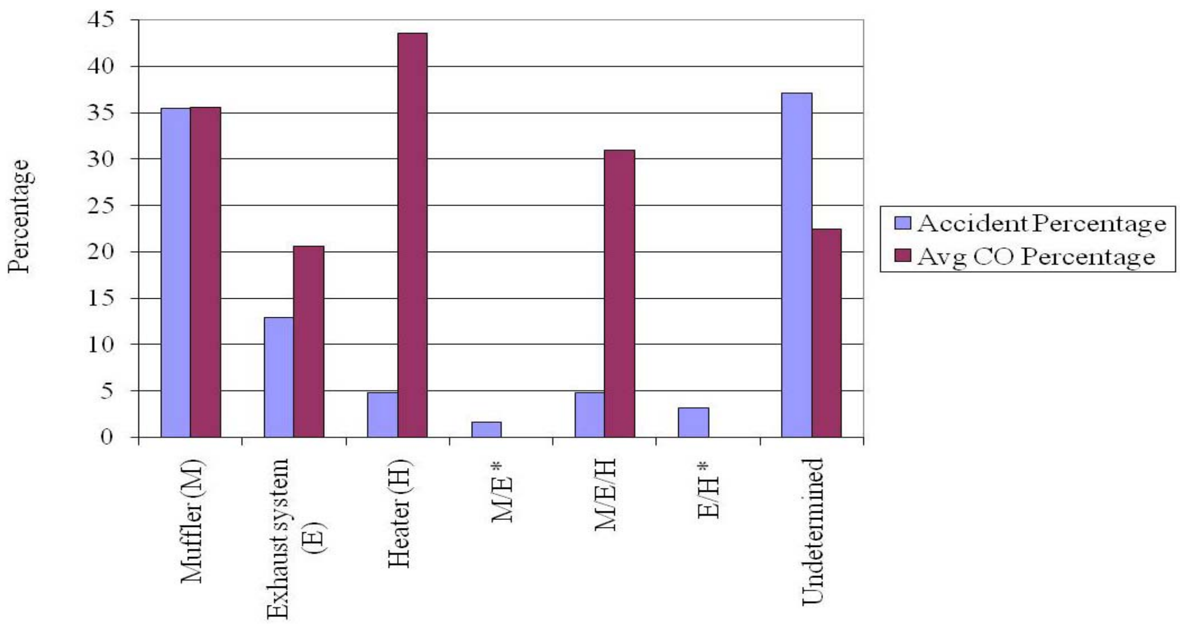

Figure A-7. Average Percentage of CO in Blood (*No CO Percentage Data Given)

Table A-1. Percentage of CO in the Blood and Possible Symptoms [A-3]

Percent CO in Blood	Typical Symptoms
<10	None
10-20	Slight headache
21-30	Headache, slight increase in respirations, drowsiness
31-40	Headache, impaired judgment, shortness of breath, increasing drowsiness, blurring of vision
41-50	Pounding headache, confusion, marked shortness of breath, marked drowsiness, increasing blurred vision
>50	Unconsciousness, eventual death if victim is not removed from the source of CO

For most cases after 1990, the NTSB database accident reports included longer narratives that included forms containing maintenance and inspection information. The full narratives of the NTSB database reports typically classified the cases into four different maintenance or inspection categories, as shown in figure A-8. From the NTSB database accident/incident reports [A-1], "inadequate maintenance" indicates that the maintenance or repair on a part was not approved or was not performed adequately (e.g., poor weld, poorly repaired or improperly modified muffler), "inadequate inspection" indicates the inspection missed a problem that existed at the time of the inspection (e.g., holes or cracks in the muffler that were missed), "inadequate maintenance and inspection" indicates both inspection and maintenance were not performed adequately, and "missed inspection" indicates the aircraft missed its required annual or 100-hour inspection.

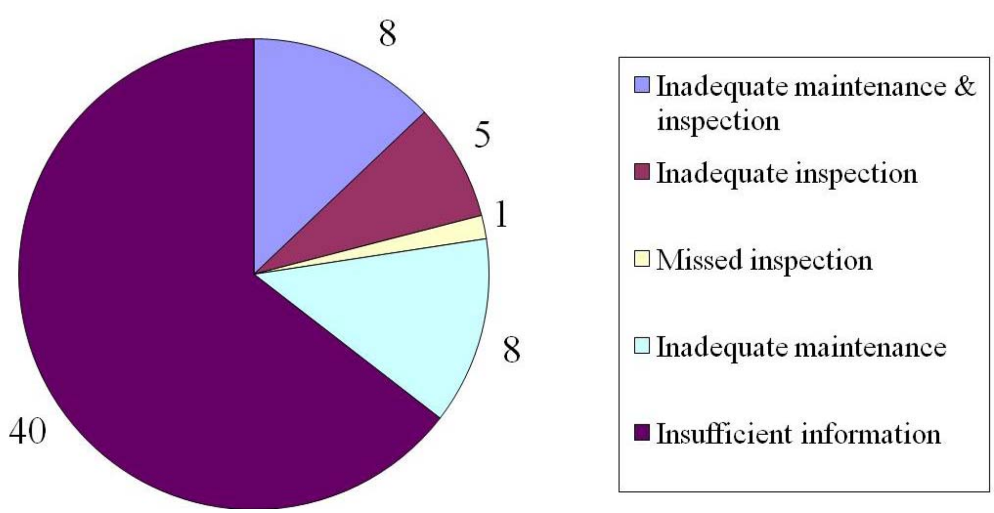

Figure A-8. Inspection and Maintenance Issues for CO-Related Cases

Due to insufficient information (or the case not being inspection- or maintenance-related), most cases could not be classified under one particular category. The largest number of cases with a known inadequate inspection or maintenance contributor in figure A-8 was "inadequate maintenance and inspection" and "inadequate maintenance." When the CO-related cases were categorized according to these inspection and maintenance classifications, including those cases before 1990 that had no such inspection- or maintenance-related statements (i.e., insufficient information), an obvious conclusion or relationship based on this classification alone was not apparent. However, focusing on the cases where there was information related to maintenance and inspection, as shown in figure A-9, the majority of the maintenance and inspection issues were related to the muffler and exhaust system. Additionally, all of the "inadequate inspections" cited the muffler as the source of CO exposure.

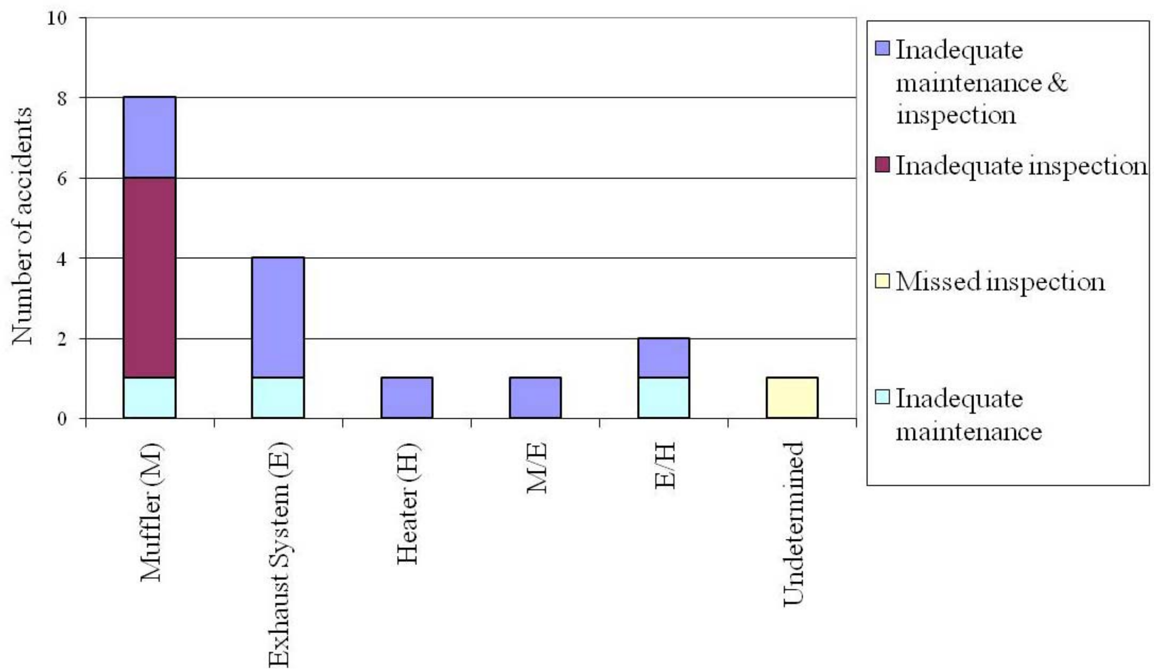

Figure A-9. Inspection and Maintenance Issues for CO-Related Cases Based on Cause of Accident/Incident

Some of the NTSB accident narratives indicated the hours that the muffler had been in use. For the CO-related cases where the muffler was identified as the source of the CO leakage, 13 cases identified the number of aircraft flight hours in the accident narrative. As shown in figure A-10, 12 of the 13 cases (92%) had mufflers with the flight hours exceeding 1000 hours, eight of the 13 cases had mufflers with the flight hours exceeding 1500 hours (62%), and six of the 13 cases (46%) had flight hours exceeding 2000 hours. Thus, based on available data, it appears that when the muffler was identified as the source of CO leakage, the majority of mufflers had more than 1000 hours. This is consistent with at least one manufacturer service manual [A-4], which recommends replacing the muffler after every 1000 hours of use.

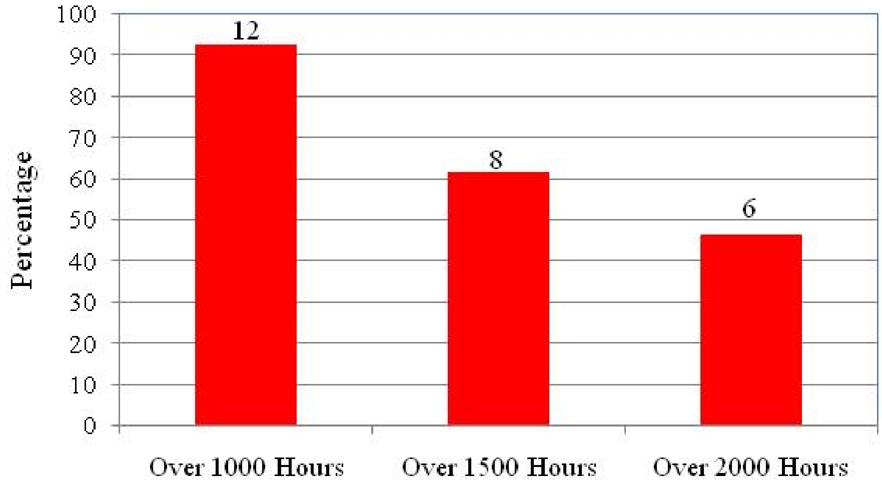

Figure A-10. Percentage of GA Aircraft CO-Related Accidents/Incidents as a Function of Hours of Muffler Use

The second part of the CO-related accident/incident review included a review of the Federal Aviation Administration (FAA) SDR database. The objective for reviewing the SDR database was to identify reported maintenance issues with respect to exhaust systems, which may provide insight into inspection and maintenance practices. The SDR database contains maintenance records of aircraft being serviced from 1995 to present, and separates the GA from the commercial airliners and other non-GA aircraft. However, the database contains only the reports that are voluntarily submitted. This indicates that the reports in the SDR database may represent a small percentage of all the maintenance performed and maintenance issues found.

The SDR database was searched using keywords related to exhaust systems such as "muffler," "heat exchanger," and "heater shroud," which resulted in approximately 400 reported cases. All cases whose failed part was related to the exhaust system, including exhaust stacks, firewall, heat exchanger, etc., were separated so as to identify any major issues that appeared. Each incident had its own specific circumstance. Therefore, each keyword-selected case was then read to identify any key notes by maintenance personnel or issues from manufacturers. Among the approximately 400 cases identified, no general trends could be observed. However, there were specific cases of interest. One case specifically mentioned that a pressure test was performed, and another report stated that a pressure leak was discovered. Two reports mentioned that the mufflers were old and should have been replaced earlier, whereas some reports mentioned failures of newly repaired welds on the muffler. The SDR database also had several remarks about muffler problems that were discovered upon the removal of the muffler shroud during an inspection.

A.3 CONCLUSIONS.

The review of the NTSB accident/incident database indicates that CO-related accidents due to muffler and exhaust system leakage were more prevalent in the colder months. However, CO accidents occur throughout the year, including the summer months. Additionally, inadequate maintenance and inspections (e.g., poor weld, poorly repaired or improperly modified muffler, holes or cracks in the muffler that were missed) were involved in a sizeable proportion of the CO-related accidents. The NTSB accident/incident data supports the known difficulty of inspecting mufflers and the joints in the exhaust system already identified by the FAA through various communications. Furthermore, reports from the SDR database revealed some case-by-case issues with mufflers, but no general trends could be identified. Finally, the review of the NTSB accident/incident database indicates a strong relationship between the lifespan of mufflers and their failure, where a large majority of the mufflers that were determined to be the cause of the CO exposure had muffler usage greater than 1000 hours.

A.4 REFERENCES.

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A-4. Aircraft Corporation, "Piper PA-28 Cherokee Series Service Manual," last revision 2002.

APPENDIX B—CARBON MONOXIDE DETECTOR EVALUATION

B.1 INTRODUCTION.

Carbon monoxide (CO), a byproduct of the combustion of fuel, is emitted in the exhaust of fuel-powered equipment and engines and is formed by the incomplete combustion of carbon-containing materials that are present in aviation fuels. CO is a hidden danger because it is a colorless and odorless gas. Exposure to CO can cause harmful health effects depending on the concentration and duration of exposure. Acute CO poisoning is associated with headaches, dizziness, fatigue, nausea, and at elevated doses, neurological damage and death [B-1]. Exposure to CO can result in individuals becoming confused or incapacitated before being able to leave the contaminated environment. When this occurs in an aircraft, the end result could be an accident.

The Federal Aviation Administration (FAA) standard for CO in the aircraft cabin is no more than 50 parts per million (ppm) [B-2], but there currently is no requirement to monitor for CO in the cabin. Due to the colorless and odorless characteristics of CO, it is extremely difficult to determine if hazardous levels of CO are in the cabin without some type of CO detector technology. However, little guidance exists regarding suitable CO detector technology for use in general aviation (GA) aircraft. Additionally, if CO detectors are used in the cabin of GA aircraft, no guidance exists to suggest the best placement for the CO detector to detect CO quickly and accurately. Therefore, the major objectives of this research were to (1) review and summarize CO detector technology and performance characteristics to identify CO detectors that may be suitable for use in GA aircraft, and (2) determine the best placement of the CO detector inside the cabin. Portable CO detector devices were reviewed without consideration of the approval process for the design and installation of permanently installed CO detectors.

B.2 THE CO DETECTOR EVALUATION.

B.2.1 THE CO DETECTOR TECHNOLOGY.

The following approach was followed: (1) current CO detector technology was identified and reviewed, (2) CO detector specifications were identified, and (3) CO detector specifications that are important to consider for use in a GA environment were prioritized.

CO detectors generally fall into five technology categories based on the type of sensor. The different types are discussed in reference B-3 through B-14.

B.2.1.1 Electrochemical Sensors.

Electrochemical sensors function by measuring the amount of electrical current generated by the reaction of CO on a platinum sensor. The platinum sensor catalyzes the oxidation of CO at the anode. With the presence of water in the electrolyte solution, this oxygen-reduction reaction produces carbon dioxide, hydrogen ions, and excess electrons. Although numerous products result, the overall reaction is restricted to produce only the carbon dioxide product at the end, leaving the sensor unchanged. The electrical current based on this reaction is proportional to the amount of CO present. These detectors can be both portable (powered by batteries) or fixed units (alternating current (ac) powered).

Electrochemical sensors typically provide an accurate (to within ±3%) means of detecting CO levels and are regarded as the most accurate and dependable sensor type available to the consumer [B-3]. Electrochemical sensors are usually small and require little power, which may be beneficial for portable use. Electrochemical sensors can be used over a wide range of temperatures and can be gas-specific. However, cross-sensitivity with other gases may occur and thus provide inaccurate readings of actual CO exposure. Manufacturers of electrochemical detectors usually provide a summary of cross-sensitivity analysis conducted on a particular detector. However, Austin, et al. [B-4], indicated there may be other airborne contaminants (e.g., hydrogen sulfide) not documented by manufacturers, which may lead to false positive readings of the detector in conditions where the target gas (specifically CO) is not present. Under proper conditions (conditions absent of methanol or ethanol), electrochemical detectors can be very useful for monitoring exposure to toxic gases such as CO [B-4].

B.2.1.2 Biomimetic Sensors.

Biomimetic sensors use a sensor that mimics the effect of CO on hemoglobin. The presence of CO results in a change of color (darkening) on a gel-coated disc. A light sensor detects changes in color and trips an alarm in the event of a color change (i.e., CO exposure). Depending on the manufacturer, these detectors are powered by batteries or can be powered by ac.

Typically, biomimetic CO detectors are simple to use and cost less than other types of CO sensor technology. Power consumption for these types of sensors is generally low and thus provides an option for portability. However, biomimetic sensors can be easily contaminated by high and low temperatures, and high- and low-humidity levels [B-5]. Furthermore, the response time (i.e., the time between obtaining data from the sensor and displaying the data on the detector) for these sensors are generally slow, and once an exposure has occurred, the sensor requires time to reset (sometimes up to 48 hr [B-6]).

B.2.1.3 Spot Detectors.

Spot detectors use a sensor that mimics the effect of CO on hemoglobin, similar to the biomimetic sensor. However, spot detectors merely change color in the presence of CO and are not capable of actively alerting the pilot of the presence of CO in the cabin. Manual visual inspection is necessary to determine if the sensor indicates the presence of CO; however, CO exposure determination is subject to pilot interpretation.

It appears that many pilots of GA aircraft use spot detectors due to their low absolute cost on an individual sensor basis [B-7]. However, spot detectors provide slow reaction (i.e., slow, gradual change in color) when exposed to CO and are easily contaminated by aromatic cleaners, solvents, and other chemicals that are routinely used in aircraft maintenance. Once contaminated, it is difficult to distinguish whether the change in color is due to contamination or to actual CO exposure. Also, spot detectors cannot distinguish between acute and chronic exposures to CO, as a change in color simply signifies that CO is present, with no regard to dose.

Different dose levels may warrant different actions (e.g., high acute exposure levels may require immediate attention, while low-level chronic exposure may allow more time to react).

Spot detector manufacturers indicate the useful life of a spot detector to range between 30 and 60 days, and thus necessitate replacement on a frequent basis. Once spot detectors are exposed to CO and a change of color is present, the spot detector will gradually return to its normal color once the CO exposure has subsided. However, spot detectors are also susceptible to discoloration over time, thus providing the potential for false positive readings [B-8].

B.2.1.4 Infrared Sensors.

Infrared (IR) detectors measure the specific wavelength of CO. The presence of CO will increase the resistance in the circuit, which triggers an alarm. IR detectors can detect gases in inert atmospheres and can be gas-specific by measuring a specific wavelength. These detectors are typically manufactured for both portable and fixed use and thus can be battery-operated or ac-powered.

IR detectors require less frequent calibration than other sensors, may operate in inert environments (no oxygen present) [B-9], and provide high levels of sensitivity and accuracy. However, IR detectors are usually made to detect methane, carbon dioxide, and nitric oxides and are not commonly available (commercially) in single-gas units. A recent review indicated that IR technology sensors are superior to other sensor technology types, but due to their high cost, no residential IR-CO detector is presently available on the market [B-10].

B.2.1.5 Semiconductor Sensors.

Semiconductor sensors use an electrically powered sensing element, a thin layer of tin oxide placed over a ceramic base, which is monitored by an integrated circuit. Since the ceramic base does not conduct electricity, an open circuit is produced in the absence of CO. In the presence of CO, the flow of electrons is increased and the resistance between the wires is decreased. This results in a closed circuit and the semiconductor output varies logarithmically with CO gas concentration.

Semiconductor sensors typically have a long useful life [B-11]. However, the stability and repeatability of semiconductor sensors are generally poor, as semiconductor detectors sample in cycles; the updated cycle is obtained by burning the last cycle's sample. The output of semiconductor sensors varies logarithmically with CO concentration and thus reduces the detector's accuracy and overall measuring range. High and low humidity reduces the sensor's sensitivity as the sensitivity of the sensor to a specific gas (CO) is mediated by a codependence on water [B-12]. High and low temperatures affect the sensitivity of the sensor as the electrical resistance of the sensor material depends upon the temperature [B-12 and B-13]. Since oxygen is involved in the chemical reaction, semiconductor sensors require sufficient oxygen for the sensor to operate [B-13]. Furthermore, power consumption in semiconductor detectors is high due to the need to heat the element within the device, which limits the portability of semiconductor sensors.

B.2.1.6 Summary.

The most common types of consumer-based CO sensors are biomimetic, semiconductor, and electrochemical, whereas infrared sensors are used primarily for research purposes [B-11].

An overview of selected properties of the three predominant types of sensors is presented in table B-1.

Table B-1. General Performance of Three Predominant Sensor Types for CO Detectors [B-11]

Sensor Property	Electrochemical	Biomimetic	Semiconductor
Durability			
Lifetime	>5 yrs	>5 yrs	5-10 yrs
Short-term stability	Good	Unknown	Fair
Performance			
Resolution and accuracy	Good	Fair	Fair
Sensitivity drift	Moderate	Unknown	Moderate
Response time	Good	Fair	Fair
Immunity to false alarms	Good	Fair	Good
Immunity to false negatives	Good	Good	Good
Temperature and humidity dependence	Good (humidity) Fair (temperature)	Fair	Fair
Selectivity	Good	Good	Good
Immunity to poisoning	Good	Good	Good
Consumer Preferences			
Power consumption	Low	Low	High
Sensor cost	Low	Low	Low
Primary advantages	Reasonable cost, low power consumption, good performance	Low power consumption, Simple	Long life
Primary disadvantages	Temperature and humidity dependence, lack of long-term sensitivity data	High interference, difficult to reset quickly after CO exposure, rarely equipped with digital displays	High input power, high interference, inaccuracy

Resolution and accuracy refers to the detection limits and how close the measured value is relative to the true CO level. False alarms are instances where the detector alarms even though CO levels are low; false negatives refer to instances where the detector fails to alarm when CO levels are high. Selectivity is the detector's ability to distinguish between CO and other gases, and immunity to poisoning refers to the detector's resistance to interference from other substances or pollutants in indoor air.

Collectively considering the advantages and limitations of the various CO detector technologies, electrochemical sensors appear to be the most suitable for use in a GA environment due to their relatively high accuracy, quick response time, inherent immunity to false alarms, and low power consumption. Similar conclusions have been presented by other research regarding electrochemical sensors with respect to cost and performance [B-10].

B.2.2 THE CO DETECTOR PERFORMANCE PARAMETERS AND SPECIFICATIONS.

The Society of Automotive Engineers (SAE) Aeronautics Standard AS412 (1972) for CO detectors provides general requirements for cockpit instrument panel-mounted CO detectors [B-14]. The Standard recommends CO detectors to be functional under certain environmental conditions, such as ambient temperature (-30° to 50ºC for heated areas and -55° to 70ºC for unheated areas), humidity (0%-95% at 32ºC), altitude (detector should withstand pressure equivalent to altitudes of -1,000 to 40,000 ft), and vibration (the detector should function and not be adversely affected when subjected to vibrations of prescribed maximum amplitudes or maximum acceleration). The Standard also provides performance requirements, such as response time, stability, temperature, humidity, and vibration testing, as well as contamination testing. This SAE standard applies to fixed, panel-mounted CO detectors, which will not be considered in this review of commercially available, portable, lightweight CO detectors.

To compare the CO detectors available on the consumer market, a comprehensive list of performance parameters and specifications were identified. This comprehensive list should allow users to make informed decisions on what may be the most appropriate CO detector for their use. These performance parameters and specifications, as well as their respective definitions, are described below:

- Set points—The CO threshold levels (in ppm) at which the device will alarm and how it will alarm (e.g., more intense alarm for higher ppm threshold)

- Measuring range—The CO range the device measures (in ppm)

- Alarm loudness—The alarm loudness level (in dBA)

- Battery/sensor warning—States whether the device warns users if the device is no longer in operating condition (e.g., low batteries, failed circuitry)

- Power source—The source of power for the device (e.g., batteries)

- Instrument life—The life of the CO detector device (usually the warranty duration of the device)

- Sensor life—The life of the CO sensor. This is different from instrument life as the sensor may fail and degrade through extensive use independent of the instrument.

