CHARACTERIZING MAC REFRIGERANT EMISSIONS FROM HEAVY-DUTY ON AND OFFROAD VEHICLES IN CALIFORNIA

ARB Contract No. 06-342

Final Report

Prepared for:

The California Air Resources Board
and the
California Environmental Protection Agency

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September 2010

Disclaimer

Acknowledgements

The contributions of the California Air Resources Board staff, particularly Dr. Tao Huai, Dr. Tao Zhan, Dorothy Shimer, and Dr. Alberto Ayala who made invaluable suggestions as Project Officers were greatly appreciated. Dr. Denis Clodic at the Center for Energy Studies, Ecole des Mines de Paris, and Dr. Winfried Schwarz of Öko-Recherche GmbH provided critical input regarding testing design and peer review of study findings. Additional input regarding study design and data sources were provided by Jim Baker of Delphi Corporation, Gary Hansen of Red Dot Corporation, and Dr. Stephen Andersen of the US Environmental Protection Agency.

This Report was submitted in fulfillment of ARB contract number 06-342, "Characterizing MAC Refrigerant Emissions from Heavy-Duty On and Offroad Vehicles in California," by Eastern Research Group, Inc. under the sponsorship of the California Air Resources Board. Work was completed as of July 30, 2010.

Table of Contents

List of Figures

List of Tables

Abstract

In a first of its kind study, data regarding heavy-duty vehicle mobile air conditioning (MAC) system refrigerant (R134a) leak rates were collected by directly measuring leak rates from in-use medium- and heavy-duty on- and off-road equipment, and by analyzing large transit bus refrigerant use records provided by fleet managers. The estimated average annual leak rates for all types of MAC systems and vehicles (except large buses) may be higher for older vehicles (2005 and older model years) and averaged 306 g/yr (0.675 lb/yr) per vehicle. The average annual leak rates for 2006 and newer systems are estimated to be 103 g/yr (0.227 lb/yr) per vehicle. Average annual leak rates for all model years combined are estimated at 257 g/ yr (0.567 lb/yr). These values represent leaks resulting from typical in-use operation, and do not include leaks from equipment servicing, technician error, sudden discharge events (e.g., as a result of accidents), or other sources. The distribution of the measured leak rates cannot be firmly established, but it appears to resemble a log-normal distribution, with most results being grouped at the low-end and a few "gross emitters" with emission rates several times higher than average. These gross emitters have a disproportionate effect on the overall emission inventory. The annual R134a leak rate from large buses was estimated to be nearly 1,340 g/year (2.9 lb/year) per bus. Unlike the estimates for other vehicle types, this estimate includes all types of leaks from the MAC system. Leak rates were combined with the offroad and medium/heavy-duty on-road vehicle population data for California to estimate annual R134a emissions. Estimated annual leakage of R134a from heavy-duty vehicles in California is estimated to be 1.35 MT CO_2E per year, assuming different leak rates by age group. Due to small sample sizes and simple assumptions for projecting leak rates to an "annualized" basis, substantial uncertainty remains regarding emission inventory estimates for this population. Results from this study should be combined with future interview and survey results from large fleet maintenance personnel to address the most significant sources of uncertainty and knowledge gaps.

Executive Summary

This study provides a first-of-its-kind, mass-based measurement of R134a emissions from heavy-duty MAC systems. This groundbreaking effort also collected key information regarding the characteristics of these systems, and provides a foundation for improved emission inventories and for continued reduction of GHG emissions from the heavy-duty vehicle sector in both California and throughout the United States.

Background

R134a is one of the most common refrigerants used in mobile air conditioning (MAC) systems today, and is a powerful greenhouse gas that may contribute to climate change. Specifically, R134a (1,1,1,2-tetrafluoroethane) has a global warming potential (GWP) of 1,300.(1) ARB has estimated that total R134a emissions from all MAC systems in California (including light-duty vehicle systems) came to approximately 4 million metric tons of CO_2-equivalent (CO_2E) in 2004.(2)

Estimates of R134a leak rates from the light-duty fleet have been calculated from surveys. The purpose of this research was to begin collecting similar data for the heavy-duty fleet by measuring actual leak rates from MAC systems used to cool operator and passenger compartments in heavy-duty vehicles. A gravimetric method developed by Dr. Denis Clodic of the Paris Ecole des Mines was adapted for use in a garage environment and used to measure leak rates from 66 on-road and off-road vehicles in the Sacramento area.(7) No appropriate large buses were identified for measurement in this study, so transit bus fleet operators from around the state were interviewed instead to estimate leak rates for large bus (i.e. 40 foot coach) MAC systems.