- Battery life—The life of the battery (conditions are stated, e.g., 3000 hr without backlight).

- Mountability—Indicates how the device may be mounted.

- Response time—The time period between obtaining data from the sensors and displaying the data [B-15].

- Accuracy—Closeness of a reading or indication of a measurement device to the actual value of the quantity being measured (indicated by "±," e.g., ±0.5%).

- Resolution—The smallest digit CO concentration level displayed on the screen (ppm).

- Temperature—The operating temperature range of the device.

- Pressure—The operating pressure range of the device.

- Humidity—The operating relative humidity (RH) range of the device (% RH noncondensing).

- Calibration method—Method by which the device is calibrated. A full calibration is the adjustment of the instrument's reading to coincide with a known concentration (generally a certified standard) of test gas [B-16]. Another method of calibration, referred to as the bump test, verifies calibration by exposing the instrument to a known concentration of test gas [B-16]. The resultant reading is observed and then compared to the actual concentration of gas present. The bump test is considered successful if readings fall within the required tolerances.

- Calibration frequency—How often the device should be calibrated. According to the International Safety Equipment Association (ISEA) [B-16], a full calibration of direct-reading portable gas monitors should be made before each day's use in accordance with manufacturer's instructions, using an appropriate test gas. ISEA also provides certain criterion that requires less frequent verification.

- Calibration time—The time it takes to calibrate the device.

- Alarm type—States whether the device has audio, visual, and/or vibrating alarms.

- Weight—Weight of the device (grams).

- Long-term output drift—Measure of loss of sensitivity and/or environmental influences on the device's response after a long period of time.

- Repeatability—The closeness of agreement amongst a number of consecutive measurements of the output for the same value of input under the same operating condition.

- Enclosure protection rating (Ingress Protection, IP)—A two-digit international rating system that classifies the ability to withstand ingress from either solid particles or liquids [B-17].

- First IP digit—protection against solid objects

  0 - No protection
  1 - Protected against solid objects up to 50 mm (e.g., accidental touch by hands)
  2 - Protected against solid objects up to 12 mm (e.g., fingers)
  3 - Protected against solid objects over 2.5 mm (e.g., tools and wires)
  4 - Protected against solid objects over 1 mm (e.g., tools, wire, and small wires)
  5 - Protected against dust, limited ingress (no harmful deposit)
  6 - Totally protected against dust

  Second IP digit—protection against liquids

  0 - No protection
  1 - Protection against vertically falling drops of water (e.g., condensation)
  2 - Protection against direct sprays of water up to 15º from the vertical
  3 - Protected against direct sprays of water up to 60º from the vertical
  4 - Protection against water sprayed from all directions—limited ingress permitted
  5 - Protected against low pressure jets of water from all directions—limited ingress
  6 - Protected against low pressure jets of water (e.g., for use on ship decks)—limited ingress permitted
  7 - Protected against the effect of immersion between 15 cm and 1 m
  8 - Protects against long periods of immersion under pressure

- Radio frequency protection—The detector's ability to protect the readings from interference caused by radio waves, pulsed power lines, transformers, and generators [B-15].

- Datalogging—Specifies whether the device has datalogging capabilities.

- Datalogging features—Identifies the datalogging features of the device.

- Sampling method—How the sensor comes in contact with the atmosphere [B-15]. Involves the collection of the target matter (CO). There are two primary sampling methods: sample draw where the sample is moved to the sensor via a hollow tube using a pump, and diffusion where air is absorbed into the sensor.

- Certifications—Notable safety/quality/health certifications, such as ISO 9001, UL, Hazardous rating (Class 1, Division 1, Groups A, B, C, D).

- Manual/information—Source of information and/or manual for the device.

- Sensor type—CO-detecting technology (electrochemical, semiconductors, biomimetic, infrared, or spot detectors).

B.2.3 PRIORITIZATION OF CO DETECTOR SPECIFICATIONS.

From the list of CO detector performance parameters and specifications identified in the previous section, a priority list was developed categorizing the performance parameters and specifications into four tiers, based on the importance of application in a GA environment.

B.2.3.1 Tier 1.

Tier 1 performance parameters include specifications that are considered to be important for operation in a GA environment and are listed below:

- Set point: It is imperative in a GA environment that CO detectors alarm at certain levels. Although the Federal Aviation Administration (FAA) requirement is 50 ppm, a lower alarm level that protects against the chronic effects of CO may be desired. The ability to program these alarm levels may be desirable in that alarm set points can be changed to correspond with the FAA CO requirement or other desirable lower ppm levels.

- Measuring range (10-50 ppm): This is a very important parameter in a GA environment as it would be of little or no benefit if the CO detector measured CO concentrations outside the range for GA safety consideration. However, most detectors measure well within a desirable range (10-50 ppm), which includes the threshold level regulated by the FAA (50 ppm).

- Alarm loudness: Sound levels within the GA cabin may reach 90 dB or higher [B-18], thus an alarm loudness level at or higher than 90 dB is desirable to alert the pilot. Many CO detectors alarm below 90 dB, which may be less desirable for use in a GA environment if the cabin noise levels are higher than the audible alarm level of the CO detector.

- Battery or sensor warning: A CO detector should have the capability to warn the pilot about low-battery levels or about device malfunctions to assure the pilot that the CO detector is functioning properly.

- Power source: CO detectors should draw power from batteries and not from external power sources (i.e., aircraft power supply) to prevent interference with aircraft electrical circuitry. Thus, only portable, battery-powered CO detectors were considered in this investigation as opposed to fixed CO detectors.

- Price: A CO detector should not be so cost prohibitive as to raise resistance from pilots to incorporate the use of CO detectors within the aircraft.

- Useful life: Three parameters, instrument-, sensor-, and battery life, were considered under this category. The instrument life should be as long as possible to reduce the frequency of replacement. Frequent replacement increases the cost, and the possibility of a delayed replacement would void any safety benefits of the CO detector. Similar to instrument life, a long sensor life is desired. Battery life of the CO detector should be long enough for the pilot to use for the duration of a flight. A longer battery life is desirable.

- Mountability: The means by which the CO detector can be mounted to a surface within the cabin.

B.2.3.2 Tier 2.

Tier 2 performance parameters are considered to be of secondary importance for a GA environment and are not ranked as high a priority as those categorized into Tier 1. Additionally, most CO detector performance parameters categorized as Tier 2 shared similar specifications for these parameters across many detectors. For example, response time was considered to be a critical performance parameter when CO detectors are used in a GA environment. However, CO detectors available on the market all had similar response times, which were all less than 1 minute. Tier 2 performance parameters are listed below:

- Accuracy: Accuracy of the reading is an important parameter for any measurement device, especially a safety-measuring device. However, the accuracy of the CO reading was categorized as Tier 2, as most of the CO detectors exhibited comparable reported accuracy.

- Resolution: It is important that pilots be able to distinguish varying levels of CO exposure in smaller increments (i.e., increments of 1 ppm are better than 10 ppm). Most CO detectors exhibited similar reported resolution levels (1 ppm/5 ppm); therefore, CO detector resolution was considered to be a Tier 2 performance parameter.

- Environmental Conditions: Environmental conditions, such as temperature, humidity, and pressure, are important factors to consider as the accuracy of CO detectors may be adversely affected by these factors. The reported environmental performance specifications for most CO detectors fell within similar ranges; therefore, these performance parameters were categorized as Tier 2.

- Calibration (frequency, method, and time): Calibration is necessary to verify the CO detector-measuring accuracy. Calibration was not considered to be unique for GA applications; thus, it was not considered to be a Tier 1 parameter.

- Alarm type: Alarm methods (i.e., auditory, visual, and vibratory) are important for safety devices to alert the pilot of cautionary conditions. Most CO detectors exhibited multiple alarm methods, many including auditory, visual, and vibratory mechanisms. Although redundancy (having more than one alarm method) is an important safety feature, redundant alarm methods were considered to be a Tier 2 performance parameter (as opposed to CO detectors possessing an audible alarm mechanism at a level loud enough to be heard in the cabin of a GA aircraft (Tier 1 category)).

- Weight and dimensions: Physical characteristics of the CO detector (weight and dimensions) are important parameters in a GA environment where space and weight are critical. However, these specifications were considered to be Tier 2 parameters since most portable CO detectors were similar in size and weight.

B.2.3.3 Tier 3.

Tier 3 performance parameters consist of features and specifications that were considered to be of lower importance for a GA environment than the first two tiers. Tier 4 performance parameters are listed below:

- Long-term output drift: Loss of CO detector sensor sensitivity over time may affect the performance of the CO detector. However, long-term output drift was considered a Tier 3 performance parameter as this loss in response sensitivity occurs in any device after prolonged use. Furthermore, frequent calibration (a Tier 2 performance parameter) and proper replacement of the CO detector sensor, according to the manufacturer's recommendation, ensures device accuracy.

- Repeatability: Repeatability of the CO measurement was considered a Tier 3 performance parameter since most CO detectors were reported to possess similar repeatability performance.

- Enclosure protection rating: The enclosure of the CO detector should be protected from the surrounding environment. The intended use of these detectors for GA applications may not be directly impacted by extreme environments.

- Radio frequency (RF) protection: The CO detector should be protected from RF disturbances. However, the specifications for many CO detectors did not provide this information.

- Datalogging: Datalogging capability was considered a Tier 3 performance parameter as pilots may be of little or no use.

B.2.3.4 Tier 4.

Tier 4 performance parameters were miscellaneous parameters that were not considered to be important for GA applications. Tier 4 performance parameters are listed below:

- Sampling method: The specific method (i.e., sample draw, diffusion) may not be that important as long as samples are indeed taken.

- Certifications: Safety, quality, and health certifications are miscellaneous information pertaining to an individual CO detector. Furthermore, no certifications are currently available for GA use.

- Manual/information: Source of information and manuals were merely miscellaneous information pertaining to where information for a specific CO detector may be obtained. This information may be important to obtain subsequent information, such as the performance specifications of a certain CO detector.

- Sensor type: The specific sensor type (e.g., biometric, electrochemical, semiconductor) was considered to be a Tier 4 performance parameter since the characteristics and specifications of these sensor types (e.g., accuracy, power source, measuring range, etc.) are already addressed in the higher priority performance parameter categories.

Performance parameters and specifications (i.e., Tiers 1 through 4) of various CO detectors on the market were compiled into a database, which allowed for a comparison of CO detector performance parameters and specifications with respect to the GA environment. Tier 1 through Tier 4 CO detector performance parameters and specifications are shown in tables B-2 through B-5.

Table B-2. Tier 1 CO Detector Performance Parameters and Specifications

Company	Model	Set Points (ppm)	Measuring Range (ppm)	Alarm Loudness	Battery/ Sensor Warning	Power Source	Price	Instrument Life	Sensor Life	Battery Life	Mountability
Kidde Safety	KN-COB-B	NP/70, 150, 400	30-999	85 dB at 10 ft	Yes	3 AA alkaline batteries	$24.95	5-yr warranty			Accessories for wall mounting
Kidde Safety	KN-COPP-B	NP/ 70, 150, 400	30-999	85 dB at 10 ft	Yes	3 AA alkaline batteries	$39.97	5-yr warranty			Accessories for wall mounting
CO Experts	2004	NP/10, 25, 35,50, 70	10-70	85 dB at 10 ft	Yes	9-V alkaline battery	$120	1-yr warranty (5-yr expectancy)	10-12 yrs	Lifetime	
Extech Instruments	CO50	NP/30	0-10,000		Yes	2 AA batteries	$229		3 yrs	30 hrs with backlight	
BW Technologies	GAXT-M-DL	P	0-1,000	95 dB	Yes	3-V camera battery	$295/ $395 with datalogger	2-yr warranty	2 yrs	2 yrs	Alligator clip
Industrial Scientific	Gas Badge Pro	P	0-1,500	95 dB at 10 cm	Yes	3-V, CR lithium battery	$375	Life		2600 hr	Docking compatible
Industrial Scientific	Gas Badge Plus	P	0-1,500		Yes	Nonreplaceable lithium	$195	2 yrs		2 yrs	
Industrial Scientific	T40 Rattler	P	0-999			1 AA battery	$195	2 yrs		1500 hr	
Enmet Corp	TX-2000	P/2 set points	0-500		Yes	3 alkaline batteries	$595	1-yr warranty	2 yrs	1000 hr	Belt clip
Enmet Corp	RECON/4	P	0-1,000		Yes	Lithium rechargeable	$595	1-yr warranty			Belt clip
ATMI Sensoric	CO 3E 300		0-500					2-yr warranty	>36 months		
ATMI Sensoric	CO 3E 500 S		0-500					12 months	>24 months		

Table B-2. Tier 1 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Set Points (ppm)	Measuring Range (ppm)	Alarm Loudness	Battery/ Sensor Warning	Power Source	Price	Instrument Life	Sensor Life	Battery Life	Mountability
City Tech	IRidium® 50		0%-15%			Outlet (<1W avg power)		1-yr warranty			
City Tech	4CF-CO (with H2S and SO2 filter)		0-500 (1,500 max overload)			Connected via PCB sockets		2 yrs			
Lumidor	MiniMax Xt	NP/35, 100	0-200	95 dB at 10 cm	Yes	3.6V nonreplaceable	$195	2 yrs	24 months from activation		Belt clip
MSA	Altair	P/25, 100	0-500	95 dB at 1 ft	Yes	Lithium nonreplaceable	$120	>2 yrs			Rugged clip
Drager	PAC 5000	NP/35, 50 (can be requested)	0-500	90 dB at 11.8 in.	Yes	Lithium	$245	>2 yrs	>2 yrs	>10,400 hr	Clip
Oldham	RX500		0-1,000	80 dB at 30 cm	Yes			>2 yrs	>2 yrs		Anti-skid clasp, armband
Biosystems	Toxi-Vision EX	Factory set alarm levels (P via PC)		92 dBA at 1 ft		Rechargeable NiMH	$395	2-yr warranty	2 yrs	15 hr	Steel clip
Biosystems	Toxipro	P/4 user specified set points	0-1,000		Yes	Lithium	$239	>2 yrs		9,000 hr	Alligator clip
Biosystems	TOXILTD	P/4 user specified set points	0-1,000		Yes	Lithium	$239	2-yr disposable		2 yrs	Alligator clip
Biosystems	TOXI3LTD	P/4 user specified set points	0-1,000		Yes		$239	3-yr disposable		3 yrs	Alligator clip

Table B-2. Tier 1 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Set Points (ppm)	Measuring Range (ppm)	Alarm Loudness	Battery/ Sensor Warning	Power Source	Price	Instrument Life	Sensor Life	Battery Life	Mountability
Aerion Technologies	Shield	NP/35, 200	0-995	85 dB at 1 ft	Yes			2 yrs (max 36.5-alarm hrs)			Alligator pocket/belt clip
Crowcon	Gasman	NP/35 (2 set points available upon request)	0-500	95 dB	Yes	Lithium-ion rechargeable	$410	2 yrs	2 yrs	12 hr	Pocket clip
Cosmos	XC-2000	NP/50, 150	0-300		Yes	Lithium (reusable with new batteries)				2 yrs (without alarming)	Attachment clip, strap
Cosmos	XC-341	NP/50, 150	0-300			2 AA manganese dry cell				200 continuous hrs	Leather carrying case, optional tripod
Cosmos	XP-333H	NP/50, 150	0-300			4 AA alkaline				16 hrs without alarming	Leather carrying case
Quest Technologies	Safetest 90	P	0-1,500		Yes	Alkaline/ lithium	$410	1-yr warranty	1 yr	Alkaline: 5,000 hrs, Lithium: 10,000 hrs	
Quest Technologies	Safelog 100	P	0-999		Yes	Replaceable 9V battery	$810	1-yr warranty	2 yrs	100-hr continuous	
Quantum Eye	Passive Spot CO Detector	N/A	3 warning levels: Danger (Dark Blue), Caution (Green), Normal (Yellow)	N/A	No	N/A	$9.75 (several cheaper prices)	18 months	18 months, reusable if not over-exposed	N/A	Adhesive backing mounts anywhere

Table B-2. Tier 1 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Set Points (ppm)	Measuring Range (ppm)	Alarm Loudness	Battery / Sensor Warning	Power Source	Price	Instrument Life	Sensor Life	Battery Life	Mountability
RKI	Gas Watch 2	NP/ 25, 50 (TWA 25)	0-500	87 dB at 3 ft	Yes	Lithium	$323	2-yr warranty	2 yrs	About 3000 hrs with no alarms or Backlighting (about 1 yr normal use)	Watchband (optional), belt clip
RKI	01 Series Monitor	NP/ 25, 50 (TWA 25)	0-500	87 dB at 3 ft	Yes	2 AAA	$395	2-yr warranty	2 yrs	>3000 hrs at 25°C and no backlighting	Belt clip/ alligator clip, wrist strap
Uei	CO Detector (CO71)	NP/>35	0-999			9V battery	$275	3 yrs			Carrying case
Pro Tech	7035	NP/40-70 (chronic at 60-240 min), 400 (acute at 4-15 min)	10-500	85 dB at 10 ft	Yes	9V DC battery	$83.99	5-yr warranty	Sensor life monitor	5 yrs	Mounting accessories
Pro Tech	7035 - SL	NP/40-70 (chronic at 60-240 min), 400 (acute at 4-15 min)	10-500	85-dB pulsating alarm	Yes	9V lithium- 5-yr battery life	$65.83	6-yr warranty	Sensor life monitor	6 yrs	Mounting accessories
Pro Tech	8505	NP (TWA <=8 hr 20; TWA <=6 hr 45; TWA <=1 hr 100)	10-200	85 dB at 10 ft	Yes	9V DC battery	$78.75	2-yr (1-yr warranty)	Sensor life monitor		Mounting accessories

Table B-2. Tier 1 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Set Points (ppm)	Measuring Range (ppm)	Alarm Loudness	Battery/ Sensor Warning	Power Source	Price	Instrument Life	Sensor Life	Battery Life	Mountability
Quantum	Costar P-1	NP/35-70 (4 beeps under 60 min), 70 at 60-240 min, 150 at 10-50 min, 400 at 4-15 min		70 dB at 2 in.	Yes	9V Battery	$41	5 yrs (1-yr warranty)		About 1 yr	Clips
The Pocket CO		NP/25, 35 (OSHA TWA), 125, 400	0-600		Yes	Battery	$129	1 yr	1 yr	About 1 yr	Clip/ pocket-size
CO Guardian	AERO-152A (for aviation use) (higher-end models available)	NP/50-70 (10 min), 70-150 (5 min), 200 (3 min), 300 (1 min), 400 instant	40-900	85 dB at 10 ft	Yes	DC 12-30V (cigarette lighter)	$179	7 yrs (3-yr warranty)	5-7 yrs	N/A	Portable
CO Guardian	Aero 152WD	NP/50-70 (10 min), 70-150 (5 min), 200 (3 min), 300 (1 min), 400 instant	40-900	85 dB at 10 ft	Yes	DC 12-28V (cigarette lighter)	$149	1-yr limited warranty		N/A	Portable
COMAG IR	Smart-scan ppm 4021H	P	0-100, 0-250, 0-500, 0-1,000 user selectable			110-220VAC				N/A	Wall mounting
Testo	CO Stick	P	0-1,999		Yes	2 AAA	$229.95	2-yr warranty	3 yrs	150 hr (with alarm off)	Belt clip

Table B-2. Tier 1 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Set Points (ppm)	Measuring Range (ppm)	Alarm Loudness	Battery/ Sensor Warning	Power Source	Price	Instrument Life	Sensor Life	Battery Life	Mountability
MSA	Pulsar+ Single Gas Detector	Factory set alarm levels 35, 100(P)	0-500	95 dB	Yes	Replaceable 3V lithium battery	$405.95	Lifetime (chassis, electronics)	2 yrs		Belt clip
Extech Instruments	CO10	Audible Alarm starts at 35 ppm	0-1,000			9V battery	$245.00		3 yrs	50 hr with alkaline battery	
Professional Equipment			0-1,000			4-pcs 1.5V (AAA size) UM-4 R03	$199.95			200-hr Typical	
RAE Systems	Toxi RAE		0-99.9 100-2,000	90 dB		2 AAA	$100.00	2 yrs (nonconsuming component), 1 yr for others		1000 hrs	
Passive CO Detector Badge		N/A	N/A	N/A	No	N/A	$2.95			N/A	
CO Detector		N/A	N/A	N/A	No	N/A	$4.25			N/A	
BW Technologies	Gas Alert Extreme			95 dB		Lithium polymer battery				14 hr; Recharge in <3 hrs	

N/A = Not applicable
NP = Nonprogrammable
P = Programmable
TWA = Time weighted average

Table B-3. Tier 2 CO Detector Performance Parameters and Specifications

Company	Model	Response Time	Accuracy	Resolution (ppm)	Temperature (°F)	Pressure	Humidity (RH)	Calibration Frequency	Calibration Method	Calibration Time	Alarm Type	Weight	Dimensions (in inches)
Kidde Safety	KN-COB-B			1	40-100		5-95%				Audio/visual	299.4 g	5.25 (Diameter) ×1.06
Kidde Safety	KN-COPP-B	15 s	0-999 ppm ±20% ±15 ppm	1	40-100		up to 95%				Audio/visual	299.4 g	5.5 (Diameter) ×1.4
CO Experts	2004	10 s	±5 ppm	1	32-122		15-90%	Self auto recalibration	Recalibration service available for $80/unit/yr		Audio/visual	260 g	6×3.7×1.7
Extech Instruments	CO50	<5 s	100 ppm ±5%	1	32-122		5%-95%			5 min	Audio/visual	100 g	10×1.5×1.1
BW Technologies	GAXT-M-DL	1- to 60-s intervals (default 5s)		1	-22-122	Not suitable for GA, Pressurized cabin	15%-90%	Once every 6 months	Auto-zero/calibration (dock available)	5 min	Audio/visual vibration	82 g	1.1×2×3.75
Industrial Scientific	GasBadge Pro	<12 s (T50)	<±5%		-40-140		0%-99%		Simple 3-step			85 g	3.7×2×1.1
Industrial Scientific	GasBadge Plus				-40-140		0%-99%	User-adjustable set points	Calibration station (optional)		Audio/visual vibration	72 g	3.2×1.9×1.1
Industrial Scientific	T40 Rattler			1	-4-122		15%-95%	User-adjustable set points	Flip-cap routine		Audio/visual vibration	98 g	3.375×2.3.75
Enmet Corp	TX-2000	<45 s	<5%	1	14-104			Twice/yr	Push-button calibration, optional calibration kit for bump test		Audio/visual	95 g	2.4×3.5×1
Enmet Corp	RECON/4				"-4-122		5%-95%, noncondensing				No vibration	200 g	2.6×4.6×1.2
ATMI Sensoric (gas sensor)	CO 3E 300	<10 s (T50), <30 s (T90)	70 ppm ±20 ppm (Sensitivity)	<3	-40-122		15%-90%						
ATMI sensoric (gas sensor)	CO 3E 500 S	<10 s (T50), <30 s (T90)	70 nA/ppm ±20 nA/ ppm	<3	"-40-122		15%-90%, noncondensing						
City Tech Ltd.	IRidium® 50	<8 s (T10-T90)	0-7%: ±0.15% abs., 7.01-15%: ±15% rel		32-122	813-1060 mBar	0%-90%					114 g	6.5×1.2×1.6
City Tech Ltd.	4CF-CO (with H2S and SO2 filter)	<30 (T90), 7 to 8 s (T50)	0.07 ±0.015 ppm	1	-4-122		15%-90%					5 g	
Lumidor	MiniMax Xt			1	-4-122		5%-95%	Daily/after gas alarm	Zero adjustment (optional span)		Audio/visual vibration	73 g	3.4×2×1.1
MSA	Altair				-4-122		10%-95%	2 yrs maintenance-free operation	Bump test, built-in calibration		Audio/visual vibration	113.4 g	3.4×2×1
Drager	PAC 5000			1	-20-120	20.7-38.4 Hg	10%-90%	2 yrs maintenance-free operation	Bump test, connecting cradle with software		Audio/visual vibration	106 g	2.5×3.3×0.8
Oldham	RX500	Continuous			5-104	"+/1 10%	20%-90%	No calibration	N/A	N/A	Audio/visual vibration	100 g	3.2×2.4×1.4
Biosystems	ToxiVision EX							One-button automatic calibration			Audio/visual vibration-optional	218 g	3.5×2.5×1.25
Biosystems	Toxipro			1				Advised prior to each day's use	Fully automated fresh air/zero, span calibration		Optional built-in vibrating		

Table B-3. Tier 2 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Response Time	Accuracy	Resolution (ppm)	Temperature (°F)	Pressure	Humidity (RH)	Calibration Frequency	Calibration Method	Calibration Time	Alarm Type	Weight	Dimensions (in inches)
Biosystems	TOXILTD			1				Advised prior to each day's use	Fully automated fresh air/zero, span calibration		Optional built-in vibrating	105 g	3.3×2.2×1.2
Biosystems	TOXI3LTD			1				Advised prior to each day's use	Fully automated fresh air/zero, span calibration		Optional built-in vibrating	106 g	3.3×2.2×1.2
Aerion Technologies	Shield			5	-4-122		15%-90%		Bump test		Audio/visual vibration	105 g	3.2×2×1.2
Crowcon	Gasman	20 s			-4-131		0%-99%		Calibration cap, zero		Audio/visual vibration	80 g	3.5×1.9×.95
Cosmos	XC-2000	<30 s	Standard range ±10% FS(0-150)		32-104				Auto zero calibration		Audio/visual	69 g	2.6×2×0.8
Quest Technologies	Safetest 90		"±5%	1	14-104		15%-90% continuous				Audio/visual	180 g	1.3×3×3.9
Quest Technologies	Safelog 100	1 sample per second	"±5%	1	14-104		15%-90% continuous				Audio/visual	250 g	4.5×3.0×1.5
Quantum Eye	Passive Spot CO Detector			N/A				N/A	N/A	N/A	Passive-does not alarm		Business card size
RKI	Gas Watch 2	30 s (T90)	"±5 ppm (up to 150 ppm)	1	-4-104		0%-85%		Calibration kit ($245)		Audio/visual vibration	60 g	2.5×1.7×0.9
RKI	01 Series Monitor	30 s (T90)	"±5 ppm (up to 150 ppm)	1	-4-122		0%-90%		Calibration cap and kit sold separately		Audio/visual vibration	100 g	1.4×4.1×0.8
Uei	CO Detector (CO71)		3% + 1ppm	1	32-104			Auto zero upon turn on			Audio/visual		
Pro Tech	7035	(Set points)	"±30% at 30-500 ppm		40-100						Audio/visual		6×3×1
Pro Tech	7035 - SL	(Set points)	"±30% at 30-500 ppm		40-100						No vibration		6½×3¾×1¾
Pro Tech	8505	(Set points)	"±5 ppm or 5% whichever is greater	1	40-100		10%-90%				Audio/visual	226.7 g	5×3×1
Quantum	Costar P-1	(Set points)			-40-151		15%-95%				Audio/visual	141.7 g	4×2×1
The Pocket CO		<30 s to 90%	±10% at standard conditions		32-105	Reading decreases with decreasing pressure (70% at 10,000 ft)	0%-100%	No maintenance required			Audio/visual	20 g	2.4×1.4×0.6
CO Guardian	Aero-152A		Sensor tested to 13,500' (cabin altitude)		30-120		10%-90%		Every 3 yrs. Recalibration service $99				5×1.9×1.1
CO Guardian	Aero-152WD		Sensor tested to 13,500' (cabin altitude)		30 to 120		10%-90%						5×1.9×1.1

Table B-3. Tier 2 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Response Time	Accuracy	Resolution (ppm)	Temperature (°F)	Pressure	Humidity (RH)	Calibration Frequency	Calibration Method	Calibration Time	Alarm Type	Weight	Dimensions (in inches)
COMAG IR	Smartscan ppm 4021H	15 to 60 s	±10 ppm in 15°-30°C range ±15 ppm outside the range	±2							Audio-optional	5 Kg	360×310×210 mm
Testo	CO Stick	40 s	±5%	1	23-113			Self-test, No zeroing and test gas required			Audio/visual		
MSA	Pulsar+Single Gas Detector	90% of final reading in 60 s		1	-4-122		15%-90% continuous		One push button calibration with optional calibration kit		Audio/visual vibration-optional	125 g	4.5×2.5×.75
Extech Instruments	CO10		±10 ppm	1	32-122		5% to 95%, noncondensing					6.35 oz (180 g)	6.3×2.2×1.6
Professional Equipment					4 -140 for storage and 32 to 105 for operating							5.64 oz	7.95×1.73×1.57
RAE Systems	ToxiRAE II			1	-40-131		0% to 95%		Auto-zero at startup, user-initiated span		Audio/visual vibration	102 g	3.6×1.9×0.9
Passive CO Detector Badge													
CO Detector													
BW Technology	Gas Alert Extreme				-22-122		15%-90%	Maintenance free	Automatic		Audio/visual vibration	82 g	1.1×2×3.75

FS = Full scale

Table B-4. Tier 3 CO Detector Performance Parameters and Specifications

Company	Model	Long-Term Output Drift	Repeatability	Protection Rating	Radio Frequency Protection	Datalogging	Datalogging Features
Kidde Safety	KN-COB-B					No	
Kidde Safety	KN-COPP-B					No (peak level memory)	
CO Experts	2004					No (peak reading, days, hours and minutes since peak occurred, duration of CO Exposure)	
Extech Instruments	CO50					No (peak level memory)	
BW Technologies	GAXT-M-DL			IP 66/67	Complies with 89/336/EEC	Yes	Over 1 month of data at 5-second intervals
Industrial Scientific	GasBadge Pro					Yes	1 year at 1-minute intervals, last 15 alarm events
Industrial Scientific	GasBadge Plus			IP 66/67		Yes	Logs last 15 alarm events
Industrial Scientific	T40 Rattler				Yes	No (peak hold)	
Enmet Corp	TX-2000	<20 ppm per 6 months		IP 65		No (the lowest and highest measurement detected since the instrument was switched on)	
Enmet Corp	RECON/4			IP 66		No (The lowest and highest measurement detected since the instrument was switched on)	

Table B-4. Tier 3 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Long-Term Output Drift	Repeatability	Protection Rating	Radio Frequency Protection	Datalogging	Datalogging Features
ATMI Sensoric (gas sensor)	CO 3E 300	<10% signal loss/6 months					
ATMI Sensoric (gas sensor)	CO 3E 500 S	<2% per Month					
City Tech Ltd.	IRidium® 50		Range ±0.06% abs				
City Tech Ltd.	4CF-CO (with H_2S and SO_2 filter)	<5% signal loss/yr	<2% of Signal				
Lumidor	MiniMax Xt			IP54		No (peak level memory)	
MSA	Altair			IP67		No (eventlogger-25 latest events)	
Drager	PAC 5000			IP65		Event logger (60 events)	Downloaded via PC
Oldham	RX500			IP66		No (peak level memory)	
Biosystems	ToxiVision EX			IPX5	RFI immunity up to 40 V/m	Eventlogger and standard black box recorder (full datalogger available for $60 extra)	
Biosystems	Toxipro			IP57		Eventlogger and standard black box recorder (full datalogger available for $60 extra)	20 Events including max, avg, time, and duration
Biosystems	TOXILTD			Meets IP65/ IP67 water and dust rating		N/A	N/A
Biosystems	TOXI3LTD			Meets IP65/ IP67 water and dust rating		N/A	N/A

Table B-4. Tier 3 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Long-Term Output Drift	Repeatability	Protection Rating	Radio Frequency Protection	Datalogging	Datalogging Features
Aerion Technologies	Shield					No (peak level memory)	
Crowcon	Gasman			IP65/IP67		Yes	3000 hrs
Cosmos	XC-2000						
Quest Technologies	Safetest 90	<2%		IP54	300 kHz-100 GHz	No (memory)	
Quest Technologies	Safelog 100	<2%		IP54		Yes	60+ hrs of 1-minute data
Quantum Eye	Passive Spot CO Detector					No	
RKI	Gas Watch 2					No (peak, time, TWA)	
RKI	01 Series Monitor					No (peak, TWA)	
Uei	CO Detector (CO71)					No (Maxcapture)	
Pro Tech	7035					No (peak and duration of peak)	
Pro Tech	7035-SL					No (memory)	Peak and duration of peak
Pro Tech	8505					No (peak, peak duration, last 7 days)	
Quantum	Costar P-1					No	
The Pocket CO						No (Total exposure, TWA, MAX, time and duration of MAX)	

Table B-4. Tier 3 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Long-Term Output Drift	Repeatability	Protection Rating	Radio Frequency Protection	Datalogging	Datalogging Features
CO Guardian	Aero-152A				Shielded to prevent EMI	No	
CO Guardian	Aero-152WD						
COMAG IR	Smartscan ppm 4021H		±5 ppm			No	
Testo	CO Stick					No	
MSA	Pulsar+Single Gas Detector		+5 ppm CO or 10% of reading, whichever is greater			No (peak, TWA, STEL)	
Extech Instruments	CO10						
Professional Equipment							
RAE Systems	ToxiRAE II			IP65	RFI resistant	No (peak, TWA, STEL)	
Passive CO Detector Badge							
CO Detector							
BW Technologies	Gas Alert Extreme			IP66-67	Resistant housing	Yes (optional)	

EMI = Electromagnetic interference
RFI = Radio frequency interference
TWA = Time-weighted average
MAX = Maximum
STEL = Short-term exposure limit

Table B-5. Tier 4 CO Detector Performance Parameters and Specifications

Company	Model	Sampling Method	Certifications	Manual/Info	Sensor Type
Kidde Safety	KN-COB-B	Diffusion		www.kiddeus.com/utcfs/ws-384/Assets/KN-COB-B(9CO5)en.pdf	Electrochemical
Kidde Safety	KN-COPP-B	Diffusion		www.kiddeus.com/utcfs/ws-384/Assets/KN-COB-B_KN-COPP-Ben.pdf	Electrochemical
CO Experts	2004	Diffusion		www.coexperts.com/2004brochure2.pdf	Electrochemical
Extech Instruments	CO50	Diffusion	ISO 9001:2000	www.extech.com/instrument/products/alpha/manuals/CO50_UM .pdf#search=%22Extech%20Instruments%09CO50%22	Cross-filtered electrochemical
BW Technologies	GAXT-M-DL	Diffusion		http://www.zefon.com/analytical/download/2006-SE-Catalog-Section -4-GasDetection.pdf	Electrochemical
Industrial Scientific	GasBadge Pro	Diffusion		Brochure	Electrochemical
Industrial Scientific	GasBadge Plus	Diffusion		Brochure	Electrochemical
Industrial Scientific	T40 Rattler	Diffusion		Brochure	Electrochemical
Enmet Corp	TX-2000	Diffusion		www.enmetgasdetection.com/pdf/Manual/TX2000Manual.pdf	Electrochemical
Enmet Corp	RECON/4	Diffusion		http://www.enmet.com/literature /Recon4%20Portable%20Gas%20Detector.pdf	Electrochemical
ATMI Sensoric (gas sensor)	CO 3E 300	Diffusion		www.sensoric.de/pdf/TechData_CO_3E_300_rev0306.pdf	Electrochemical
ATMI Sensoric (gas sensor)	CO 3E 500 S	Diffusion		http://www.citytech.com/PDF-Datasheets/co3e500s.pdf	Electrochemical
City Tech Ltd.	IRidium® 50	Diffusion		www.citytech.com/PDF-Datasheets/iridium50.pdf	Electrochemical
City Tech Ltd.	4CF-CO (with H_2S and SO_2 filter)			www.citytech.com/PDF-Datasheets/4cf.pdf	

Table B-5. Tier 4 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Sampling Method	Certifications	Manual/Info	Sensor Type
Lumidor	MiniMax Xt	Diffusion		www.zell.com.br/pdf/minimaxxt_english.pdf (manual available on hand)	Electrochemical
MSA	Altair	Diffusion	Class 1, Division 1, Groups A, B, C, and D	www.media.msanet.com/NA/USA/PortableInstruments /ToxicGasandOxygenIndicators/Altair/0800-31.pdf	Electrochemical
Drager	PAC 5000	Diffusion	CE marked, ATEX, UL, and cUL	www.afcintl.com/pdf/pac5000.pdf	Electrochemical
Oldham	RX500	Diffusion		http://www.spero.co.za/shares/downloads/brochures/rx500.pdf	Electrochemical
Biosystems	ToxiVision EX	Diffusion		www.biosystems.com/products/product.asp?id=43	
Biosystems	Toxipro	Diffusion		www.biodownloads.com/files/manuals/13-264.pdf	Electrochemical
Biosystems	TOXILTD	Diffusion		http://www.biodownloads.com/files/literature/Bio_Toxi-Pro-Ltd-3Ltd.pdf	Electrochemical
Biosystems	TOXI3LTD	Diffusion		http://www.biodownloads.com/files/literature/Bio_Toxi-Pro-Ltd-3Ltd.pdf	Electrochemical
Aerion Technologies	Shield	Diffusion	Class 1, Division 1, Groups A, B, C, and D	www.aimsafety.com/aimsafet/files/products_docs/Shield--new-.pdf	Electrochemical
Crowcon	Gasman	Diffusion	Class I Division 1, Groups A, B, C, and D	www.crowcon.com/pdf_datasheets/gasman-iss2.pdf#search =%22Crowcon%20Gasman%22	Electrochemical
Cosmos	XC-2000	Diffusion		www.new-cosmos.co.jp/en/gas_detectors/img/GDCTLGLight.pdf	Electrochemical
Quest Technologies	Safetest 90	Diffusion	Class I,II,III Division 1, Groups A, B, C, D, E, F, and G	www.quest-technologies.com/PDFs/Manuals/Gas/ST90_ATEX_Warning .pdf#search=%22Safetest%2090%22	
Quest Technologies	Safelog 100	Diffusion	Class I, II, III, Division 1, Groups A, B, C, D, E, F, and G	www.quest-technologies.com/PDFs/Manuals/Gas/SL100_ATEX_Warning .pdf#search=%22Safelog%20100%22	Electrochemical
Quantum Eye	Passive Spot CO Detector			www.safehomeproducts.com/shp2/sc/shopexd.asp?id=1002&source =shopzilla	Biomimetic Chemical

Table B-5. Tier 4 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Sampling Method	Certifications	Manual/Info	Sensor Type
RKI	Gas Watch 2	Diffusion	Class I, Division 1, Groups A, B, C, and D	www.skcgulfcoast.com/rki/RKI_Gas_Watch_2_Data_Sheet.pdf	Electrochemical
RKI	01 Series Monitor	Diffusion	Class I, Division 1, Groups A, B, C, and D	www.skcgulfcoast.com/rki/RKI_01_Series_Monitors.pdf	Electrochemical
Uei	CO Detector (CO71)			www.tequipment.net/pdf/UEi/UEiCO71_manual.pdf	Electrochemical
Pro Tech	7035		OSHA, NIOSH ACGIH	http://www.protechsafety.com/manual/dc.pdf	Electrochemical
Pro Tech	7035 - SL		OSHA, NIOSH ACGIH	http://www.protechsafety.com/7035sl.html	Electrochemical
Pro Tech	8505		OSHA, NIOSH ACGIH	http://www.protechsafety.com/manual/8505.pdf	Electrochemical
Quantum	Costar P-1			www.at-fairfax.com/PDF/Quantum/COSTAR-P1.pdf	Solid-state infrared (SIR) with reservoir system
The Pocket CO		Diffusion		http://www.aeromedix.com/product-exec/parent_id/1/category_id/7 /product_id/1237/nm/Pocket_CO_Cabon_Monoxide_Detector	Electrochemical
CO Guardian	Aero-152A			www.coguardian.com/	
CO Guardian	Aero-152WD			http://www.coguardian.com/	
COMAG IR	Smartscan ppm 4021H			www.comag-ir.com/download/Comag4021H.pdf	Nondispersive infrared
Testo	CO Stick			www.professionalequipment.com/images/pdf/g503-3173_manual.pdf	
MSA	Pulsar+ Single Gas Detector	Diffusion		www.professionalequipment.com/xq/ASP/ProductID.2745/id.6/subID .64/qx/default.htm#	

Table B-5. Tier 4 CO Detector Performance Parameters and Specifications (Continued)

Company	Model	Sampling Method	Certifications	Manual/Info	Sensor Type
Extech Instruments	CO10			www.professionalequipment.com/xq/ASP/ProductID.860/id.6/subID.64/qx/default.htm	
Professional Equipment				www.professionalequipment.com/xq/ASP/ProductID.2319/id.6/subID.64/qx/default.htm	
RAE Systems	ToxiRAE II			http://www.raesystems.com/products/toxirae_ii	Electrochemical
Passive CO Detector Badge				http://testproducts.com/safecart/product_info.php/cPath/28/products_id/37?osCsid=ccb07e842d5cbca0997056d5297eaf89	Biomimetic Chemical
CO Detector				http://www.bestglide.com/CO_Detector_Info.html	Biomimetic Chemical
BW Technologies	Gas Alert Extreme		ATEX, UL	http://www.gasmonitors.com/main.cfm?page=prodpage1&pid=31&cat=23&sub1=19&sub2=44	Electrochemical

ACGIH = American Conference of Governmental Industrial Hygienists
ATEX = A set of European Directives relating to Hazardous Area Installations that takes its name from the French "Atmosphères Explosibles."
CE = Certifies that a product has met European Union consumer safety, health, or environmental requirements.
cUL = Certifies that a product has met Canadian safety requirements.
NIOSH = National Institute for Occupational Safety and Health
OSHA = Occupational Safety and Health Administration
UL = Underwriter laboratory

B.3 THE CO DETECTOR LOCATION.

If portable CO detectors are used in GA aircraft, it is essential that they be positioned in location(s) in the cabin that ensured early and consistent detection when CO enters the cabin. Additionally, CO detectors should be placed in cabin locations where the pilot can be sufficiently alerted to the presence of CO at a certain level. Thus, the primary objective of this portion of the research was to identify the best location(s) to position CO detectors in the cabin of a GA aircraft. A secondary objective was to determine ambient levels of CO in different locations in the cabin under normal operating conditions.

B.3.1 EXPERIMENTAL SETUP.

CO was monitored over a 12-month period from several single-engine GA aircraft during student flights of an Aviation Department of the Kansas State University at Salina. Multiple portable battery-operated, single-gas CO detectors with datalogging capability (GasBadge® Pro, Industrial Scientific, Oakdale, PA, USA) were placed in multiple locations in the aircraft cabin. The locations of the CO detectors were based upon potential pathways of CO into the cabin, which were determined from maintenance manual schematics, as well as from results of the NTSB's determination of potential sources of CO exposure in CO-related accidents. Potential pathways of CO into the cabin for many aircraft types included the heater vents, unsealed holes in the firewall, and fresh air vents. Thus, the following locations were selected to meet the above-mentioned objectives:

- Instrument panel (figure B-1)—This location is visible and accessible to the pilot, is located close to the engine compartment firewall, and relatively close to heater vents.

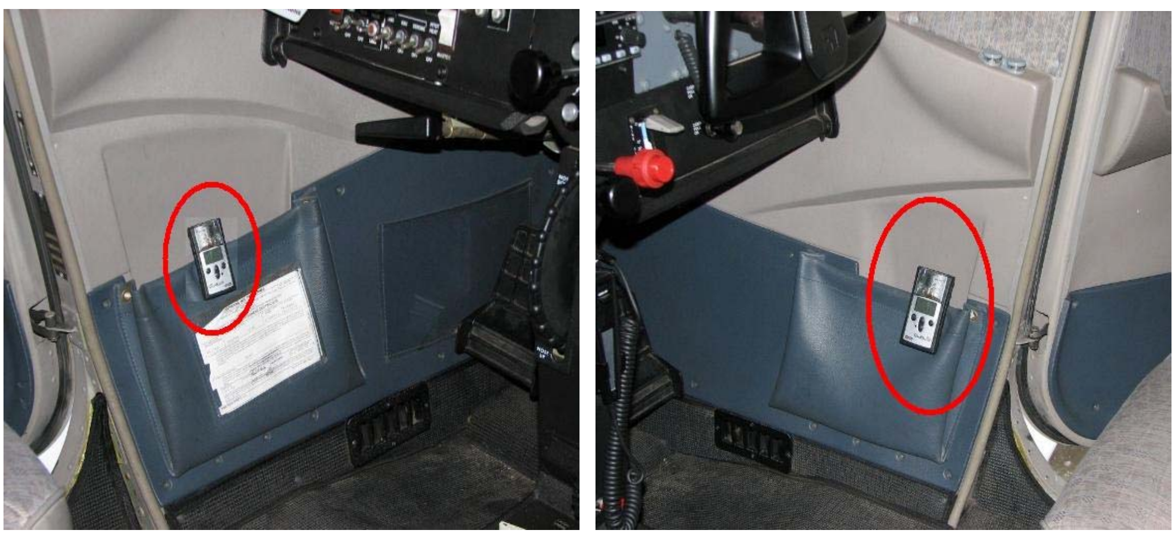
- Door pockets (figure B-2)—CO detectors were placed by the right- and left-door pocket areas, which are visible to the pilot and close to floor-level heater vents.

- Visor (figure B-3(a))—One CO detector was located near the visor on the pilot side, which is clearly visible and accessible to the pilot.

- Back seat (figure B-3(b))—One CO detector was located in the back-seat area, clipped to the back of the pilot's seat, which is near a fresh air vent for outgoing air ventilation. It was chosen to measure the ambient CO level throughout the cabin, even though it was not accessible to the pilot.

The instrument panel CO detector was attached to the instrument panel with a belt clip, whereas the other four CO detectors were attached to their respective locations using a suspender wire clip. All five locations are shown schematically in figure B-4.

Figure B-1. Carbon Monoxide Detector Attached to the Instrument Panel With a Belt Clip



(a) (b)

Figure B-2. Carbon Monoxide Detectors Attached to the Left-Door Pocket (a) and Right-Door Pocket (b) With Suspender Clips

(a) (b)

Figure B-3. Carbon Monoxide Detectors Located (a) Near the Pilot-Side Visor and (b) the Back-Seat Area With Suspender Clips

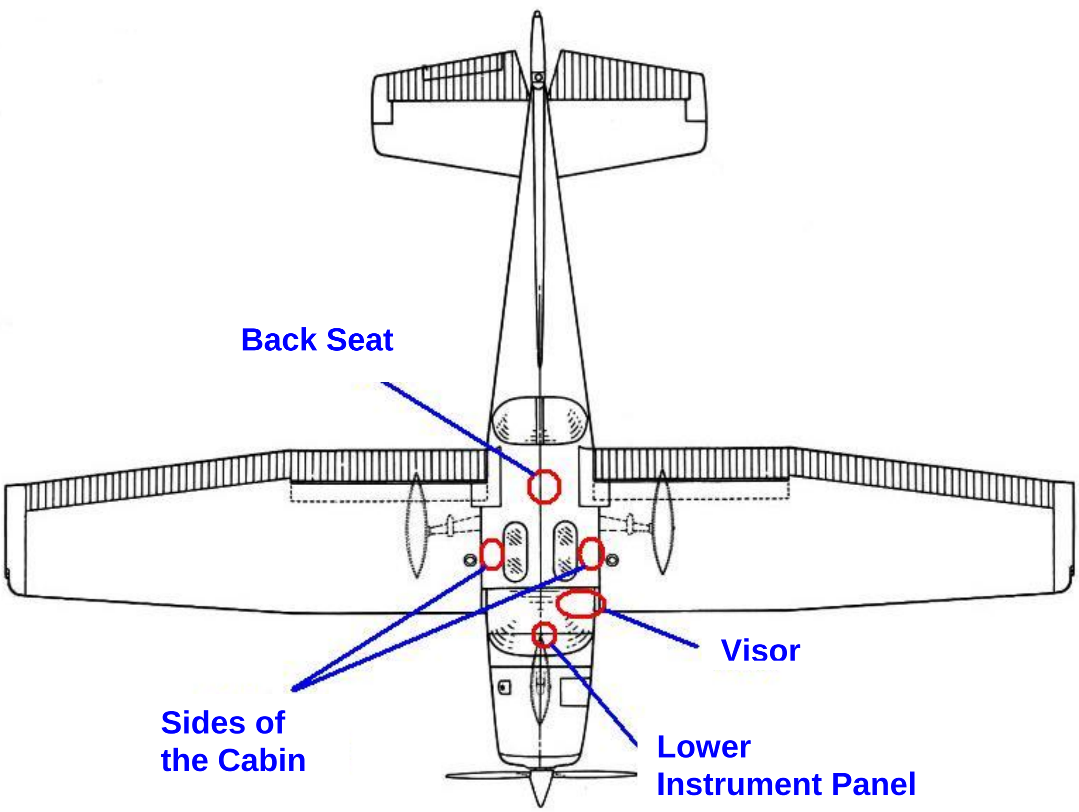


Figure B-4. Top View of CO Detector Locations in the High-Wing Aircraft Model

Monitoring CO in GA aircraft occurred over a 12-month period. For the first 8 months, different aircraft (high-wing model) were monitored each week using five CO detectors at designated locations in the cabin. At the beginning of each week, the CO detectors were installed in the cabin by a technician. The detectors remained on the particular aircraft for the whole week, continuously monitoring CO (at a rate of one sample every 10 seconds, or 0.167 Hz). At the end of each week, all CO detectors were removed from the aircraft, the data were downloaded, and the detectors were recalibrated. The calibrated CO detectors were then placed on a different aircraft (same model type) for the next week of CO monitoring. This procedure was performed each week for 8 months.