Methods

Refrigerant emission factor data were collected in two ways: by directly measuring leak rates from MAC systems in medium and heavy-duty equipment; and by analyzing large bus maintenance information provided by fleet managers. The direct measurement method involved charging a known mass of R134a into the MAC system of a sample vehicle and then recovering and precisely measuring the refrigerant three to six months later. The difference between the charged and recovered masses was assumed to have leaked from the MAC system. From March 2009 until April 2010, 66 medium and heavy-duty vehicle MACs from 12 fleets in the Sacramento area were sampled and measured in this way. The sample was divided among several categories of vehicles and uses, although the vehicles were not randomly chosen and may not be statistically representative of the fleet at large. The three to six-month results were then projected to estimate annual leak rates. Due to the relatively low sample sizes in this study, and the fact that most sampled MAC systems were very similar, the results from all vehicles were aggregated together for analysis.

Interviews of fleet managers were used to estimate R134a leak rates from large (e.g., 40 foot coach) buses. The interview results (from 2009) were used to estimate annual leak rates not only from the bus MAC system itself, but also from equipment used to service the bus MAC and from possible errors made by service technicians (such as disconnecting hoses while refrigerant tank valves are still open). As a result, these findings estimate overall leak rates from both bus operation as well as service maintenance. The bus fleets that participated were from five metropolitan areas around the state, representing a wide range of climates. The fleets were not randomly chosen and may not be representative of bus fleets statewide.

Results

The annual R134a leak rate from medium and heavy-duty vehicle MAC systems of all types (except large buses) may be higher for older vehicles (2005 and older model years). The average leak rate of R134a from 2005 and older MAC systems was projected to be 306 g/year (0.675 lb/yr) per vehicle and the average from 2006 and newer systems was projected to be 103 g/year (0.227 lb/yr) per vehicle. However, the emission rate estimates have a wide distribution with substantial uncertainty. As such, differentiating rates by model year groups may not be warranted. Accordingly, a fleet-average annual emission rate of 257 g/ yr (0.567 lb/yr) was also estimated. Regardless, the distribution of the measured leak rates cannot be firmly established, but it appears to resemble a log-normal distribution, with most MAC systems grouped at the low-end and a few "gross emitters" with emission rates several times higher than the rest. Accordingly, these gross emitters have a disproportionate effect on the overall emission inventory.

The measured emission rates do not include leaks from MAC service equipment, technician error, and other sources. Nevertheless, the measured emission estimates may be high for two reasons. First, since the sample size is relatively small, the average leak rate calculated from the sample may be disproportionately influenced by "outliers/gross emitters". Second, these measurements were taken at the time of the highest leak rates (i.e., when the system had just been filled and average operating pressures were highest. Therefore, using a the linear projection method to estimate annual leak rates may overestimate values, since many of the lower leak rates could go on for some time before the operator would notice and have it serviced. During this time the system's average operating pressure would decline, as would the leak rate.

The annual R134a leak rate from large buses was estimated to be nearly 1,340 g/year (2.9 lb/year) per bus. This includes leaks from the MAC system, the equipment used to service the MAC, possible technician errors, theft, etc. The MAC capacities on these buses are much larger than for the other MAC systems covered in the study and are serviced more frequently to help minimize passenger complaints. (As a point of comparison, according to public transport fleet manager contacts, the nominal refrigerant charge for a large bus averages around 6 kg while the range found in the gravimetrically analyzed vehicles with smaller capacity systems averaged 1.3 kg.) As such, each service event is an opportunity for additional refrigerant leakage over and above the normal leaks that occur during bus operation.

Conclusions

Initial steps toward better estimates of R134a leak rates from medium and heavy-duty vehicles were taken in this study. Older vehicle MAC systems appear to leak more than newer systems by a factor of about three, although the large range in the distribution of leak rates makes this conclusion highly uncertain. Large gaps in the overall emissions inventory also remain. Results from this study should be combined with future interview and survey results from large fleet maintenance personnel to fill the most significant knowledge gaps.