The CO detectors sampled CO continuously, which included when the aircraft was taxiing, flying, and when parked and not in use. Therefore, to ensure proper analysis of the data, it was necessary to correspond the detected CO to the status of the airplane. Two different methods were used. First, a battery-operated GPS device (GPS TrackStick, RE Williams, Inc., Valencia, CA, USA) sampling at a rate of one per minute (0.017 Hz) was placed in the cabin, which was used to identify the altitude, location, and time of takeoff and landing of the aircraft. Second, a questionnaire was used that included a time log for flight events, such as engine startup, takeoff, landing, and engine shutdown (see figure 6 in section 4.2). The questionnaire was completed by the pilot for each flight. From the GPS device and the questionnaire time log, the relevant operation times between engine startup and engine shutdown could be determined for each flight.

Analysis of the CO sampled from each of the five CO detectors after 8 months of data collection indicated that the CO detector near the pilot's visor was detecting much smaller magnitudes of CO during operation of the high-wing aircraft compared to the other four CO detector locations. Thus, a decision was made to reduce the number of detectors for the remaining 4 months of data collection for the high-wing models and to expand the monitoring of CO to another GA aircraft model (low-wing aircraft, higher performance engine) at similar cabin locations as the high-wing models. Thus, the CO detector locations in both types of aircraft (high-wing and low-wing) included the right- and left-door pocket areas, the instrument panel, and the back-seat area.

Figure B-5 shows the type of data collected during a flight. The x axis defines the time and the y axis is the level of CO detected in ppm. The red-dashed vertical lines represent takeoff and landing of the aircraft. As stated previously, the takeoff and landing times were determined based on the available GPS data and the questionnaire completed by the pilot. The CO sampled from each of the CO detectors was first analyzed for the identification of "CO events." CO events were defined as non-zero CO levels measured by any detector. Different CO events were separated by periods of zero-level CO recorded by the detector.

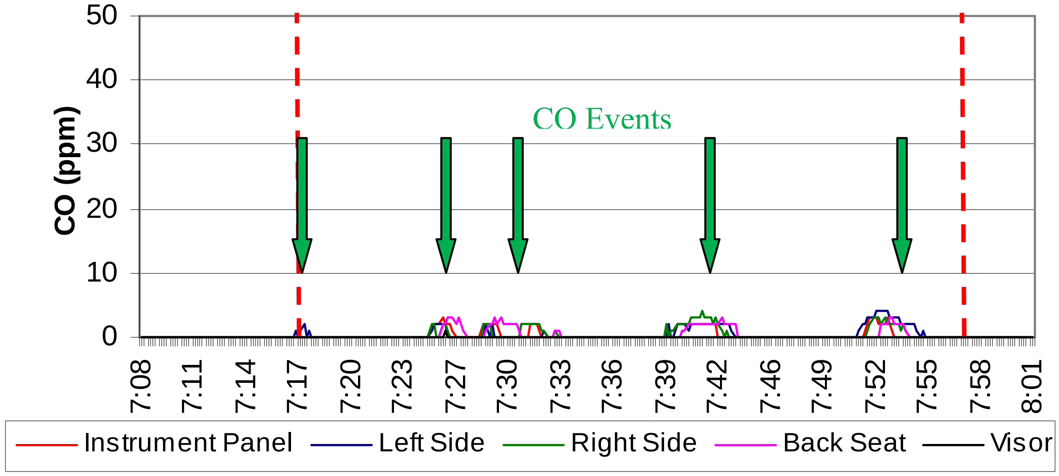


Figure B-5. Identification of CO Events During a Typical Flight
(The CO events are separated by periods of zero-level CO detected in the cabin.)

The CO events from each of the monitored flights were analyzed collectively in several different ways. To determine the best location within the cabin to place a CO detector (primary objective), two criteria were used: sensitivity and specificity. The sensitivity of a CO detector indicates the probability of a CO detector detecting a certain level of CO that may be present anywhere in the cabin. For example, if 50 ppm of CO is present anywhere in the cabin, sensitivity is the probability that a CO detector will detect this level of CO (true positive), no matter where the CO detector may be located in the cabin. The specificity of a CO detector indicates the probability of a CO detector correctly measuring CO below a certain threshold of interest. For example, if it is of interest for the CO detector to alarm when CO is above 50 ppm anywhere in the cabin, the specificity identifies the probability that a CO detector correctly identifies CO levels that are below 50 ppm (true negatives).

The secondary objective of this portion of the research was to determine the ambient levels of CO present in the GA aircraft cabin during normal operating conditions. Thus, ambient levels of CO were determined as a function of aircraft model (high-wing, low-wing) and the location of the aircraft during operation (before/after takeoff on the ground or in the air).

B.3.2 CARBON MONOXIDE DETECTION RESULTS.

Monitoring of CO for the first 8 months consisted of monitoring the high-wing aircraft model using five CO detectors at different locations within the aircraft cabin. Figure B-6 shows the sensitivity for each CO detector location for detecting CO anywhere in the cabin when the CO was above different levels anywhere in the cabin. If the CO level was above 20 ppm anywhere in the cabin, the CO detector at the instrument panel detected levels greater than 20 ppm about 82% of the time, whereas the CO detector located near the pilot's visor detected CO levels above 20 ppm only 22% of the time. Similarly, when the CO level was above 40 ppm anywhere in the cabin, the CO detector at the instrument panel correctly detected CO levels greater than 40 ppm

70% of the time, whereas the CO detector located near the pilot's visor detected CO greater than 40 ppm only about 40% of the time. Finally, when the CO level in the cabin was at or above 50 ppm, the CO detector at the back seat detected CO at levels above 50 ppm 50% of the time, whereas the CO detectors at the left- and right-side doors detected CO above 50 ppm only 25% of the time. The instrument panel CO detector detected CO levels above 50 ppm 75% of the time, and the CO detector located near the pilot's visor detected CO levels above 50 ppm only about 25% of the time when it was, in fact, greater than 50 ppm somewhere in the cabin.

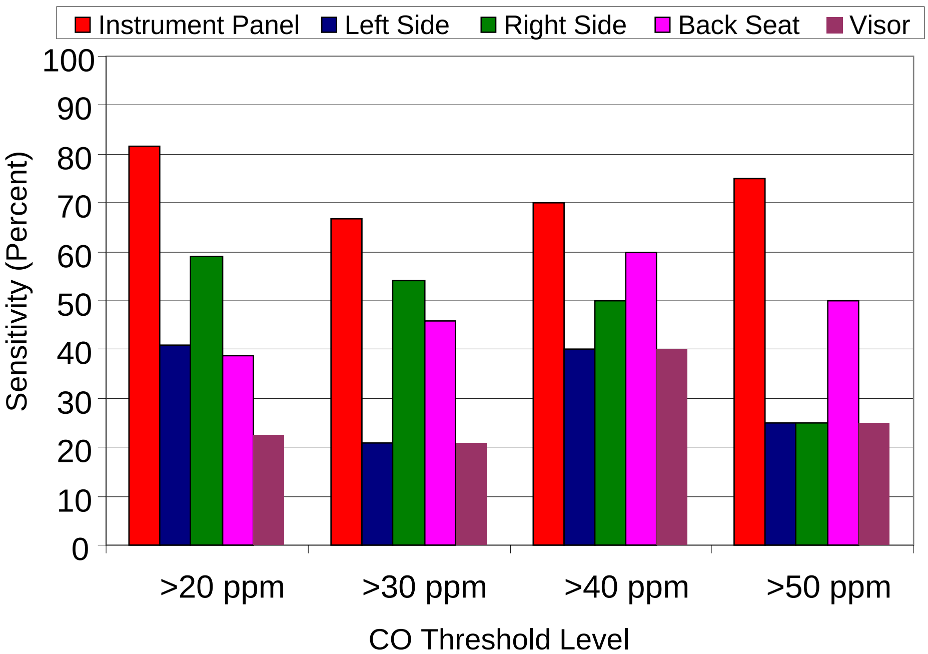


Figure B-6. Sensitivity of CO Detectors for Detecting CO Events Above Certain Thresholds

The findings from the first 8 months of CO monitoring, as shown in figure B-6, resulted in two changes to the data collection protocol and data analysis procedures. First, since the CO detector located near the pilot's visor consistently resulted in the lowest sensitivity for detecting CO above certain threshold levels, it was decided to continue the remaining 4 months of data collection without the visor CO detector for the high-wing aircraft, and use that CO detector and three additional CO detectors to monitor ambient CO levels in a low-wing aircraft model. Second, also shown in figure B-6, when CO was greater than 50 ppm anywhere in the cabin, none of the four remaining CO detector locations were able to detect levels above 50 ppm 100 percent of the time (e.g., sensitivity was less than 100%). Thus, it was decided to assess the sensitivity and specificity of the different CO detectors for their ability to detect if there was at least 50 ppm of CO anywhere in the cabin by setting the threshold alarm levels lower than 50 ppm.

B.3.3 SENSITIVITY OF CO DETECTORS AS A FUNCTION OF AIRCRAFT MODEL AND LOCATION.

Figures B-7 and B-8 show the CO detector sensitivity for the high-wing aircraft in the air and on the ground, respectively. Figure B-7 shows (aircraft in the air) the sensitivity of the instrument panel and right-side locations for CO detectors were higher than the other locations when CO levels were greater than 20 ppm and greater than 30 ppm anywhere in the cabin. When CO levels in the cabin were greater than 40 ppm, all but the instrument panel CO detectors were able detect these levels. However, when CO levels were greater than 50 ppm anywhere in the cabin, only the back seat CO detector was able to detect this level of CO.

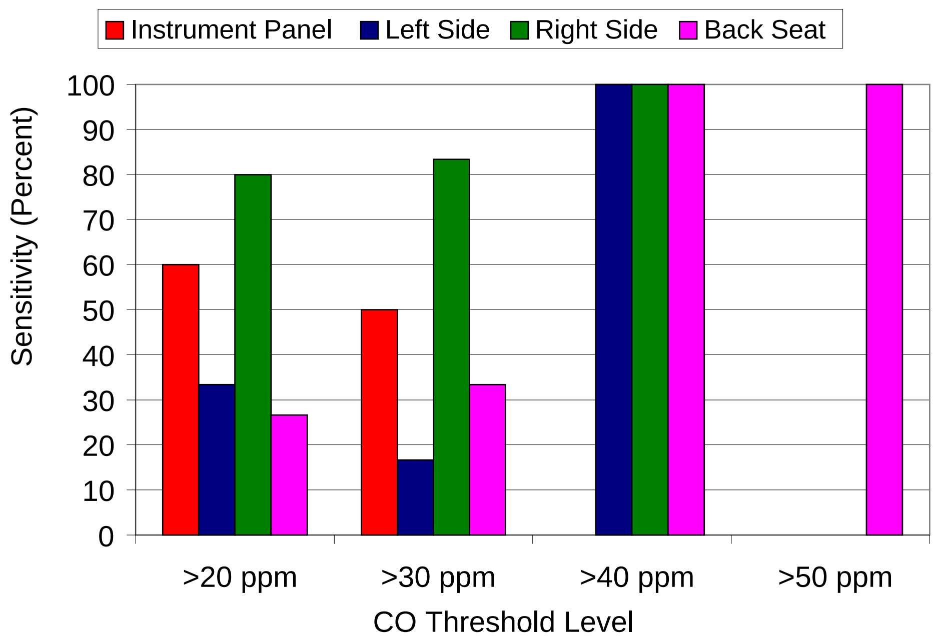


Figure B-7. The CO Detector Sensitivity for Detecting CO Above Different CO Levels for the High-Wing Aircraft in the Air

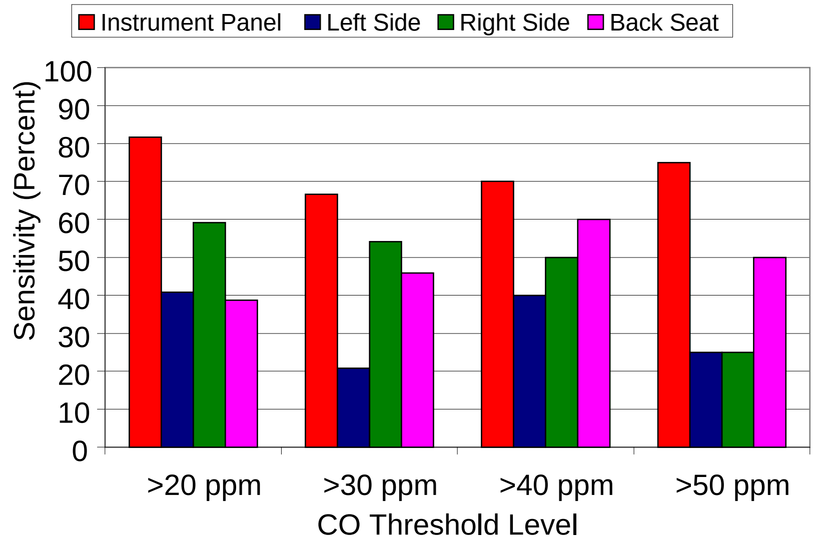


Figure B-8. The CO Detector Sensitivity for Detecting CO Above Different CO Levels for the High-Wing Aircraft on the Ground

For detecting different CO levels when the aircraft was on the ground (before takeoff and after landing), figure B-8 shows that the instrument panel sensitivity was the highest of all the CO detector locations when detecting CO above different thresholds, with sensitivities ranging from approximately 65% to 80%. Figures B-9 and B-10 show the CO detector sensitivity for low-wing aircraft in the air and on the ground, respectively. For the low-wing aircraft, the results indicated that CO detectors at the instrument panel and left-side locations have higher sensitivity than the other locations for either air or ground events.

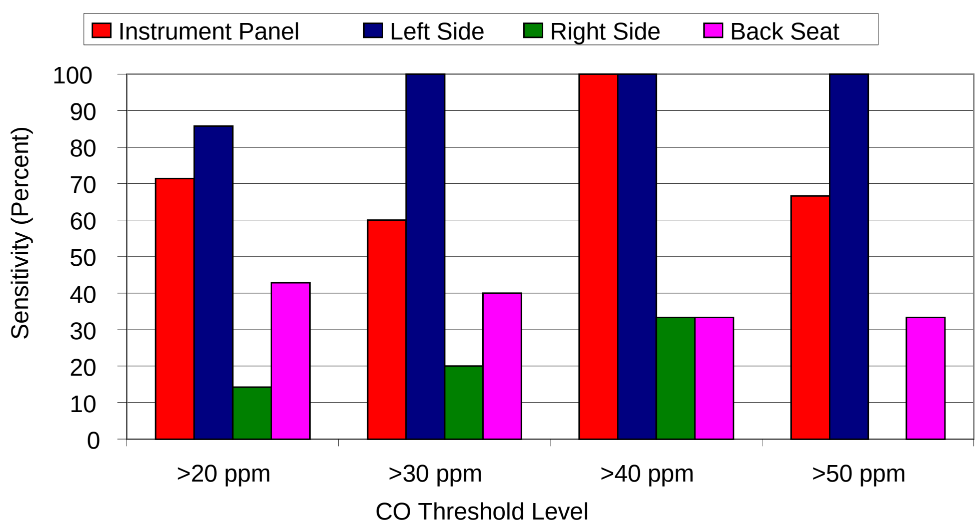


Figure B-9. The CO Detector Sensitivity for Detecting CO Above Different CO Levels for the Low-Wing Aircraft in the Air

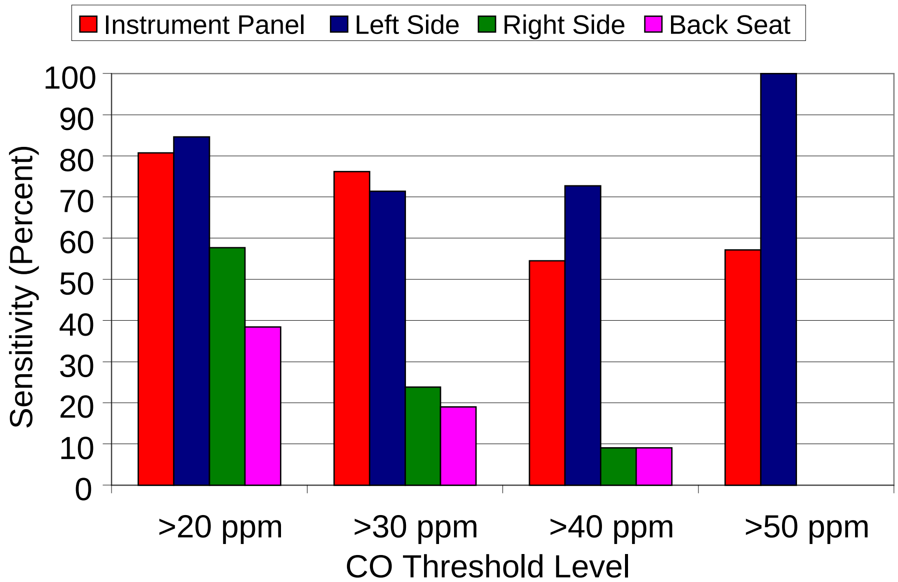


Figure B-10. The CO Detector Sensitivity for Detecting CO Above Different CO Levels for the Low-Wing Aircraft on the Ground

B.3.4 DETERMINATION OF APPROPRIATE CO DETECTOR ALARM THRESHOLD VALUE.

The FAA CO requirement [B-2] indicates that CO should not exceed 50 ppm anywhere in the cabin. Thus, a CO detector, no matter where it is placed in the cabin, should be able to alert the pilot when CO is present above 50 ppm anywhere in the cabin. As shown in figures B-7 through B-10, none of the locations for the CO detectors that were near CO entrance pathways into the cabin and were within reach of the pilot (i.e., instrument panel, door panels) were able to detect all instances when at least 50 ppm of CO was present anywhere in the cabin. Thus, a strategy to increase the probability of detecting CO greater than 50 ppm anywhere in the cabin would be to set the alarm threshold of CO detectors at a lower CO concentration level to ensure that the pilot would be made aware of CO levels above 50 ppm anywhere in the cabin.

For the high-wing aircraft model, the sensitivity of the CO detectors for detecting at least 50 ppm anywhere in the cabin by setting the threshold levels lower are shown in figure B-11 while the aircraft were in the air and in figure B-12 while the aircraft were on the ground. With the aircraft in the air (figure B-11), all CO detectors demonstrated 100% sensitivity for detecting at least 50 ppm CO anywhere in the cabin with alarm levels set at 35 ppm and below. The back seat CO detector sensitivity remained at 100% for alarm thresholds up to 50 ppm, whereas the instrument panel CO detector sensitivity dropped to 0% at alarm levels of 40 ppm and above, and the right-side CO detector sensitivity dropped to 0% at alarm levels of 45 ppm and above.

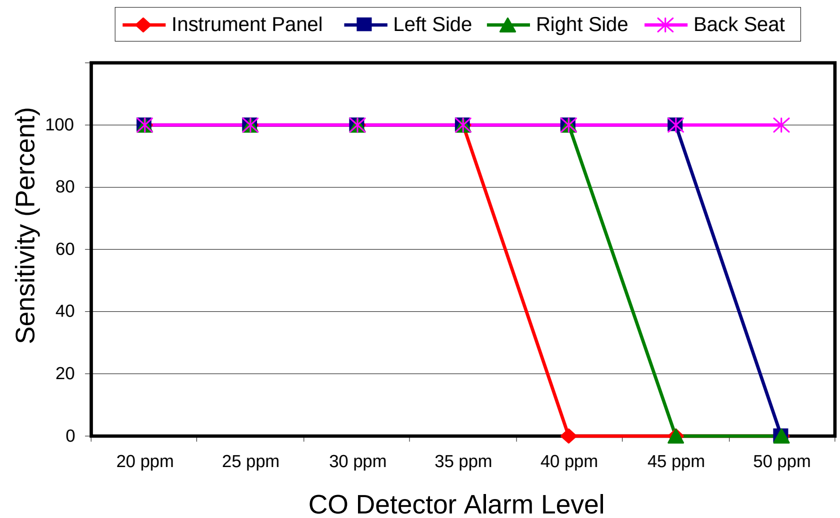


Figure B-11. The CO Detector Sensitivity for Detecting ≥50 ppm Anywhere in the Cabin With the CO Detector Alarm Level Set at Lower CO Threshold Levels (High-Wing Aircraft in Air)

When the high-wing aircraft were on the ground (figure B-12), the sensitivity of the CO detector at the instrument panel for detecting 50 ppm CO levels anywhere in the cabin with lower alarm threshold levels was greater than all other CO detector locations, for all threshold alarm levels. The instrument panel CO detector sensitivity was 100% for alarm threshold levels up to 30 ppm, which then dropped to approximately 75% sensitivity for CO threshold alarm levels set at 35 ppm and above.

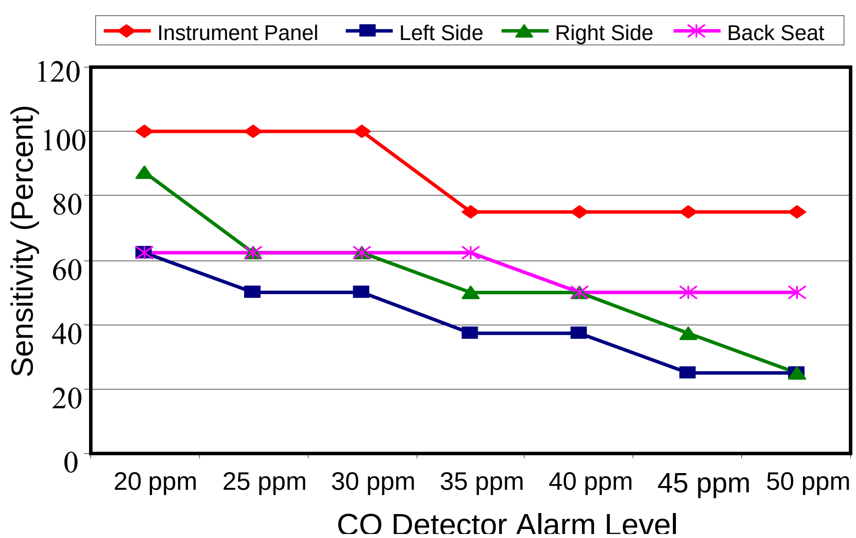


Figure B-12. The CO Detector Sensitivity for Detecting ≥50 ppm Anywhere in the Cabin With the CO Detector Alarm Level Set at Lower CO Threshold Levels (High-Wing Aircraft on the Ground)

For the low-wing aircraft model, the sensitivity of the CO detectors for detecting at least 50 ppm anywhere in the cabin by setting the threshold levels at lower levels is shown in figure B-13 while the aircraft were in the air and in figure B-14 while the aircraft were on the ground. With the aircraft in the air (figure B-13), the detectors located at the instrument panel and the left-side door panel demonstrated 100% sensitivity for detecting at least 50 ppm CO anywhere in the cabin when the CO detector alarm levels were set at 40 ppm and below. The left-side door panel CO detector sensitivity remained at 100% for alarm thresholds up to 50 ppm, whereas the instrument panel CO detector sensitivity dropped to 65% at alarm levels of 45 ppm and above.

When the low-wing aircraft were on the ground (figure B-14), the detectors located at the instrument panel and left-side door panel demonstrated 100% sensitivity for detecting at least 50 ppm CO anywhere in the cabin with alarm levels set at 30 ppm and below. The left-side door panel CO detector sensitivity remained at 100% for alarm thresholds up to 50 ppm, whereas the instrument panel CO detector sensitivity dropped to 75% at alarm levels of 35 and 40 ppm, and dropped again to 58% at alarm levels of 45 and 50 ppm. The sensitivity of the CO detectors located at the instrument panel and left-side door panel were greater than the sensitivity of the CO detectors located in the back-seat area and at the right-side door panel for all CO detector alarm threshold levels.

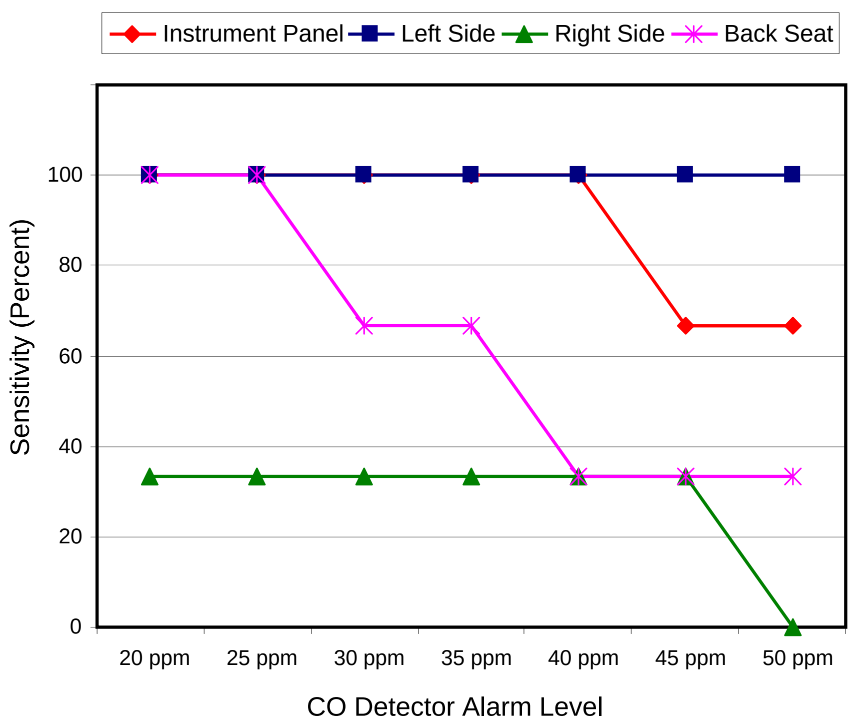


Figure B-13. The CO Detector Sensitivity for Detecting ≥50 ppm Anywhere in the Cabin With the CO Detector Alarm Level Set at Lower CO Threshold Levels (Low-Wing Aircraft in Air)

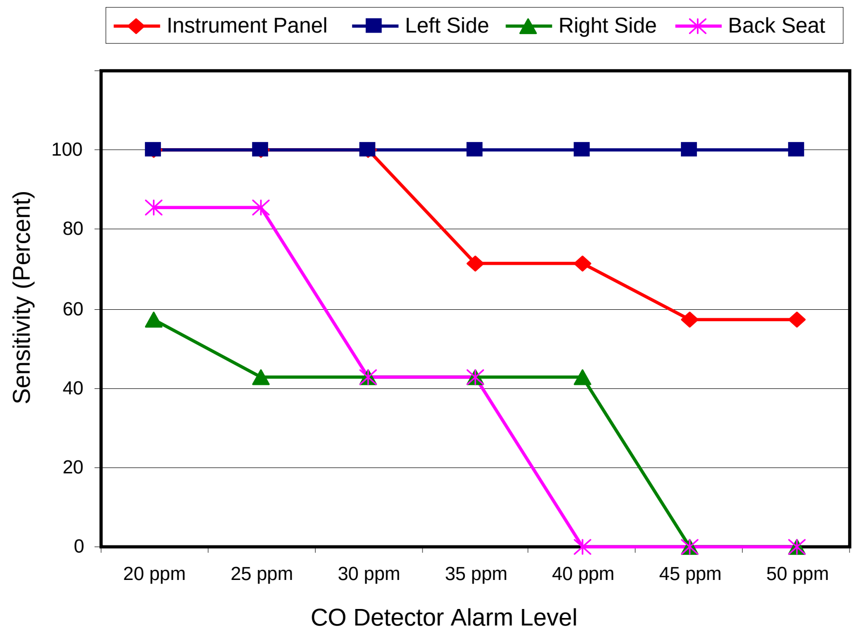


Figure B-14. The CO Detector Sensitivity for Detecting ≥50 ppm Anywhere in the Cabin With the CO Detector Alarm Level Set at Lower CO Threshold Levels (Low-Wing Aircraft on the Ground)

While setting the CO detector alarm levels to lower thresholds was shown to increase the sensitivity for detecting CO above 50 ppm anywhere in the cabin, this may also increase the likelihood that false alarms may occur. For example, if a CO detector alarm level was set at 30 ppm to increase the probability that CO levels greater than 50 ppm anywhere in the cabin would be detected, then a CO level of 40 ppm detected by the CO detector would set off the alarm; however, this CO level is not above the FAA requirement of 50 ppm. This alarm event would be considered a false alarm or a false positive. To determine the ability of different CO detectors to reduce the false alarm potential when setting the alarm thresholds at levels lower than 50 ppm, the specificity of each of the CO detectors at different alarm threshold values was determined. Specificity is the probability that a CO detector correctly identifies a true nonalarm CO level.

For the high-wing aircraft model, the specificity of the CO detectors when alarm threshold levels were set at lower levels to detect at least 50 ppm anywhere in the cabin are shown in figure B-15 while the aircraft were on the ground and in figure B-16 while the aircraft were in the air. With the aircraft on the ground (figure B-15), all CO detectors demonstrated close to 100% specificity for detecting at least 50 ppm CO anywhere in the cabin with alarm levels set at 35 ppm and above. Thus, very few false alarms occurred when the CO detector alarm threshold was set at 35 ppm and above while the aircraft were on the ground. When the high-wing aircraft were in the air (figure B-16), all CO detectors demonstrated close to 100% specificity for detecting at least 50 ppm CO anywhere in the cabin with alarm levels set at 30 ppm and above. Thus, very few false alarms occurred when the CO detector alarm threshold was set at 30 ppm and above while the aircraft were in the air.

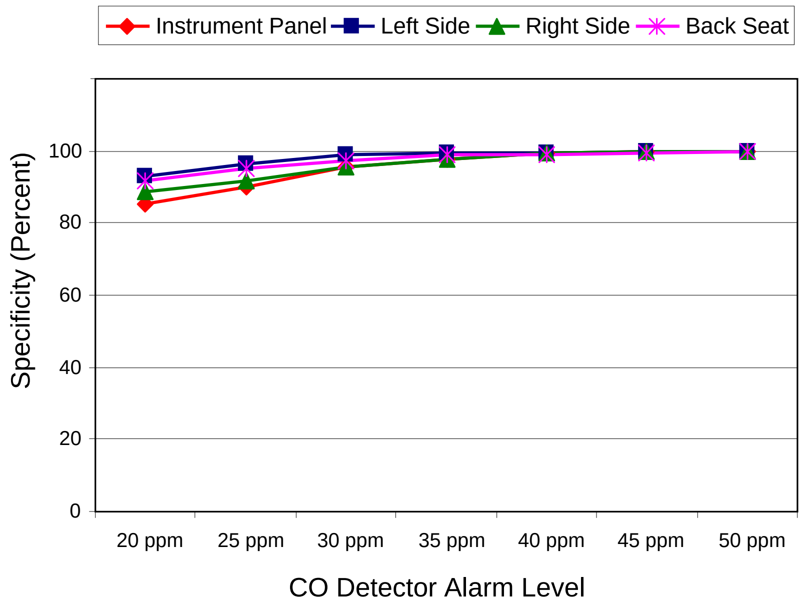


Figure B-15. The CO Detector Specificity for Detecting ≥50 ppm Anywhere in the Cabin With the CO Detector Alarm Level Set at Lower CO Threshold Levels (High-Wing Aircraft on the Ground)

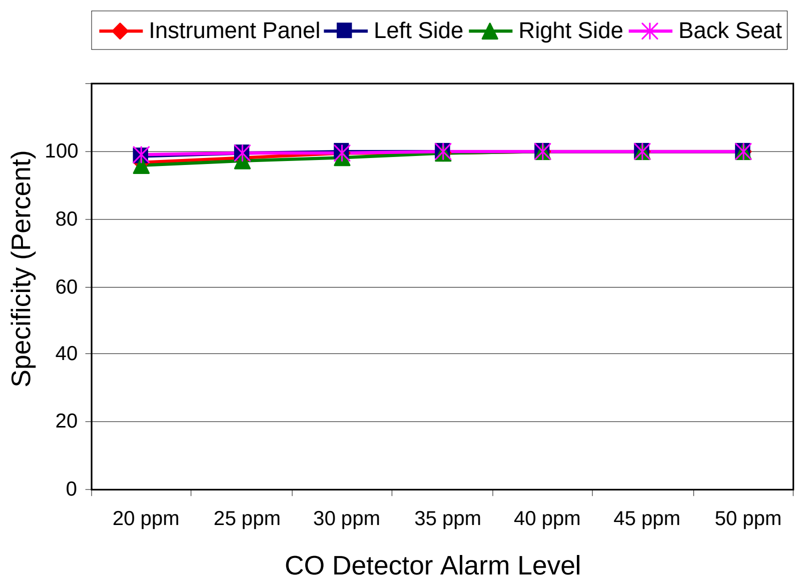


Figure B-16. The CO Detector Specificity for Detecting ≥50 ppm Anywhere in the Cabin With the CO Detector Alarm Level Set at Lower CO Threshold Levels (High-Wing Aircraft in the Air)

For the low-wing aircraft model, the specificity of the CO detectors when alarm threshold levels were set at lower levels to detect at least 50 ppm anywhere in the cabin are shown in figure B-17 while the aircraft were on the ground and in figure B-18 while the aircraft were in the air. When the low-wing aircraft were on the ground (figure B-17), the CO detectors located in the back-seat area and the right-side door panel area demonstrated close to 100% specificity for detecting at least 50 ppm CO anywhere in the cabin with alarm levels set at 30 ppm and above, whereas the other two CO detector locations had specificity ranging between 80% and 90% with CO detector alarm threshold levels set between 25 and 35 ppm. At CO detector threshold levels set at 40 ppm or greater, the specificity for all CO detectors was close to 100%, indicating few false alarms at these threshold levels. When the low-wing aircraft were in the air (figure B-18), all CO detectors demonstrated close to 100% specificity for detecting at least 50 ppm CO anywhere in the cabin with alarm levels set at 30 ppm and above. Thus, very few false alarms occurred when the CO detector alarm threshold was set at 30 ppm and above while the aircraft were in the air.

B.3.5 AMBIENT CO LEVELS DURING NORMAL FLIGHT OPERATION.

During the CO monitoring period, 166 high-wing (over a 12-month period) and 51 low-wing (over a 4-month period) aircraft flights were monitored. Figures B-19 and B-20 show the percentage of non-zero CO events as a function of exposure level for those high-wing and low-wing aircrafts, respectively.

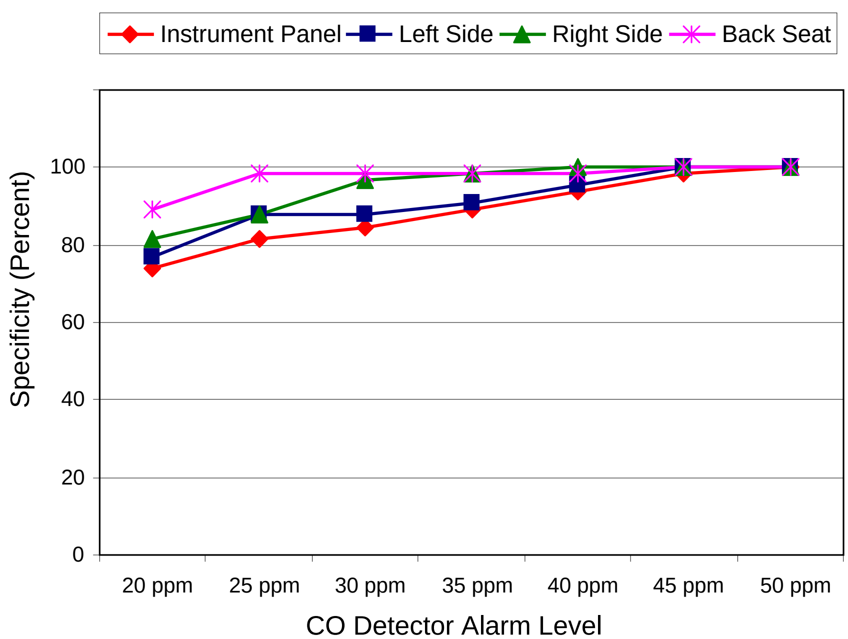


Figure B-17. The CO Detector Specificity for Detecting ≥50 ppm Anywhere in the Cabin With the CO Detector Alarm Level Set at Lower CO Threshold Levels (Low-Wing Aircraft on the Ground)

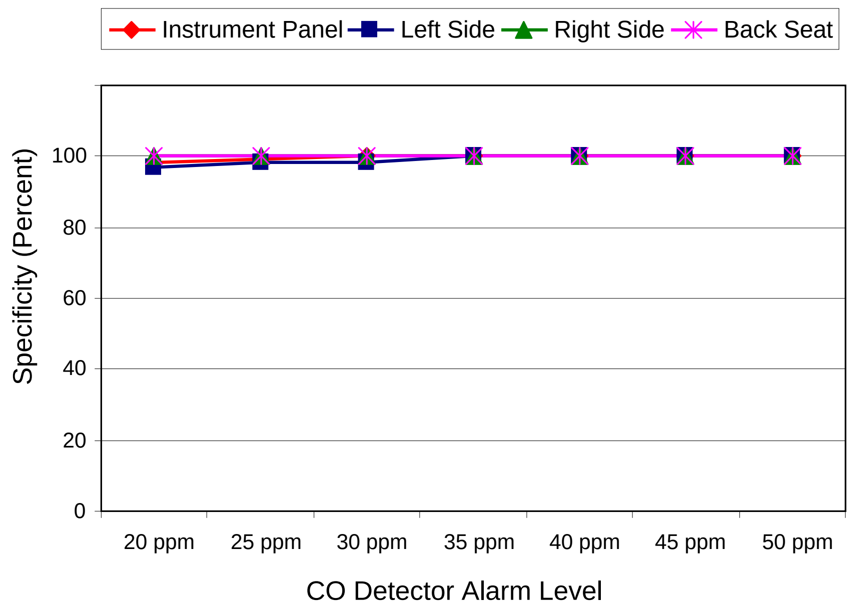


Figure B-18. The CO Detector Specificity for Detecting ≥50 ppm Anywhere in the Cabin With the CO Detector Alarm Level Set at Lower CO Threshold Levels (Low-Wing Aircraft in the Air)

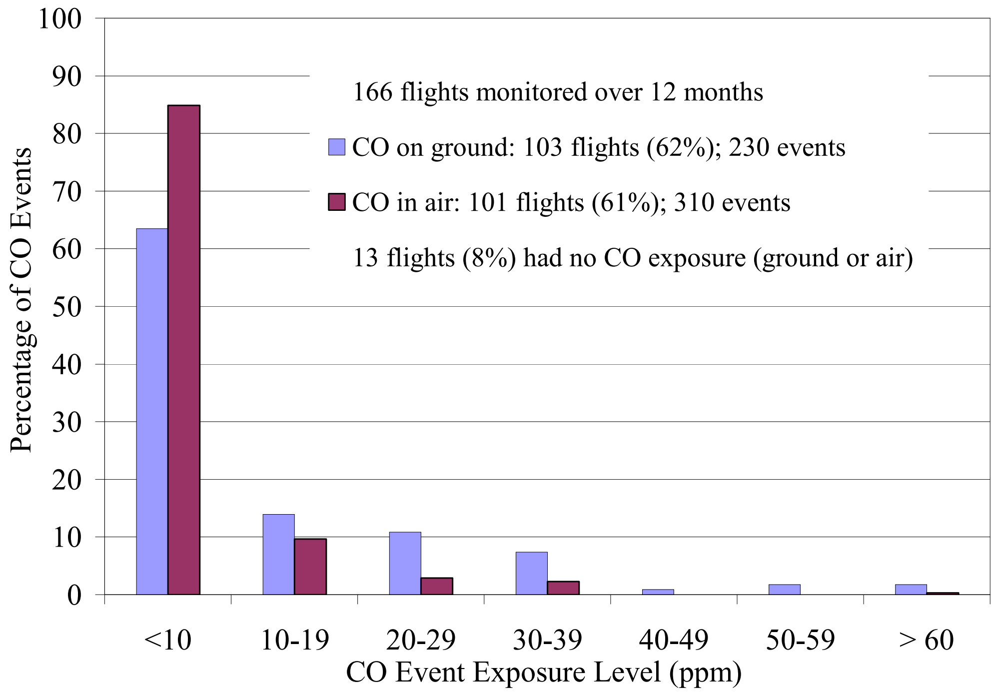


Figure B-19. Percent of CO Events Within Different CO Level Categories for the High-Wing Aircraft on the Ground and in the Air

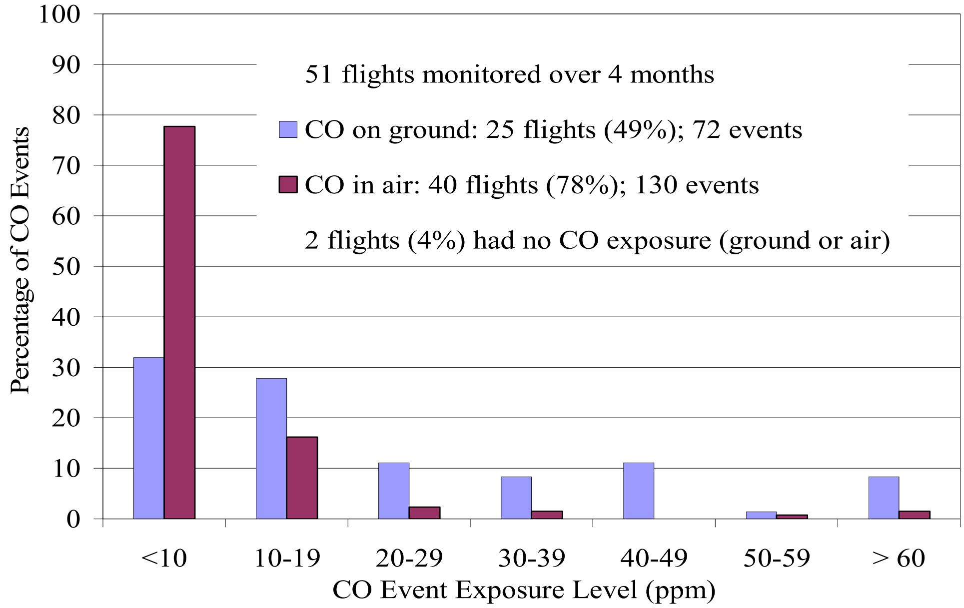


Figure B-20. Percent of CO Events Within Different CO Level Categories for the Low-Wing Aircraft on the Ground and in the Air

As shown in figure B-19, very few flights of the high-wing aircraft resulted in no CO being detected (8% of flights) while either on the ground or in the air. CO was detected in the cabin during 61% of the flights when the aircraft were in the air and 62% of the flights when the aircraft were on the ground. Although CO was detected on more than 90% of the flights monitored (either on the ground, in the air, or both), the majority of CO events detected were less than 10 ppm (85% while in the air, 62% while on the ground), with a very small percentage detected with levels above 50 ppm. The duration of these higher ppm events were typically only a few seconds in duration.

As shown in figure B-20, very few flights of the low-wing aircraft resulted in no CO detected (4% of flights) while either on the ground or in the air. CO was detected in the cabin during 78% of the flights when the aircraft were in the air and 49% of the flights when the aircraft were on the ground. CO was detected on all but two flights (either on the ground, in the air, or both). The majority of CO events detected when the aircraft were in the air were less than 10 ppm (78%), whereas approximately 60% of the CO events detected when the aircraft were on the ground were less than 20 ppm. While in the air, approximately 3% of the events were above 50 ppm, and approximately 10% were above 50 ppm when the aircraft were on the ground.

The peak CO event detected during each flight for high-wing and low-wing aircraft are shown in figures B-21 and B-22, respectively. For the high-wing aircraft flights (figure B-21), 46% of the flights had peak CO levels detected that were less than 10 ppm (either on the ground or in the air), whereas approximately 6% of the flights resulted in peak CO levels detected that were greater than 50 ppm (either on the ground or in the air).

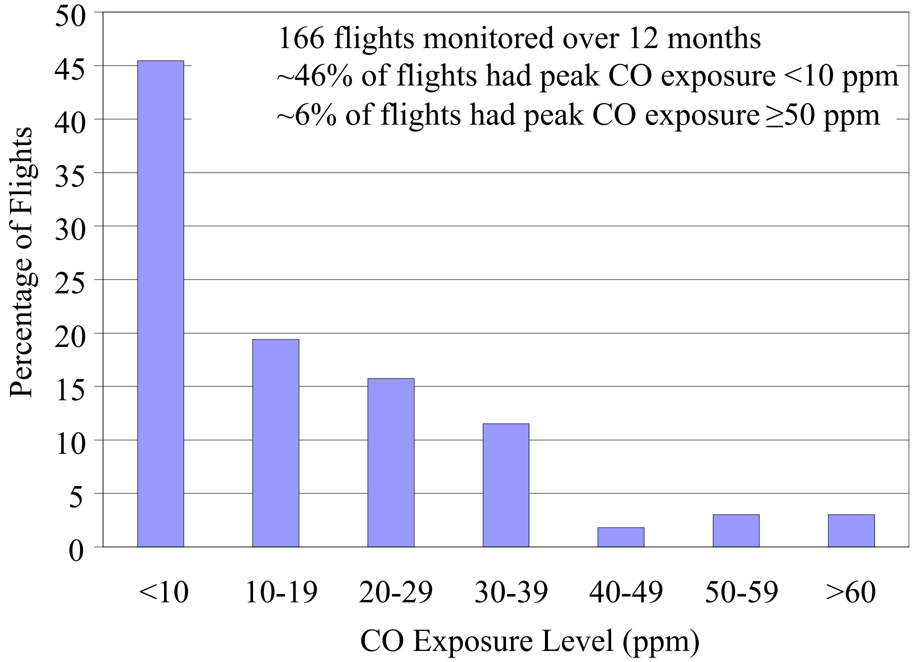


Figure B-21. Percent of Peak CO Events Within Different CO Level Categories for the High-Wing Aircraft on the Ground and in the Air

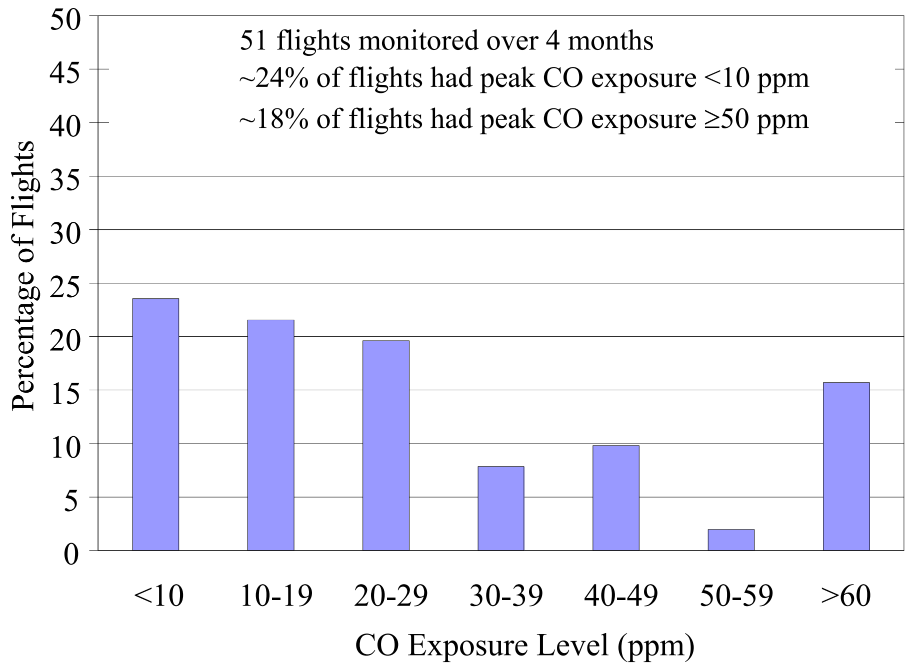


Figure B-22. Percent of Peak CO Events Within Different CO Level Categories for the Low-Wing Aircraft on the Ground and in the Air

For the low-wing aircraft flights that were monitored (figure B-22), 24% of the flights had peak CO levels detected that were less than 10 ppm, and approximately 64% of the flights had peak CO levels detected that were less than 30 ppm. The lower-peak CO levels detected were somewhat more equally distributed than those for the high-wing aircraft flights. For the higher-peak CO levels detected, approximately 18% of the flights had peak CO levels detected that were greater than 50 ppm (either on the ground or in the air).