1.0 Introduction

Project Background

Refrigerants used in mobile air conditioning (MAC) systems can enter the atmosphere through a number of mechanisms, including low-level long-term leaks, rapid leaks caused by discrete incidents (e.g., system failure), regular system servicing, and end-of-life losses. R134a is one of the most common refrigerants used in MAC systems today, and is a powerful greenhouse gas that may contribute to climate change. Specifically, HFC-134a (1,1,1,2-tetrafluoroethane) has a global warming potential (GWP) of 1,300.(1) ARB has estimated that total R134a emissions from all MAC systems in California (including light-duty vehicle systems) came to approximately 4 million metric tons of CO_2-equivalent (CO_2E) in 2004.(2)

The California Air Resources Board (ARB) has been at the forefront of controlling greenhouse gas emissions from MAC refrigerant systems, having adopted AB1493 to limit such emissions from light-duty on-road vehicles. Other studies have been conducted by the California Air Resources Board (CARB) to characterize refrigerant emissions from MAC systems in light-duty vehicles. This study intends to begin building a knowledge base concerning R134a leak rates from heavy-duty vehicles in California.

Project Objectives

The current study was designed to accurately characterize in-use emissions from heavy-duty on and offroad vehicles. Specifically, the study estimated long-term leakage from MAC systems using R134a as a refrigerant, and combined these values with vehicle and equipment population estimates to develop an annual emission inventory for the state. To accomplish this goal the study involved several steps. First the types of different MAC systems currently on the market and those anticipated for the future, were characterized and evaluated. Candidate leak flow rate measurement methodologies were then identified and verified for use, characterizing expected precision and measurement uncertainty. Next, target vehicles were identified and recruited for measurement. Data was then collected from a sample of the different vehicle types over a period of several months to establish in-use leak rates. Finally, the findings were evaluated to determine average leak flow rates for the different vehicle and system types, and combined with population data to estimate an emission inventory for the 2010 calendar year. The study concluded with an evaluation of areas of uncertainty and recommendations for improving the emission inventory estimates in the future.

Report Organization

The following sections of this report document the study methodology followed for conducting the data collection, and present the measurement results. A discussion of the results, including an analysis and assessment of data set completeness is then presented. A summary of the major findings of the study are presented next. Finally, recommendations for future refinement of the resulting emission inventory estimates are provided.

2.0 Materials and Methods

This section of the report documents the data collection methods used for the study.

2.1 MAC System Review

One way to estimate an accurate fleet-average refrigerant leak rate would be to randomly sample a statistically significant number of vehicles from the entire fleet of interest. When adequate information regarding fleet characteristics is available, stratified-random sampling is an option. This approach is more efficient than a purely random sample because it can target specific types of systems with higher emission rates than the fully random sample. Ideally, the stratification parameters selected will reflect those factors that have the greatest impact on refrigerant leak rates.

Some MAC systems are more likely to have higher in-use leak rates than others. For example, leak rates from systems with more flexible hosing tend to be higher than from systems with more rigid, metal tubing. Similarly, systems with belt-driven compressors are likely to have higher emission rates than those with electric, hermetically sealed compressors.(3) To identify potential stratification parameters, ERG first evaluated the MAC system characteristics indicated to be significant in the light-duty vehicle (J-2727) specification. Operational parameters that could theoretically influence leak rates (e.g., expected compressor on-time) were also identified and considered.

After conducting the initial literature review, a list of potentially significant system and operational factors were developed for review by industry experts in order to:

- Identify key MAC system components and operational characteristics likely to have a significant impact on refrigerant leak rates;
- Identify the range of MAC systems in-use in the non-light-duty on and offroad vehicle fleets in California;
- Estimate the prevalence of the different MAC systems by major vehicle type (e.g., transit buses, tractor-trailers rigs with sleeper cabs, medium-duty delivery vehicles, offroad construction equipment with enclosed operator cabs, etc.).