B.3.6 SUMMARY OF CO AMBIENT LEVELS AND CO DETECTOR PLACEMENT.

The current FAA requirement for CO in the cabin indicates that no more than 50 ppm of CO is allowed anywhere in the cabin [B-2]. Ambient levels of CO in the cabin of two types of GA aircraft (high-wing and low-wing) with CO detectors positioned strategically at locations consistent with potential pathways for CO to enter the cabin indicated the following:

- CO was detected in the aircraft cabin, with the aircraft either on the ground or in the air, in 92% of the flights for the high-wing models tested, and in 96% of the flights for the low-wing models tested.

- The majority of CO detected was less than 10 ppm for both high-wing (76% of CO events detected) and low-wing (66% of CO events detected) GA aircraft models tested.

- CO above 50 ppm occurs during ambient operating conditions, where 6% of CO events for the high-wing aircraft tested were above 50 ppm, and 18% of CO events for the low-wing aircraft tested were above 50 ppm.

- Exposure to CO with the aircraft on the ground increases during taxiing and holding short, especially with windows open.

If portable, battery-operated CO detectors are to be used in the cabin to detect and alert pilots of specific thresholds of CO in the cabin (e.g., 50 ppm), it is likely that only one CO detector would be used. The ability of CO detectors to detect at least 50 ppm anywhere in the cabin, using CO detectors strategically positioned at locations consistent with potential pathways for CO to enter into the cabin indicated the following:

- None of the CO detectors positioned at locations within the cabin that were visible and easily accessible to the pilot were able to detect CO above 50 ppm in the cabin 100% of the time when CO was above 50 ppm somewhere in the cabin.

- Setting CO detector alarm levels at ppm levels less than the FAA requirement (i.e., 50 ppm) increased the probability of CO detectors identifying when greater than 50 ppm of CO was present somewhere in the cabin, while keeping the probability of false alarms low.

    - For the high-wing aircraft tested, the sensitivity was 100% (no false negatives) and the specificity was approximately 95% (very few false alarms) for the CO detector positioned at the instrument panel when the alarm threshold was set at 30 ppm.

- For the low-wing aircraft tested, the sensitivity was 100% (no false negatives) for the CO detectors at the instrument panel and the left-side door panel when the alarm threshold was set at 30 ppm. The specificity for the CO detectors at the instrument panel and the left-side door panel was approximately 90% (very few false alarms) when the aircraft was on the ground, and between 95% and 100% (very few false alarms) when the aircraft was in the air.

B.4 CONCLUSIONS.

The five prominent sensor technology types for carbon monoxide (CO) detectors (i.e., biomimetic, electrochemical, spot, infrared, and semiconductor) each have advantages and limitations in comparison. Considering detector technology variables that are important for the general aviation (GA) environment, such as detector accuracy, quick response time, low false alarms, and low power consumption requirements, it appears that electrochemical sensor-based CO detectors may be the most suitable technology for use at this time in a GA environment.

Thorough inspection of CO detector performance specifications resulted in a prioritized list with respect to consideration for use in a GA environment. General CO detector performance parameters and specifications were divided into tiers based on their importance to the GA environment, with Tier 1 representing important performance parameters within a GA environment and Tier 2 indicating secondarily important performance parameters and specifications for detector selection considerations within a GA environment. With the categorization of the detector performance parameters based upon the GA environment, and the documentation of these specifications, these data can be used to allow pilots to make informed decisions about which CO detector technology to select for secondary methods to prevent accidents and incidents due to CO exposure in GA aircraft.

Monitoring of ambient levels of CO during flights indicated CO was present in the cabin when the aircraft was on the ground and in the air. Exposure on the ground occurs when taxiing and holding while waiting for takeoff, especially when the windows of the aircraft are open. The majority of CO detected in the cabin was below 10 ppm, well below the Federal Aviation Administration requirement of 50 ppm, with much of the CO detected with the aircraft on the ground before takeoff and after landing. However, a small percentage of CO in the cabin was above 50 ppm. To detect CO above 50 ppm somewhere in the cabin, the instrument panel appeared to be the optimal location for the CO detector, although setting the CO detector alarm levels at 50 ppm resulted in a large number of false negatives (missed alarms). To increase the probability of being able to detect at least 50 ppm anywhere in the cabin and to reduce the occurrence of false alarms, it appears that the CO detector should be set at a lower alarm threshold of 35 ppm.

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APPENDIX C—EXHAUST SYSTEM MAINTENANCE AND INSPECTION

C.1 INTRODUCTION AND BACKGROUND INFORMATION.

Exposure to carbon monoxide (CO), which is formed by the incomplete combustion of aviation fuel, can lead to harmful health effects depending on the concentration and duration of exposure. Acute CO poisoning is associated with headache, dizziness, fatigue, nausea, and at elevated doses, neurological damage and death. When this occurs in an aircraft, an accident could result. Exhaust system failures in general aviation (GA) aircraft can result in CO exposure. Proper inspection and maintenance of piston engine exhaust systems is the primary mechanism for preventing CO exposure. The focus of this appendix is maintenance and inspection issues related to CO exposure in GA aircraft.

In piston engines, proper cooling of the engine cylinder is a major consideration during the design of GA aircraft. The configuration of modern aircraft piston engines is horizontally opposed so they provide a reasonably good cooling characteristic when ram air is forced into the engine cowling. To provide cabin heat, a heat exchanger is usually attached to the exhaust system of single-engine aircraft. Figure C-1 shows the overall engine in the left-hand diagram, while a breakout of the heat exchanger is shown in the right-hand diagram [C-1]. Since the exhaust gas and air for the cabin heat move along two independent tubes, the exhaust and cabin air should remain distinctly separate.

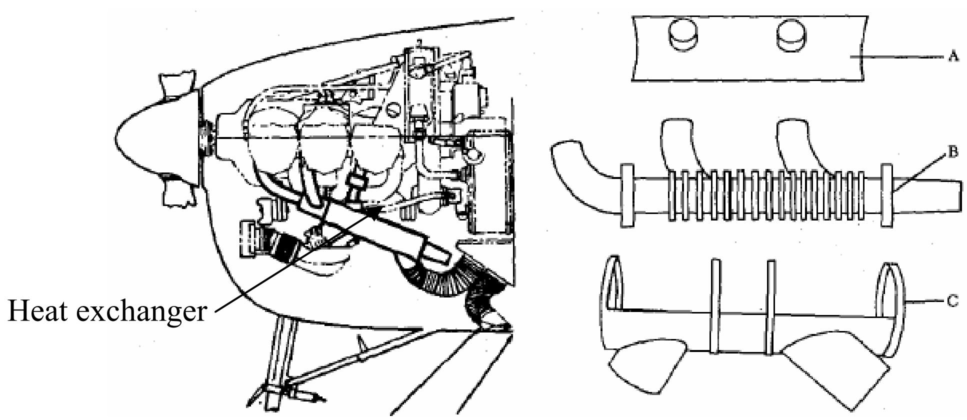

Figure C-1. Six-Cylinder, Horizontally Opposed Reciprocating Engine [C-1]
(Heat Exchanger Upper Sheet Jacket (A), Collector Tube (B), and Lower Sheet Jacket (C))

A significant hazard can result, however, when there is a failure in the piston engine exhaust system. This can occur in the form of CO entering the heat exchanger air, which is used to heat the cabin, or through a leak in the firewall between the engine compartment and cabin. A Federal Aviation Administration (FAA) report [C-2] notes that piston engine exhaust gases typically contain 5% to 7% CO, although an exhaust system failure may result in a smaller concentration of CO due to mixing with other air in the engine compartment. Irrespective of how frequently it occurs, there is a high risk for CO exposure in the cabin whenever there is an exhaust system failure. According to one FAA report [C-2], 70% of exhaust system failures result in a CO hazard. Thus, proper inspection and maintenance of the exhaust system is extremely important; textbooks on maintenance procedures [C-3 and C-4] clearly state that aircraft engine exhaust systems must be thoroughly inspected. Also, FAA regulations require inspection of exhaust systems at 100-hour and annual inspection intervals [C-5].

The exact design associated with the piston engine exhaust system varies between manufacturers and aircraft models within a given manufacturer. The common element is the large number of connections that can potentially crack or fail. One representative example of a piston engine exhaust system is shown in figure C-2 [C-1]. There are welds between the end plates and exhaust tubing, and bolts or clamps to connect tubes. Piston engines are operated at different rpm, varying from ground idle to maximum takeoff settings, that can lead to vibration-type fatigue. At the same time, piston engine exhaust is extremely hot and corrosive, so thermal fatigue or corrosion can result in any part of the exhaust system. Exhaust system deterioration can result from several factors, including:

- Engine vibration, which may eventually cause metal fatigue
- Thermal cycling during engine operation
- High temperature and corrosive effect of engine exhaust

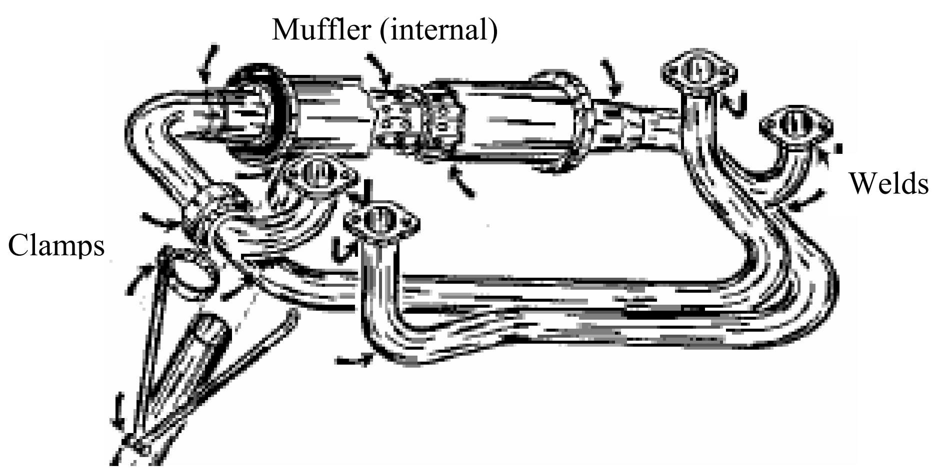

Figure C-2. Typical Exhaust System Inspection Areas [C-1]

These factors can result in fatigue of welded areas as well as clamp joints, or failure of the muffler and heat exchanger. Failure of the exhaust manifold or joints can result in CO permeation to the cockpit through the engine firewall. Failure of the muffler and heat exchanger can result in CO infiltrating into the cabin through the heater vents. Any type of obstruction in the exhaust system, for example, in the inner baffle of the muffler, can lead to local hot spots and burn-through of the tubing walls. Advisory Circular (AC) 91-59A [C-6] indicates that the most prominent problem area regarding exhaust system failures is the muffler and heat exchanger parts of the exhaust system. Some mufflers have heat transfer pins (figure C-3) that are welded to the inner wall to improve heat transfer to the air flowing within the heating system. These pins provide a significant increase in heat transfer capability, but are also additional components that must be periodically inspected and maintained. Figure C-4 [C-7] shows some of the different types of failures found in typical exhaust system mufflers, such as fatigue failure of the exhaust outlet and fatigue failure of the exhaust system wall and inlet.

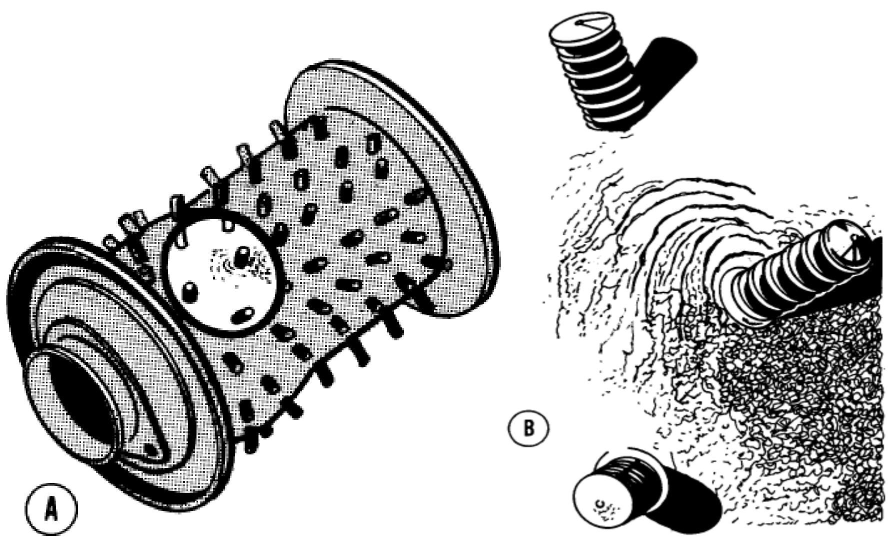

Figure C-3. An Exposed Muffler (A) and its Heat Transfer Pins (B) [C-7]

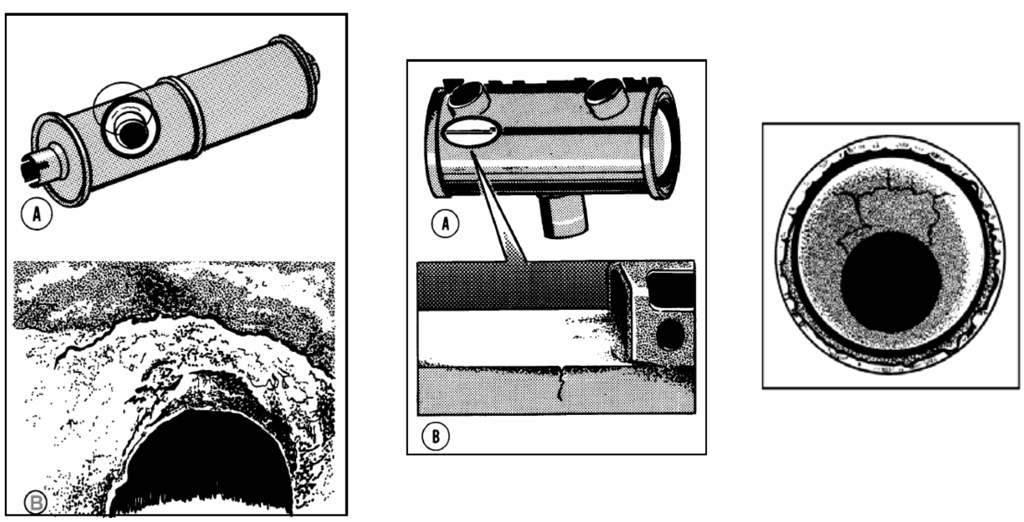

Figure C-4. Typical Muffler Failures [C-7] (Exhaust Outlet Fatigue (Left), Wall Fatigue (Middle), and End Plate Fatigue at Inlet (Right))

Besides the thermal and vibration fatigue failures mentioned earlier, another kind of failure is possible in a turbocharged piston engine. Figure C-5 [C-1] shows how the exhaust gas is routed through the turbocharger to pressurize the intake air when the aircraft is flown at high altitude. At sea-level operations, a waste gate vents a large portion of the exhaust to prevent over-pressurization. Carbon buildup in the waste gate may cause the gate valve to stick, resulting in erratic operation or failure. Thus, periodic inspection and cleaning of carbon buildup is also required in turbocharged piston engines.

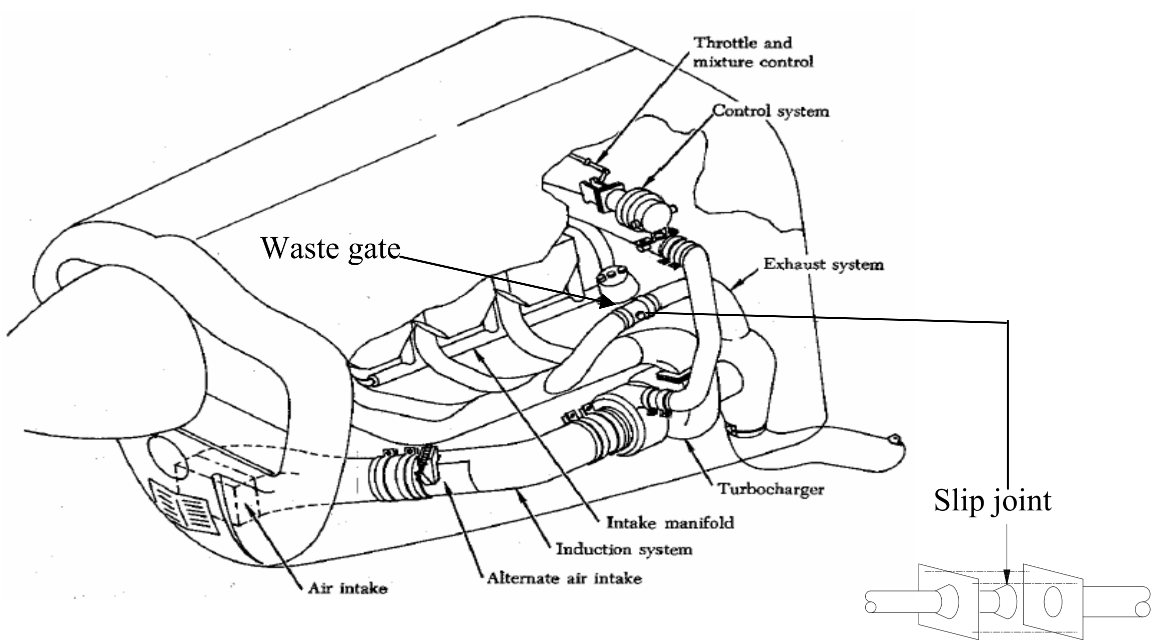

Figure C-5. Six-Cylinder, Horizontally Opposed Turbocharged Engine [C-1]

The right-hand breakout illustration of figure C-5 shows another type of exhaust system connection that can lead to potential CO exposure. A slip joint allows two different tubes to rotate and move like a ball joint. In such a configuration, there must be a gap between the "mushroom-shaped" tube's outer wall and the slip joint plate, which is hard-bolted to the opposing tube. By design, such a joint allows for a small amount of exhaust gas leakage. If these joints are not inspected and properly maintained, an excessive amount of exhaust gas leakage can occur. This also leads to the need to properly seal the engine-cabin firewall, which must then be periodically inspected and maintained.

Indications of exhaust system failure include (1) smell of smoke in the cockpit, (2) an excessive drop in engine rpm when applying carburetor heat, and (3) sooty, black discoloration on the heat exchanger shroud [C-6 through C-8]. These indicators of exhaust system deterioration rely on the subjective observation of the pilot or maintenance personnel. The presence of cracks on the exhaust system parts may allow infiltration of small amounts of CO into the cockpit through the heater vents or firewall openings.

FAA Special Airworthiness Information Bulletin, SAIB-CE-03-52 [C-9], notes that in the year 2000, the average age of the nation's 150,000 single-engine aircraft was over 30 years old. Although CO hazards are not limited to aging aircraft alone, the risk of exhaust system failure naturally increases with older aircraft. FAA AC 43.13-1B [C-7] notes that half of the (piston engine) exhaust system failures occur within 400 hours of operation. One concern expressed by the National Transportation Safety Board (NTSB) is the incidence of CO exposure, leading to a fatal accident, soon after the aircraft completes its annual or 100-hour inspection [C-10]. Part of the reason for these accidents, soon after inspection, may be due to tiny cracks on the exhaust system parts that are difficult to see in a simple visual inspection. The densely packed engine compartment makes it difficult to perform a thorough inspection unless some parts are disassembled and removed. Even if the exhaust system is intact without leaks during an inspection, it is possible that a crack or failure may occur soon after inspection due to the undetected internal deteriorations and engine vibrations because the typical exhaust systems wear from the inside out. Many failures are not evident as they are due to erosion and internal fatigue to the exhaust system. Indeed, the recent NTSB Safety Recommendation cites a number of Service Difficulty Reports where exhaust system failures were found only after disassembly and pressure testing, even though the exhaust system had passed its annual inspection just a short time earlier [C-10]. Incidents such as these suggest that CO exposure is a serious hazard that can suddenly occur at any time.

C.2 OBJECTIVES AND TECHNICAL APPROACH.

The objective of this research was to determine the possible causes of CO leakage, as well as the pathways for infiltration of CO into GA aircraft cabins. This was an important objective because exhaust and heater system maintenance is the primary mechanism for preventing CO exposure in GA aircraft. To achieve these objectives, the NTSB accident/incident database was reviewed to determine the potential causes of CO leakage and their relationship to maintenance and inspection practices. Additionally, aircraft industry maintenance practices and FAA regulations and guidelines were also reviewed to identify practices that may lead to poor maintenance and inspection of exhaust and heater systems. Furthermore, pathways for infiltration of CO into GA aircraft cockpits were determined. This step provided information about potential placement locations for monitoring CO exposure through CO detectors.

C.3. MAINTENANCE AND INSPECTION ISSUES IN THE LITERATURE.

Three major sources of information used to determine CO-related maintenance and inspection issues included (1) maintenance- and inspection-related information retrieved from CO-related accident/incident reports in the NTSB database, (2) existing regulations pertaining to GA aircraft maintenance and inspection in Title 14 Code of Federal Regulations (CFR) 91.409 [C-11], and (3) GA aircraft service manuals. Analysis of the NTSB accident/incident database revealed that two particular aircraft models stood out in terms of number of CO incidents. However, this may be due to the large number of these particular aircraft models in the GA fleet, and not likely due to an increased rate of CO incidence. Nevertheless, these two models were selected for further study due to their prevalence in the GA fleet.

C.3.1 INSPECTION REGULATIONS AND ACCIDENT/INCIDENT REPORTS.

14 CFR 91.409 [C-11] specifies the inspection of all civil aircraft at specific intervals. For GA aircraft, annual inspections and 100-hour inspections are required. Annual inspections require the aircraft to be inspected at least once a year, whereas the 100-hour inspection requires the aircraft to be inspected within 100 hours of flight time. An annual inspection is acceptable as a 100-hour inspection, but the reverse is not allowed.

A review of the NTSB accident/incident database for CO-related accident/incidents in GA aircraft revealed that the muffler was the leading source of CO leakage (figure C-6), either as the sole source (22 out of 62 cases) or in combination with other parts of the heater system (additional 4 cases for a total of 26 cases). In the accident cases where full detailed reports were available, inadequate inspection or inadequate maintenance and inspection were the most frequently cited terms (figure C-7). This finding is consistent with AC 91-59A [C-6], which indicates that inadequate and infrequent inspections are the primary reasons for most exhaust system failures.

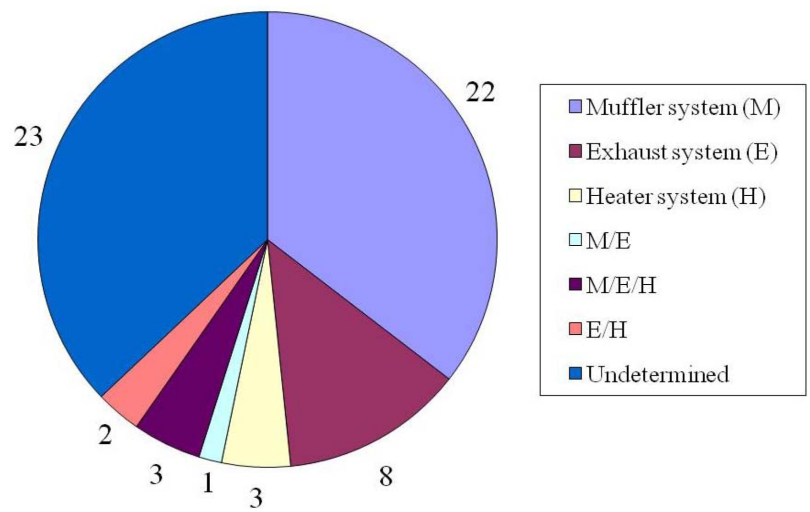

Figure C-6. Frequency of CO-Related Accidents/Incidents as a Function of the Source of CO

The analysis of the NTSB data also suggested that a trend may exist between hours of muffler use with muffler failure and exposure to CO. Where information about muffler life (in hours) was available in the accident/incident reports (13 out of 62 cases), most of the accident/incident cases had muffler usage over 1000 hours (figure C-8). Although the data suggest a clear trend in muffler failure related to the number of hours a muffler has been in use (figure C-8), a lifetime limit before replacement of mufflers does not exist in FAA regulations regarding GA aircraft mufflers (excluding some specific serial numbers of mufflers that may have a lifetime limit given in an Airworthiness Directive (AD)). However, the Piper PA-28 Service Manual [C-12] recommends that mufflers for this particular aircraft should be replaced after 1000 hours of use.

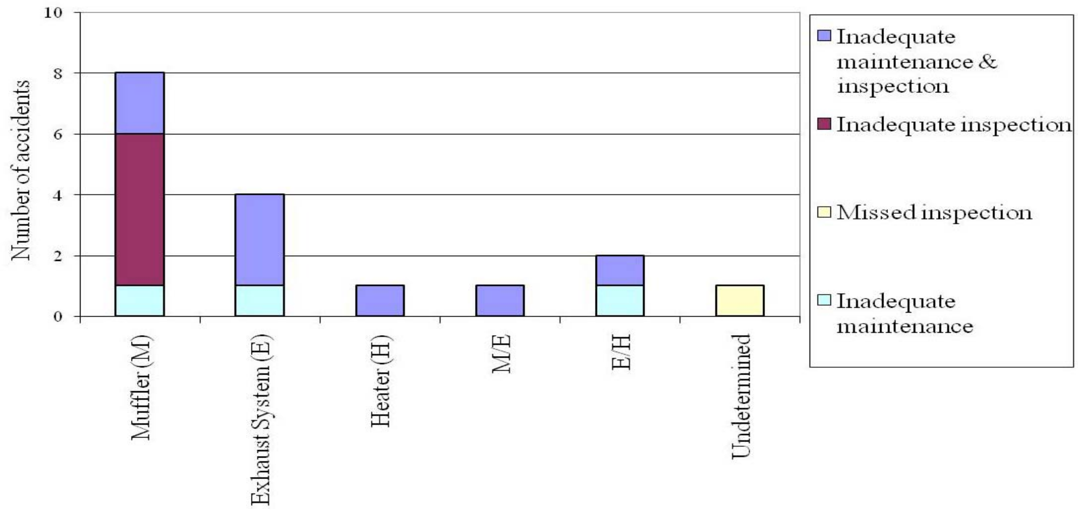

Figure C-7. Frequency of Inspection and Maintenance Issues Identified for CO-Related Cases

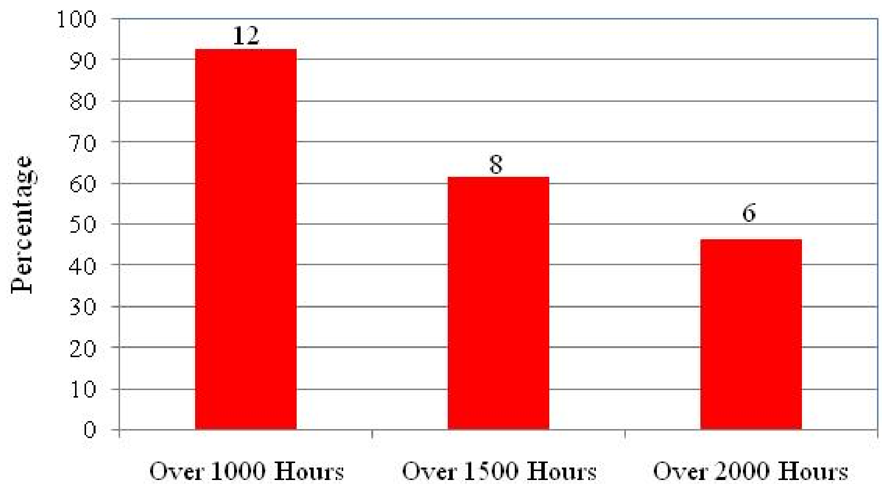

Figure C-8. Percentage of GA Aircraft CO-Related Accidents/Incidents as a Function of Hours of Muffler Use

Guidance from FAA documents and manufacturer service manuals suggests that mufflers should be pressure tested to assess the integrity of the muffler. AC 43.13-1B [C-7] suggests performing muffler pressure tests at 2 psi. The Cessna 172 Service Manual [C-13] recommends performing muffler pressure tests at 3 ±0.5 psi, while AD 90-06-03 R1 [C-14], which pertains to particular serial numbers of the Cessna 172 model, recommends performing muffler pressure tests at 5 psi. Finally, AD 70-16-05 [C-15], which corresponds to specific serial numbers of the Piper PA-28 model, recommends muffler pressure tests at 10 psi (if the muffler is repaired). Although these sources provide guidance for pressure testing mufflers, different sources recommend varying air pressure levels for the tests, and there is currently no requirement to perform pressure tests during annual or 100-hour inspection and maintenance procedures on the GA aircraft's muffler.

C.3.2 EXHAUST SYSTEM INSPECTION PROCEDURES.

Several FAA documents and manufacturer service manuals provided the following set of guidance on inspection procedures to follow when inspecting the exhaust system during the annual or 100-hour inspections [C-6 and C-7] and [C-12 and C-13]:

- Remove all the exhaust shrouds and shields to expose the exhaust system and look for signs of possible exhaust gas leakage.

- After proper cleaning, inspect all external surfaces of the exhaust system, especially welds and clamps, for cracks, dents, and missing parts.

- Examine areas around the welds, dented areas, and low spots in the system for thinning and tiny cracks.

- Dismantle the exhaust system to visually inspect internal areas, if it is necessary. Use a probe light and mirror for better inspection.

- Do not use carbon-based or lead pencils on an exhaust system since its metal carbonization and heat concentration will cause damage.

- When a thorough visual inspection of the component is unattainable, two procedures are recommended:

    - Perform an air pressure test by using the blower side of a shop vacuum connected to the exhaust system and soapy water applied throughout the exhaust system [C-16]. An alternate pressure test method[1] described in the literature [C-7, C-12, and C-13] recommends removing the component, plugging all the openings, and then submerging it in water while applying pressurized air. The formation of bubbles indicates the existence of leakage. Care should be taken in this alternate method to dry the component before reuse.

    - Use of visual inspection aids such as a powerful flashlight, a mirror with a ball joint, 2- to 10-power magnifying glass for inspection of internal exhaust system components [C-6 and C-7]. Additionally, since internal wear and damage are difficult to detect until failure has occurred, borescopes are recommended for inspection of internal exhaust system components that cannot be performed visually [C-6]. Borescopes are long, tubular instruments with built-in illumination that allow inspection of internal surfaces (e.g., exhaust system components, muffler) or otherwise inaccessible areas [C-7].

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[1] The submersion pressure test was reported to involve excessive labor and expense, thus it is unlikely to be used by inspection stations.

The Piper PA-28 Service Manual [C-12] also recommends using a CO detector, when thorough visual inspection is not achievable, by warming up the engine while the heating system is on. Although the location for the placement of the CO detector is not identified, the service manual advises that if the CO detector measurement in the cabin is higher than 50 ppm, then replacement of the muffler may be warranted [C-12].

As shown in this inspection procedure, the main approach is to perform a visual inspection. There is no requirement identified in the regulations (14 CFR 43.13 and 43.15) to perform a more thorough inspection via pressure testing or the use of a borescope to detect tiny and delicate cracks. This can be problematic in the case of muffler inspection if there are internal cracks or defects, which are difficult to see from an external visual inspection.

C.3.3 CARBON MONOXIDE INFILTRATION PATHWAYS.

Identification of potential pathways that allow CO to enter the cabin are important for secondary prevention methods, such as the use of CO detectors during aircraft operations. As indicated earlier, a review of the NTSB database for CO-related accidents/incidents in GA aircraft revealed that the muffler was the leading source of CO leakage (figure C-6), either as the sole source or in combination with other parts of the exhaust system. Further analysis by season of the year in which the accident occurred (figure C-9) indicated that the muffler was a likely cause of CO exposure during the fall, winter, and spring, but not in the summer months. This suggests that the muffler and heater system may be sources of CO in the cabin during the months when it is more likely for the pilot to use the heater system. Schematics from service manuals of Cessna 172's and Piper PA-28's show that the heater ducts supplying warm air from the heat exchanger (muffler) would be the major pathway for CO to enter the cabin should the muffler or components of the heater system fail. The heater ducts are generally located on the sides of the cabin in the Cessna 172 model and in the middle of the cabin in the Piper PA-28 model.

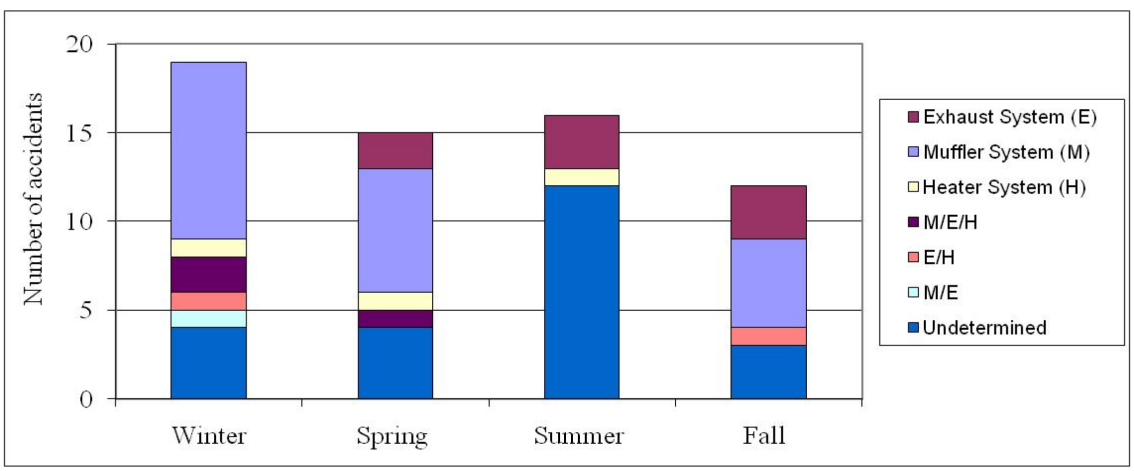

Figure C-9. Seasonal Distribution of CO-Related Accident/Incidents and Their Source of CO Leakage

The NTSB database analysis also revealed that the cause of CO leakage could not be determined in some CO-related accident/incident cases, where many of these cases occurred during the summer months (figure C-9). A review of GA aircraft service manuals and consultation with experts in maintenance and inspection suggested that a potential pathway may be the CO-rich exhaust from the tailpipe of the engine being drawn into the cabin through the fresh air intakes located on the fuselage and wing. Figure C-10 shows the exhaust tailpipe of a Cessna 172 at the front lower portion of the fuselage in comparison to the fresh air inlets, which are on the side of the aircraft and on the front edge of the wing. For the Piper PA-28, the exhaust tailpipe is located at the front lower portion of the fuselage and the fresh air inlet is located on the front edge of the wing (figure C-11). Schematics from service manuals also identified the location of the fresh air vents within the cabin. In the Cessna 172, the fresh air vents are located near the visors and upper corners of the windshields. In the Piper PA-28, the fresh air vents are located on the sides of the cabin. In some Piper PA-28 models, there is an outgoing air ventilation route located near the aft side of the cabin.

Figure C-10. Cessna 172 Locations for the Exhaust Tailpipe (1) and Fresh Air Inlets (2 and 3) [C-18]

Figure C-11. Piper PA-28 Locations for the Exhaust Tailpipe (1) and Fresh Air Inlet (2) [C-19]

C.4 CONCLUSIONS.

Federal Aviation Administration (FAA) regulations and guidance documents regarding maintenance and inspection of general aviation (GA) aircraft exhaust systems indicate that inspection procedures are generally conducted by means of visual inspection, and there are no FAA requirements to perform more thorough tests to detect possible developing interior cracks or other interior damage. GA manufacturer service manuals, however, reveal that the complexity of the muffler makes it extremely difficult to visually inspect the interior of the muffler, which increases the likelihood of missing developing or possibly even severe damage. Given the proportion of carbon monoxide (CO)-related accidents and incidents in the National Transportation Safety Board (NTSB) database where poor or inadequate maintenance and/or inspection was identified as a contributing cause, the data suggest more thorough inspection and maintenance procedures may be necessary for the exhaust system, including pressure testing for the muffler, to prevent CO exposure in GA aircraft.

An additional issue is that there are no requirements in the FAA regulations regarding mandatory replacement of the muffler with respect to hours of muffler use. Data from the NTSB database regarding muffler flight hours when the muffler was determined to be the cause of CO exposure, as well as a recommendation in a GA aircraft service manual, suggest that mufflers should be replaced after 1000 hours of use. This consideration may become increasingly important as the GA aircraft fleet continues to age.

Attention to more thorough inspection and maintenance practices, such as pressure testing of mufflers, use of a borescope for inspection of internal parts of the exhaust system, as well as specifying muffler replacement as a function of flight hours, should be considered as the primary prevention method for CO exposure in GA aircraft. To further decrease the risk of accidents and incidents due to CO exposure, secondary prevention methods of detecting the presence of CO should be considered. Heater vents and inadequately sealed holes in the firewall were identified as pathways of CO into the cabin. Additionally, it may be possible, under some conditions, for cabin air to become contaminated with CO due to exhaust exiting the tailpipe and being drawn into the cabin through the fresh air ventilation system or because of missing/defective door and window seals. This may explain the large number of undetermined causes for CO-related accident/incident cases in the summer months. Thus, secondary prevention methods to alert the pilot of potentially dangerous levels of CO in the cabin, such as the use of CO detectors, should be given consideration.

C.5 REFERENCES.

C-1. FAA Advisory Circular, "Airframe and Powerplant Mechanics Powerplant Handbook," AC 65-12A, 1976.

C-2. FAA Aviation Medicine Reports, "Carbon Monoxide In-Flight Incapacitation: An Occasional Toxic Problem in Aircraft," AM-82-15, 1982.

C-3. Jeppesen Sanderson Inc., "A&P Technician Powerplant Textbook," IAP, Casper, 1992.

C-4. M.J. Kroes, T.W. Wild, R.D. Bent, and J.L. McKinley, *Aircraft Powerplants*, McGraw-Hill, New York, 1990.

C-5. 14 CFR Part 43, Appendix D; Scope and Detail of Items (as Applicable to the Particular Aircraft) To Be Included in Annual and 100-Hour Inspections.

C-6. FAA Advisory Circular, "Inspection and Care of GA Aircraft Exhaust Systems," AC 91-59A, 2007.

C-7. FAA Advisory Circular, "Acceptable Methods, Techniques, and Practices—Aircraft Inspection and Repair," AC 43.13-1B, 1998.

C-8. FAA Advisory Circular, "Aircraft Inspection for the General Aviation Aircraft Owner," AC 20-106, 1978.

C-9. Federal Aviation Administration, "Best Practices Guide for Maintaining Aging General Aviation Airplanes," FAA Special Airworthiness Information Bulletin SAIB-CE-03-52, September 2003.

C-10. National Transportation Safety Board, "NTSB A-04-25 through -28," Washington, 2004.

C-11. 14 CFR 91.409

C-12. Piper Aircraft Corporation, “Piper PA-28 Cherokee Series Service Manual,” last revision 2002.

C-13. Cessna Aircraft Company, “Cessna 172 Skyhawk Series Service Manual,” revised 1977.

C-14. FAA Airworthiness Directive AD 90-06-03 R1, Cessna Model 172 Airplanes, 1990.

C-15. FAA Airworthiness Directive AD 70-16-05, Piper Model PA-28 Airplanes, 1970.

C-16. Shipe, J., “Exhausting Exhaust Systems,” *Pipers*, Vol. 21, No. 8, 2008, pp. 44-48.

C-17. Thielert Group. Retrieved November 2006, from http://info.thielert.com.

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APPENDIX D—BEST PRACTICES IN MAINTENANCE AND INSPECTION OF GENERAL AVIATION AIRCRAFT EXHAUST SYSTEM

D.1 INTRODUCTION AND BACKGROUND INFORMATION.

Exposure to carbon monoxide (CO), which is formed by the incomplete combustion of aviation fuel, can lead to harmful health effects depending on the concentration and duration of exposure. Acute CO poisoning is associated with headache, dizziness, fatigue, nausea, and at elevated doses, neurological damage and death. When this occurs in an aircraft, an accident could result. Exhaust system failures in general aviation (GA) aircraft can result in CO exposure. Proper inspection and maintenance of piston engine exhaust systems is the primary mechanism for preventing CO exposure. The focus of this appendix is maintenance and inspection issues related to CO exposure in GA aircraft.

In piston engines, proper cooling of the engine cylinder is a major consideration during the design of the GA aircraft. The configuration of modern aircraft piston engines is horizontally opposed so they provide a reasonably good cooling characteristic when ram air is forced into the engine cowling. To provide cabin heat, a heat exchanger is usually attached to the exhaust system of single-engine aircraft. Figure D-1 illustrates the overall engine in the left-hand diagram while a breakout of the heat exchanger is shown in the right-hand diagram [D-1]. Since the exhaust gas and air for the cabin heat move along two independent tubes, the exhaust and cabin air are supposed to remain distinctly separate.

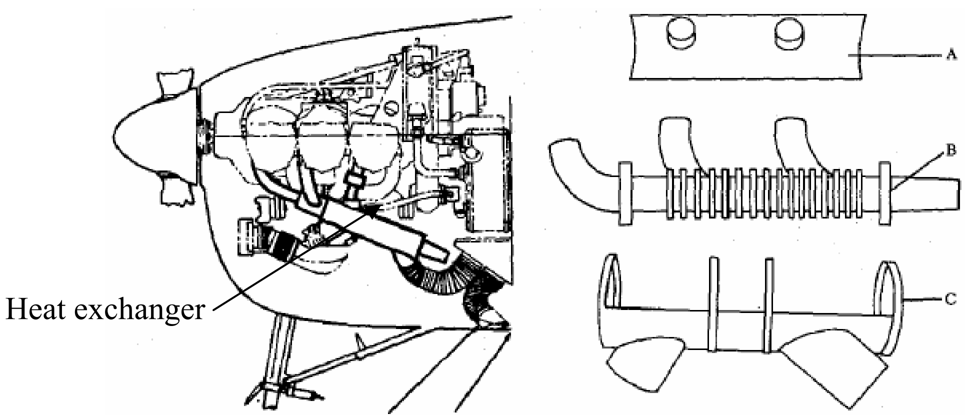

Figure D-1. Six-Cylinder, Horizontally Opposed Reciprocating Engine [D-1] (Heat Exchanger Upper Sheet Jacket (A), Collector Tube (B), and Lower Sheet Jacket (C))

A significant hazard can result, however, when there is a failure in the piston engine exhaust system. This can come in the form of CO entering the heat exchanger air, which is used to heat the cabin, or through a leak in the firewall between the engine compartment and cabin. A Federal Aviation Administration (FAA) report [D-2] notes that piston engine exhaust gases typically contain 5% to 7% CO, although an exhaust system failure may result in a smaller concentration of CO due to mixing with other air in the engine compartment. Irrespective of how frequently it occurs, there is a high risk for CO exposure in the cabin whenever there is an exhaust system failure. According to one FAA report [D-2], 70% of exhaust system failures result in a CO hazard. Thus, proper inspection and maintenance of the exhaust system is extremely important, and textbooks on maintenance procedures [D-3 and D-4] clearly state that aircraft engine exhaust systems must be thoroughly inspected.

The exact design associated with the piston engine exhaust system varies from manufacturer to manufacturer as well as model to model within a given manufacturer. Nevertheless, the common element is the large number of connections that can potentially crack or fail. One representative example of a piston engine exhaust system is illustrated in figure D-2 [D-1]. There are welds between the end plates and exhaust tubing, and bolts or clamps to connect tubes to tubes. Piston engines are operated at different rpm, varying from ground idle to maximum takeoff settings that can lead to vibration-type fatigue. At the same time, piston engine exhaust is extremely hot and corrosive so thermal fatigue or corrosion can result in any part of the exhaust system. Thus, exhaust system deterioration can result from several factors, including:

- Engine vibration, which may eventually cause metal fatigue
- Thermal cycling during engine operation
- High temperature and corrosive effect of engine exhaust

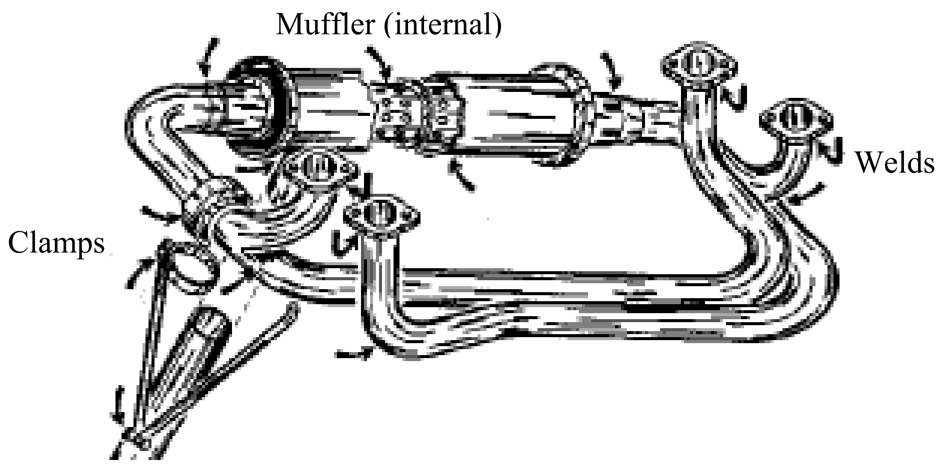

Figure D-2. Typical Exhaust System Inspection Areas [D-1]

These factors can result in fatigue of welded areas as well as clamp joints, or failure of the muffler and heat exchanger. Failure of the exhaust manifold or joints can result in CO permeation to the cockpit through the engine firewall. Failure of the muffler and heat exchanger can result in CO infiltrating into the cabin through the heater vents. Any type of obstruction in the exhaust system, for example, in the inner baffle of the muffler, can lead to local hot spots and burn-through of the tubing walls. Advisory Circular (AC) 91-59A [D-5] indicates that the most prominent problem area regarding exhaust system failures is the muffler and heat exchanger part of the exhaust system. Some mufflers have heat transfer pins (figure D-3) that are welded to the inner wall to improve heat transfer to the air that flows within the heating system. These pins provide a significant increase in heat transfer capability, but are also additional components that must be periodically inspected and maintained. Figure D-4 [D-6] illustrates some of the different types of failures found in typical exhaust system mufflers, such as fatigue failure of the exhaust outlet and fatigue failure of the exhaust system wall and inlet.