Several industry experts provided input, helping identify possible testing stratifications for the data collection portion of the study. Given that the measurement sample size was to be approximately 75 vehicles, it was only possible to consider a few sample stratifications. This limitation made it crucial to identify the most important MAC system variables impacting refrigerant emission rates, in order to focus study resources effectively. Accordingly, based on input from industry experts it was agreed that the single most important factor influencing in-use leak rates was the adoption the recent recommendations regarding refrigerant leakage reduction from the Improved Mobile Air Conditioning (IMAC) Cooperative Research Program.(4) Although these recommendations are not mandatory, they were assumed to have been introduced in the on-road fleet beginning with the 2006 model year. (IMAC-related system improvements were assumed to be limited to the on-road fleet up to this point.) (5) In addition, general operation and maintenance patterns, as determined by vehicle/equipment type, were thought to be important in determining leak rates as well.

The vehicle/equipment type grouping originally specified by ARB was retained for the study, including: full sized transit buses, shuttle buses, medium-duty utility trucks/vans, heavy-duty truck tractors, other heavy-duty trucks, construction equipment, and agricultural equipment. The final measurement targets established for the sampling plan are presented in Table 1 below.

Table 1. Target Number of Measurements by Vehicle/Equipment Type

Bin ID	Vehicle Type	# Units
1	Full Sized Transit Bus	11
2	Shuttle Bus	5
3	MD Utility Truck/Van	18
4	HD Truck Tractor	18
5	Other HD Trucks (dump, waste, etc)	9
6	Construction Equipment	5
7	Agricultural Equipment	4
	Total	**70**

Note that no additional formal stratifications were specified for this project. The practicality of coordinating this type of selection at each facility given the relatively small fleet sizes and limited equipment availability made additional selection criteria unpractical. However, ERG attempted to sample a wide range of vehicle ages and types within each equipment bin.

2.2 Identification and Validation of Appropriate Measurement Methods

The Society of Automotive Engineers (SAE) has developed a standard that can be used to estimate leak rates from new MACs for light-duty vehicles (SAE J-2727).(3) The method seems applicable to MAC systems in general, but was not developed for in-use systems, or for medium-duty or heavy-duty vehicles, so applying it to those types of systems would produce readily questionable results. Although several non-light-duty testing methods were screened for possible inclusion in this study, only two were appropriate for use out in the field settings where this study would take place. (6,7) These two methods (one developed by Dr. Winfried Schwarz and the other by Dr. Denis Clodic) were focused upon because the rest were clearly inappropriate. For example, some of the other methods required the use of a special evaporative test enclosure that does not exist in sizes that would accommodate large vehicles. ERG reviewed reports of the feasible test methods and interviewed several investigators and individuals active in the industry to assess their strengths and weaknesses.

After this assessment, ERG recommended that a method developed by Dr. Denis Clodic (Ecole des Mines, Paris, France) be modified for application in the field. At the time of our assessment, this method was also favored by the SAE IMAC panel. This test procedure was originally designed to be performed in a very controlled environment, and was not practical in a working garage where the testing for this study was to be performed. Therefore, modifications to the original method were made to allow its use in this study without excessively affecting the precision (repeatability) of the results. For example, Dr. Clodic’s method required that a vehicle be housed overnight in a climate controlled area so the MAC system components would come to thermal equilibrium at standard room temperature. The modified procedure entailed a compromise, heating the engine compartment of the vehicle for a prescribed period of time.

(Please see Section 2.3.1 for a detailed description of the final modified measurement procedure.)

The modified measurement method has several critical features intended to maximize test repeatability in the field, including:

- Maintaining system temperature;
- Controlling recovery flow rate; and,
- Minimizing leaks during recovery.

With regard to temperature, the test procedure specified that the entire MAC system should be above 20°C (70°F) during extraction, especially the compressor, condenser, and components with discontinuous surfaces (e.g., joints, fittings, and ports). To maintain this temperature it is important to heat the system during extraction to replace the heat lost as liquid refrigerant in the MAC boils to a gas during removal. If allowed to cool too much, lubricant in the MAC can congeal, trapping some absorbed refrigerant and preventing its extraction.

Recovery flow also had to be slow enough that no liquid refrigerant was extracted. This minimizes the amount of MAC system lubricant removed with the refrigerant – a major source of measurement uncertainty due to the difficulty of distilling the entrained oil from the refrigerant after the recovery.