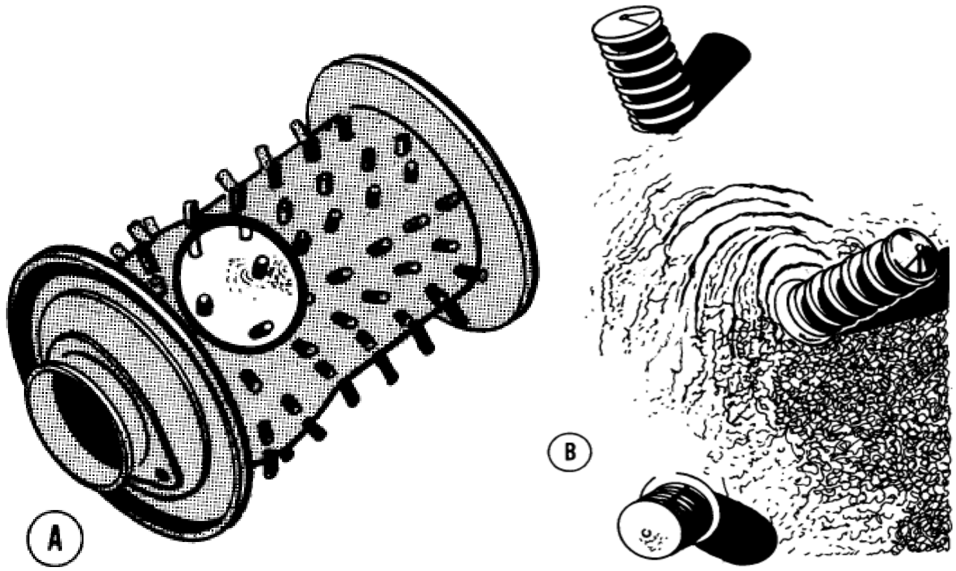

Figure D-3. An Exposed Muffler (A) and its Heat Transfer Pins (B) [D-6]

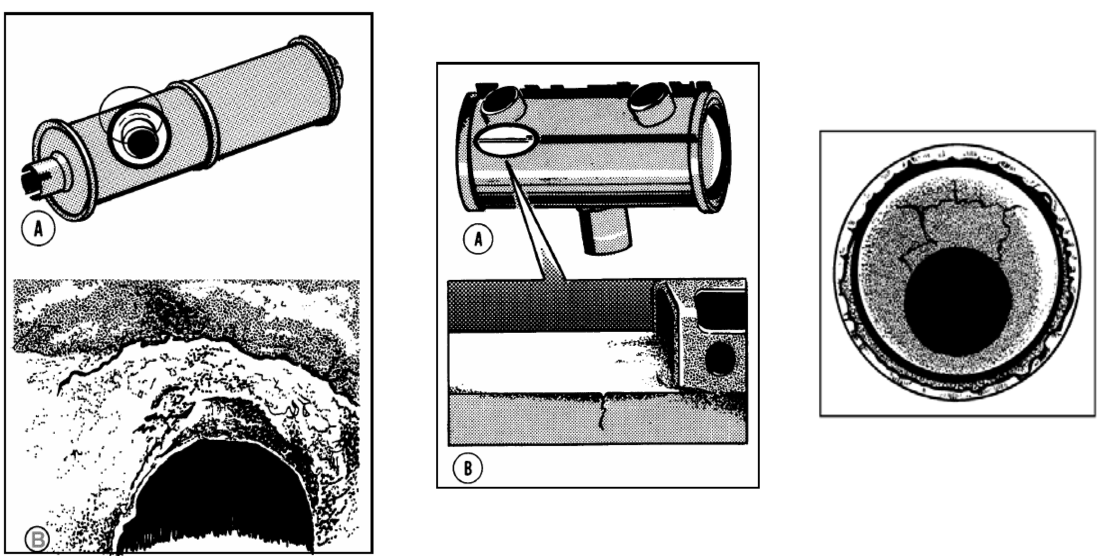

Figure D-4. Typical Muffler Failures [D-6] Exhaust Outlet Fatigue (Left), Wall Fatigue (Middle), and End Plate Fatigue at Inlet (Right)

Besides the thermal and vibration fatigue failures mentioned earlier, there is another kind of failure that is possible in a turbocharged piston engine. Figure D-5 [D-1] shows how the exhaust gas is routed through the turbocharger in order to pressurize the intake air when the aircraft is flown at high altitude. At sea level operation, a waste gate vents a large portion of the exhaust to prevent over-pressurization. Carbon buildup in the waste gate may cause the gate valve to stick, resulting in erratic operation or failure. Thus, periodic inspection and cleaning of carbon buildup is also required in turbocharged piston engines.

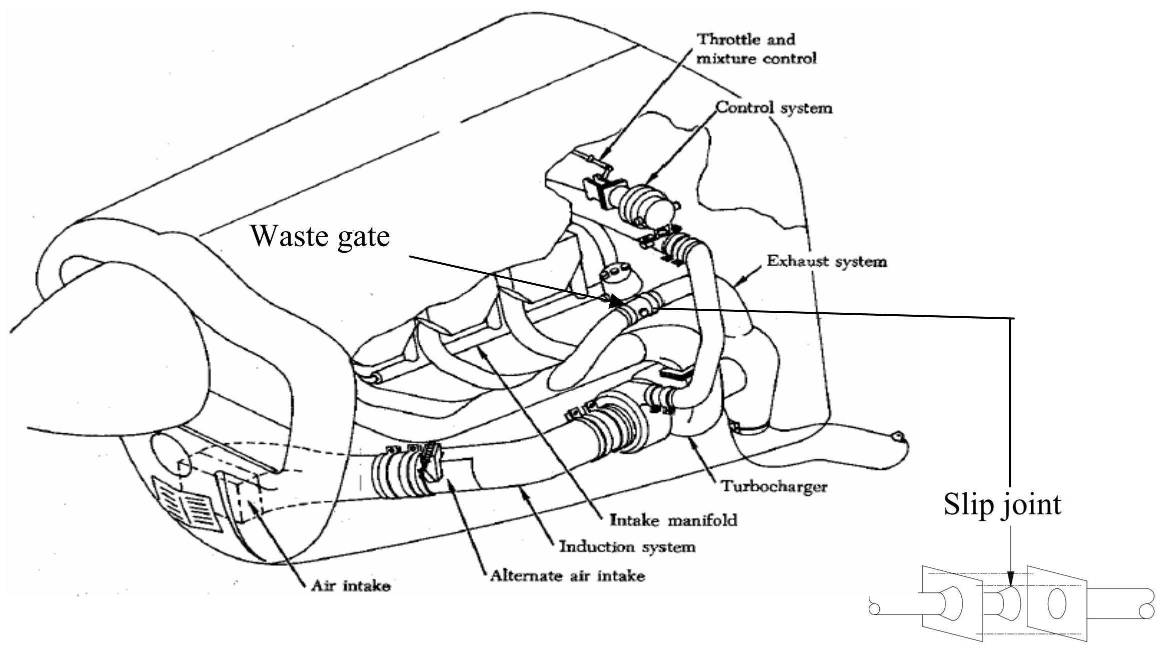

Figure D-5. Six-Cylinder, Horizontally Opposed Turbocharged Engine [D-1]

The right-hand breakout illustration of figure D-5 shows another type of exhaust system connection that can lead to potential CO exposure. A slip joint allows two different tubes to rotate and move like a ball joint. In such a configuration, there must be a gap between the "mushroom-shaped" tube's outer wall and the slip joint plate that is hard-bolted to the opposing tube. By design, such a joint allows for a small amount of exhaust gas leakage. If these joints are not inspected and properly maintained, an excessive amount of exhaust gas leakage can occur. This also leads to the need to properly seal the engine-cabin firewall, which must then be periodically inspected and maintained.

Indications of exhaust system failure include (a) smell of smoke in the cockpit, (b) an excessive drop in engine rpm when applying carburetor heat, and (c) sooty-black discoloration on the heat exchanger shroud [D-5 through D-7]. These indicators of exhaust system deterioration rely on the subjective observation of the pilot or maintenance personnel. The presence of cracks on the exhaust system parts may allow infiltration of small amounts of CO into the cockpit through the heater vents or firewall openings.

FAA Special Airworthiness Information Bulletin, SAIB-CE-03-52 [D-8], notes that in the year 2000, the average age of the nation's 150,000 single-engine aircraft was over 30 years old. Although CO hazards are not limited to aging aircraft alone, the risk of exhaust system failure naturally increases with older aircraft. FAA AC 43.13-1B [D-6] notes that half of the (piston engine) exhaust system failures occur within 400 hours of operation. One concern expressed by the National Transportation Safety Board (NTSB) is the incidence of CO exposure, leading to a fatal accident soon after the aircraft completes its annual or 100-hour inspection [D-9]. Part of the reason for these accidents, soon after inspection, may be due to tiny cracks on the exhaust system parts that are difficult to see in a simple visual inspection. The densely packed engine compartment makes it difficult to perform a thorough inspection unless some parts are disassembled and removed. Even if the exhaust system is intact without leaks during an inspection, it is possible that a crack or failure may occur soon after inspection due to the undetected internal deteriorations and engine vibrations because the typical exhaust systems wear from the inside out. Many failures are not evident as they are due to erosion and internal fatigue to the exhaust system. The recent NTSB Safety Recommendation cites a number of Service Difficulty Reports where exhaust system failures were found only after disassembly and pressure testing, even though the exhaust system had passed its annual inspection just a short time earlier [D-9]. Incidents such as these suggest that CO exposure is a serious hazard that can suddenly occur at any time.

FAA regulations and guidance documents regarding maintenance and inspection of GA aircraft exhaust systems indicate that inspection procedures are generally conducted by means of a visual inspection, and there are no requirements to perform more thorough tests, such as air pressure tests to detect possible developing internal damage. A review of GA manufacturer service manuals, however, revealed that the complexity of the muffler makes it extremely difficult to visually inspect the interior of the muffler, which increases the likelihood of missing developing or possibly even severe damage. The NTSB accident/incident database review also supports this idea, where it was found that the majority of CO-related accidents categorized as the inadequately inspected cases resulted in CO leakage in the muffler. Moreover, the NTSB has expressed concerns about CO-related accidents occurring shortly after the completion of an annual or 100-hour inspection [D-9]. Part of the reason for these accidents may be the fact that some cracks are hard to detect during a simple visual inspection.

D.2 OBJECTIVE AND TECHNICAL APPROACH.

The objective of this research was to identify exemplary inspection practices and maintenance procedures for exhaust and heater systems of GA aircraft (i.e., best practices), with the intent of reducing the risk of CO exposure during GA aircraft operations. To determine the best practices, a survey was conducted among accessible FAA-certified GA repair stations. The questionnaire used in this survey addressed the following areas:

- Events that trigger inspections of exhaust systems and mufflers

- Procedures and steps that are followed during an inspection of exhaust systems and the muffler
- Findings during inspections that may be related to CO exposure within the aircraft cabin
- Use of and familiarity with CO detector equipment during inspections
- Determining factors for the replacement of exhaust system or muffler
- Suggestions for inspection process improvements or design improvements of exhaust systems and mufflers

A sample of this questionnaire is shown in figure D-6. The following sections summarize the information gathered from questionnaire feedback, as well as the general inspection procedures available in the regulations and service manuals.

General Aviation Exhaust System Best Practices Questionnaire

- What triggers an inspection of a GA aircraft exhaust system? (e.g., sooty-black material on the exhaust system, exhaust smell in the cockpit, annual/100 hr inspection, etc.)
- What steps/procedures are followed for a GA aircraft exhaust system inspection?
- What indicators trigger a more detailed inspection of the exhaust system?
- What steps/procedures are followed in this more detailed inspection of the exhaust system?
- Based on your experience what indications have you found during inspections of exhaust systems or engine firewalls that have been a contributing factor to carbon monoxide problems within the aircraft cabin?
- During an exhaust system inspection and/or maintenance, is it common practice to conduct testing for carbon monoxide in the aircraft cabin?
- What types of carbon monoxide test equipment are you familiar with or have used during inspection/maintenance of exhaust systems? Which do you feel are the most effective?
- What factors determine when the exhaust system/muffler needs to be replaced or repaired?
- What suggestions do you have to improve the inspection process or improved exhaust system/muffler design?

Figure D-6. Questionnaire of Best Practices in GA Aircraft Exhaust System Maintenance and Inspection

D.3 EXHAUST SYSTEM INSPECTION TRIGGERS.

AC 91-59A [D-5] indicates that the most prominent problem areas regarding exhaust system failures are the muffler and heat exchanger parts of the exhaust system. References D-5 through D-7 identify several indications of exhaust system failure such as smelling smoke in the cabin, an excessive drop in engine rpm when applying carburetor heat, and sooty, black discoloration on the heat exchanger shroud. These indicators of exhaust system deterioration rely on the subjective observation of the pilot or maintenance personnel. Based on the practices performed at inspection stations, as well as indicated in the relevant literature [D-10 and D-11], the following indications were identified as possible triggers of GA aircraft exhaust system inspection:

- Annual/100-hr inspection
- Engine backfire
- Sudden loss or reduction of engine power
- Noisy engine or exhaust system compared to normal
- Rough engine run
- Higher than normal fuel burn
- Smell of the exhaust inside the cabin. It should be noted that if the exhaust system has been inspected recently with an air pressure test and soapy water, burning of the soap residuals on the exhaust system may cause a smell inside the cabin when the heater is on. Also, the smell may be associated with burning of a rubber or wire coating.
- Insufficient heat from the heating system, possibly due to damage of the heat transfer pins
- Crew experiencing light headedness, headache, or watery eyes
- Darkened or flaked color on the cowling
- Exhaust gas coming out of the cowling
- Excessive amount of sooty, black material on the exhaust system
- Bright reddish or orange residues on the exhaust system parts

D.4 EXHAUST SYSTEM MAINTENANCE AND INSPECTION TIPS.

Inspection procedures vary based on different types of aircraft. Several FAA documents (e.g., Airworthiness Directives (AD) and ACs and manufacturer service manuals) provide guidance on inspection procedures of GA aircraft exhaust systems [D-5 through D-7 and D-12 through D-15]. Research by the maintenance and inspection personnel on ADs pertinent to the make/model of the aircraft under inspection should be part of the inspection process. Usually the manufacturer's service manual is the primary source of reference during the inspection process. However, it must be noted that FAA ADs override the manufacturer's instructions in service manuals. In general, the GA aircraft exhaust system inspection procedure based on the best practices from inspection stations and relevant literature [D-5 through D-7 and D-10 through D-15] can be summarized as follows:

1. Search for FAA ADs and ACs pertinent to the make/model of the aircraft under inspection to find updated information, guidelines, and compulsory actions.

2. Remove all exhaust shields and shrouds to disclose exhaust system tubes and mufflers and look for signs of possible exhaust gas leakage.

3. If the parts are covered with dirt, dust, and/or sooty-black material, clean them before starting a visual inspection. Refer to relevant service manuals and documents for appropriate guidelines.

4. Visually inspect all external surfaces of the exhaust system, especially welds, clamps, and low spots for cracks, dents, thinning, missing hardware, corrosion, bulging, and any sign of metal fatigue. When bulging occurs, the metal crystallizes and the affected area can be felt by touching the part. If any abnormalities such as bulging, cracks, hotspots, or corrosion are detected in the part, those spots should be inspected in more detail. The detailed inspection may involve disassembling the exhaust system and inspecting the parts from the inside out using a magnifier and a flash light or a borescope.

5. Dismantle the exhaust system to visually inspect internal areas, if it is necessary. Do not reuse gaskets when the parts are reassembled.

6. Do not use carbon-based or lead pencils on exhaust system since its metal carbonization and heat concentration will cause damage.

7. For a component that is not accessible for a thorough visual inspection, perform an air pressure test by attaching the pressure side of an industrial shop vacuum to the tail pipe and squirt a soapy solution over the entire exhaust system including the muffler with its shroud removed. Any formation of bubbles will indicate the existence of leakage. This method will apply about 3 to 5 psi pressure [D-11]. It should be noted that over-pressurizing the exhaust system may cause damage.

8. An alternative method given in the literature [D-6, D-12, and D-13], which was not used by any of the maintenance and inspection centers interviewed as part of this survey, includes removing the inaccessible component for a thorough visual inspection, plugging all the openings and applying pressurized air while submerging the part in water[1]. Any bubble formation will indicate the existence of leakage.

9. Cracks or problems at round welded areas can be hard to detect visually. The location where the exhaust flange is attached to the engine cylinder is another potential location for exhaust gas leakage, which is difficult to detect visually, but can be detected by the air pressure test of the exhaust system. It must be noted, however, that even if the muffler passes the air pressure test, the presence of bulging or corrosion may increase the likelihood of failure in the near future.

10. Any exhaust system repair should be performed in accordance with FAA regulations and manufacturer requirements. Some exhaust system manufacturers do not allow any repair to their components. Additionally, repairs using incorrect material or welding rods may result in dissimilar metal problems, such as different expansion rates, which may lead to stress cracking. Any unapproved repair should be reason for rejection.

11. Maintenance personnel should ensure that intermixing different manufacturer's exhaust components is an acceptable procedure due to the difference in expansion rates. Some problems have been identified when mixing different manufacturer's components, e.g., improper clearance or inadequate sealing of joints.

Several mechanics mentioned that a certain amount of leakage is "allowed on slip joints." When the engine warms up, the slip joints tighten up. If the slip joints lock up, the pressure due to engine vibration will be transferred to both ends, which may gradually create cracks. Anytime the slip joints are locked up, they should be inspected and slightly loosened to be able to move against each other. It should be noted that the amount of leakage that may be "allowed" on a slip joint, as well as what constitutes a tight fit or too-loose a fit, is a very subjective concept. However, mechanics described the importance of maintaining some flexibility in slip joints so that they can rotate in order to relieve stresses due to vibration. This suggests that a better definition of this term or demonstration of appropriate slip joint looseness through mechanic training may be in order.

Many repair stations indicated that using the air pressure test with soapy water was the best method to inspect the exhaust system since leakage is oftentimes not visually detectable. In one instance, one of the skilled mechanics had a case in which the muffler looked good but when it was inspected using air pressure test, a leak was detected (figure D-7).

Exhaust system parts are usually manufactured from either stainless steel or Inconel material. The exhaust system lasts longer if it is made from Inconel. On the other hand, stainless steel is

[1] Water submersion air pressure test method was reported to involve excessive labor and expense, so it is unlikely to be used except by repair stations that repair the muffler.

less expensive and Inconel is more difficult to weld. Despite the fact that Inconel has the ability to resist bulging and deformation, it is sensitive to residuals in the exhaust gases which can cause internal deterioration [D-11].

Figure D-7. The Muffler That had the Leak but was not Detected by Visual Check

Exhaust system parts are usually unconditioned, that is, there is no lifetime limit identified for the part. Regarding the muffler identified as the main source of CO leakage in CO-related accidents based on the NTSB accident/incident database, the analysis of CO-related accidents/incidents indicated a strong relationship between hours of muffler use and its failure. The Piper PA-28 service manual [D-12] recommends replacing the muffler after 1000 hours of use. However, there is no general limitation on muffler lifetime hours before replacement in FAA regulations (excluding those specific serial numbers that may have a lifetime limit given in an AD).

A decision on repairing or replacing unconditioned exhaust system parts is generally based on the experience and judgment of the individual performing the inspection. The cost and availability of the part is also an important consideration. Sometimes a new part may no longer be available or it may take too long to manufacture, making repair unavoidable. In this case, repair should be carried out following FAA regulations and manufacturer requirements. However, it must always be considered that even if repaired in the best possible manner (selecting appropriate material, cleaning properly, aligning sufficiently, etc.), spot welds must be checked carefully during future inspections since welding increases the probability of corrosion. In some repair stations, the exhaust system parts were remanufactured, whereby the damaged components were detached and replaced with new components and welding was performed by experts using special equipment. These types of remanufactured parts from specialty repair shops usually last longer than locally welded and repaired parts. Any repaired portions of the exhaust system should be inspected carefully and must be checked to verify that the repairs are not prohibited by FAA regulations or manufacturer requirements.

CO exposure in GA aircraft is mainly caused by gasses entering the cabin from the engine compartment and exhaust systems. Engine compartment gasses could enter the cabin through different locations, such as the firewall. These locations should be inspected to ensure that they are properly sealed. Many times the underside of the fuselage, especially in GA aircraft with short tailpipes, becomes dirty from exhaust gasses. Existing air leaks around doors and windows, which is not unusual, together with the presence of exhaust gasses outside the cabin, could increase the changes of CO exposure. However, a cabin that is airtight will not allow CO to escape the cabin if CO happens to enter the cabin from other sources such as from the engine compartment.

D.5 USING CO DETECTOR TECHNOLOGY FOR EXHAUST SYSTEM INSPECTION.

Using CO detectors during the exhaust system inspections was not a common practice among the inspection stations surveyed. The Piper PA-28 service manual [D-12] suggests using a CO detector when a comprehensive visual inspection is not possible. Since some GA aircraft inspection and repair stations are located near airports that may have elevated levels of CO-rich exhaust gas residuals from running engines, these residual gases may lead to false or misleading measurements if used during the inspection process. If CO detectors are used during the inspection, reading the CO level from the detector could be performed as part of the run-up check, which is conducted after inspection and maintenance. However, there may be safety issues in having a single mechanic perform the run-up check and check the CO levels in the cabin at the same time. This likely would require a second mechanic.

D.6. MECHANIC/PILOT CHECKLISTS.

To achieve consistent best practices in exhaust system inspection and maintenance, a pilot and mechanics checklist was prepared based upon the review of FAA guidance documents, service manuals, and the survey of best practices in inspection and maintenance of exhaust systems. The intention of the checklists is to increase the communication between the pilot and mechanics and to aid in the process of exhaust system inspections. The pilot checklist (see figure D-8) is to be completed by the pilot and given to the mechanic as the aircraft is brought in for inspection and/or maintenance. The pilot checklist is intended to identify if triggers have been met and that a more detailed inspection is warranted. The mechanic checklist (see figure D-9) is to be completed by the mechanic during the inspection process to identify any indicators of exhaust system problems that may warrant more detailed inspections. Thus, the checklists are to be used as an aid to determine if an exhaust system problem exists. Draft versions of the checklists were reviewed by FAA-certified inspection stations that were interviewed during the best practices survey. All reviewers enthusiastically supported the utility and content of the checklists.

MAINTENANCE & INSPECTION OF GA AIRCRAFT EXHAUST SYSTEM		
Pilot Checklist		
Has an engine backfire occurred?	Yes ☐	No ☐
Have you experienced any sudden loss or reduction of engine power?	Yes ☐	No ☐
Is the engine/exhaust system noisier compared to normal?	Yes ☐	No ☐
Have you noticed a rough engine run?	Yes ☐	No ☐
Have you noticed higher fuel burn compared to normal?	Yes ☐	No ☐
Have you noticed smell of exhaust inside the cabin?	Yes ☐	No ☐
Did you experience insufficient heat from the heating system?	Yes ☐	No ☐
Have you experienced light headedness, headache, or watery eyes during flights?	Yes ☐	No ☐
Have you noticed darkened or flaked color on the cowling?	Yes ☐	No ☐
Have you noticed exhaust gas coming out of the cowling?	Yes ☐	No ☐
If you utilize CO detectors during the flight, has there been any indication of elevated CO levels?	Yes ☐	No ☐
Answering “Yes” to any of these questions may indicate the existence of an exhaust system problem.		

Figure D-8. The GA Aircraft Exhaust System Maintenance and Inspection Pilot Checklist

MAINTENANCE & INSPECTION OF GA AIRCRAFT EXHAUST SYSTEM

Mechanic Checklist		
Is there excessive amount of sooty-black material on the exhaust system?	Yes ☐	No ☐
Is there bright reddish or orange residues on the exhaust system parts?	Yes ☐	No ☐
Is there darkened or flaked color on the cowling?	Yes ☐	No ☐
Is there any exhaust gas coming out of the cowling?	Yes ☐	No ☐
Is the engine/exhaust system noisier compared to normal?	Yes ☐	No ☐

Answering "Yes" to any of these questions may indicate the existence of an exhaust system problem.

Inspection Tips:

- Inspect the exhaust system per requirements of manufacturer's service manual.
- Search for FAA ADs, ACs, and manufacturer's service bulletin/letters pertinent to the make/model of aircraft under inspection in order to find updated information.
- Remove all the exhaust shields and shrouds to make exhaust system tubes and mufflers visible.
- Do not use carbon-based or lead pencils on exhaust system parts.
- Before visually inspecting the exhaust system, clean the parts based on pertinent guidance documents.
- During visual checks, pay attention to the welds and clamps and search for any sign of leakage, cracks, missing hardware, corrosion, bulging, and hot spots.
- Tiny cracks may be detected by performing air pressure test
  - Attach the pressure side of a shop vacuum to the tailpipe
  - Apply soapy water all over the exhaust system
  - Formation of bubbles will indicate the existence of leakage
  - Pay attention to the round welded areas and locations where exhaust flanges are attached to the engine cylinders for possible leakages
- Do not reuse gaskets. Check to see if there is any lifetime limit on the exhaust system parts in the regulations or service manuals.
- Check the firewall to ensure it is properly sealed.

Figure D-9. The GA Aircraft Exhaust System Maintenance and Inspection Mechanic Checklist

D.7 CONCLUSIONS.

Hazardous situations, such as CO exposure, which may arise as a result of inefficient exhaust system maintenance and inspection together with the complexity of the exhaust system, demand effective practices in inspecting GA aircraft exhaust systems. Familiarity with the signs and causes of exhaust system failures can facilitate the identification and prevention of exhaust system failures that may result in CO exposure. Accompanied by a thorough visual inspection, an air pressure test may increase the chance of identifying cracks, damage, and developing deterioration. Performing a thorough visual inspection together with an air pressure test and considering an appropriate muffler lifetime before replacement can be considered the primary prevention methods for CO exposure in GA aircraft. Finally, utilization of the exhaust system inspection and maintenance checklists for pilots and mechanics developed in this study may aid in the process of exhaust system inspections to reduce the likelihood of missing indicators that are related to exhaust system failures.

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