It should be noted, however, that in putting this method into actual practice for this study, it was not possible to conform perfectly to these requirements. For example, the experience of Clodic was that a maximum flow rate of 10 g/min ensures that no liquid refrigerant will be extracted. However, the low-pressure service port on some MAC systems is immediately downstream of the receiver, which usually contains a significant pool of liquid refrigerant and lubricant. If the level of that pool is near enough to the port, then some liquid is inevitably entrained into the flow of the gaseous refrigerant as it leaves the MAC system. As noted above, distilling the oil from the refrigerant after the recovery process is difficult to perform, and the more oil that must be distilled, the greater the uncertainty in the overall measurement. Accordingly, the 10 g/min extraction rate was used as a general guideline while the temperature of the recovery port was monitored to determine if liquid was being collected. If a sharp drop in temperature (indicative of liquid formation) was detected, the technician then lowered the recovery rate, otherwise the recovery rate would be increased slowly. While some vehicles required lower than the 10 g/min recovery rate, most would tolerate up to 30 g/min without significant liquid entrainment.

Before implementing the modified method, ERG refined and validated it by performing it on several new vehicles twice in rapid succession. The test vehicles were prepared in the early morning. Then the vehicle MAC system was evacuated and charged with a known amount of refrigerant and operated for a short time (less than one hour). Then the method was repeated on the vehicle again that same day to determine how closely the mass of refrigerant recovered during the second test matched the mass charged into the system during the first test. After each of these vehicles was finished, ERG evaluated the results and modified the test method to improve the recovery. After three iterations the method had been refined enough that acceptable recovery (i.e., mass balance closure) was consistently achieved. Results of the validation tests are discussed in section 3.1.

2.3 Inventory Data Collection

Refrigerant leak rate data were collected in two ways; by directly measuring leak rates from MAC systems in medium and heavy-duty equipment, and by analyzing maintenance data provided by transit bus fleet managers, as described below.

2.3.1 Mass-Based Measurement Approach

Summary of Measurement Procedure

In summary, the method for measuring refrigerant leak rates involved charging a vehicle MAC with a known amount of refrigerant, allowing it to operate normally for a period of months, then recovering the refrigerant to measure the amount that remained. The difference between the original amount and the amount recovered represented what had leaked out during the intervening time. The basic steps of the refrigerant loss rate measurement included:

1) Evacuate and recover the MAC in a way that ensures as much refrigerant is extracted as possible, under reproducible temperature and pressure conditions;
2) Determine the amount of refrigerant and oil taken out of the MAC;
3) Charge a known mass of refrigerant (the manufacturer's recommended amount) and the same amount of oil that was removed in Step 1 into the evacuated MAC;
4) Allow the MAC to be used normally for a period of time greater than 3 months, with extraction occurring before the next service cycle;
5) Recover the refrigerant from the MAC under the same temperature and pressure conditions as when it was first evacuated (see Step 1);
6) Determine the mass of the recovered refrigerant; and,
7) Calculate the amount of refrigerant lost between the time the known mass was charged into the MAC and the time it was recovered from the MAC.

A step-by-step operating procedure and a standard data collection form were developed to help assure the quality of the data collected. Since servicing the MAC during the test would likely invalidate the results, steps were taken to discourage servicing the MAC systems until after our measurements were completed. A copy of the standard measurement procedure is provided in Appendix 1, and a copy of the data collection form is provided in Appendix 2.

Measurement Equipment

The equipment used to conduct the measurements included a combination of standard and customized MAC maintenance equipment and laboratory grade instruments. Some equipment was modified for this project, as explained below. Table 2 below describes the main pieces of equipment necessary for the MAC tests.

Table 2. Main Test Equipment

Item	Notes
Vacuum pump, high vacuum gauge, hose	High capacity, 2-stage vacuum pump: Mastercool model 90067 with 212 LPM (7.5 CFM) capacity and 0.37 kW (0.5 HP) motor. High vacuum gauge: For reading vacuum at 20 Pa-absolute. Resolution of 0.1 Pa.
Recovery compressor and hose	Compressor (Bacharach model Stinger 2000) and dedicated hose used to recover R134a from the MAC into the Recovery tank.
Electronic scale	Electronic balance: Citizen model SSH 93 with capacity of 30 kg (66 lb) and resolution of 0.1 g (0.0035 oz).
Recovery tank	Cylinder used only to recover R134a from the MAC. After recovery R134a is transferred from this tank to the Recycling tank.
Manifold and 3 hoses	Service manifold with dedicated hoses and gauges for the low-pressure and high-pressure sides of the MAC and with a hose to transfer R134a from and to the MAC.
Charging tank and hose	Cylinder of new or recycled and purified (of air and water) R134a with a dedicated hose.
Recycling tank	Cylinder used only to receive R134a distilled from the recovery tank.
Thermocouples and displays	K-type thermocouples and readouts to monitor various temperatures.

Examples of the above equipment are shown in use in the following series of photographs. Figure 1 shows the yellow recovery compressor being evacuated by attaching the vacuum pump to its dedicated hose and monitoring the vacuum until it falls below 20 Pa-absolute.

Figure 1. Evacuation of the Recovery Unit and Hose before a Test

Figure 2 shows a typical under-hood view of the manifold and its hoses attached to the high-pressure (red hose) and low-pressure (blue hose) service ports of the MAC during a recovery. The yellow hose from the manifold is attached to the recovery unit (not shown). Also shown are three thermocouple readouts. The thermocouple monitoring the low pressure port temperature (top center) ensures no liquid R134a flows from the MAC through the manifold. The thermocouples monitoring the compressor (lower left) and the evaporator (upper left) help ensure the system remains warm enough so refrigerant will continue to off-gas and system oil will not gel.

Figure 2. Manifold and Thermocouples during a Recovery

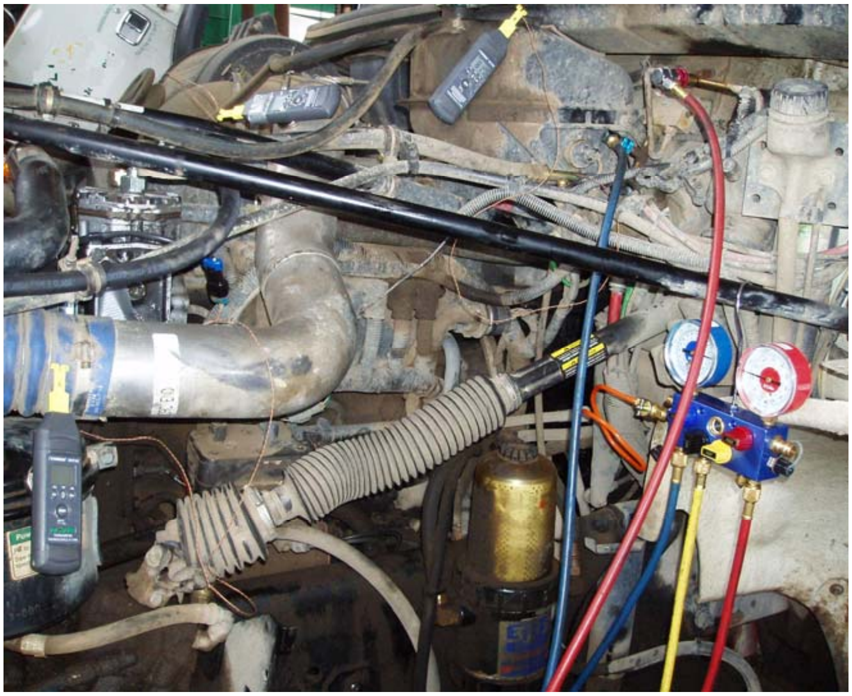


Figure 3 shows the recovery compressor, the manifold, and the recovery tank, and their associated hoses and gauges being weighed on the electronic balance beside a “cab over” style garbage truck. The blue wind screen works with the wheel of the garbage truck and another plastic shield to minimize the influence of air flow on the reading. The padded base below the scale helps isolate readings from the influence of vibrations from the garage floor.

Figure 3. Recovery System Being Weighed after a Recovery

Figure 4 shows how the MAC was recharged after R134a removal. The recharge tank of fresh R134a was placed on the scale during recharge to help approximate the manufacturer recommended MAC charge.

Figure 4. Recharging a MAC after all R134a was Removed

Figure 5 shows how labeled duct tape was placed on the MAC service ports during testing to remind the vehicle owner not to service the system unless absolutely necessary. If any evidence of servicing or tampering was found during the second recovery/recharge, further investigation was conducted to determine why the tape had been disturbed.

Figure 5. Anti-tamper Measures to Discourage MAC Service during a Test

It was necessary to customize some of the standard MAC equipment for several reasons:

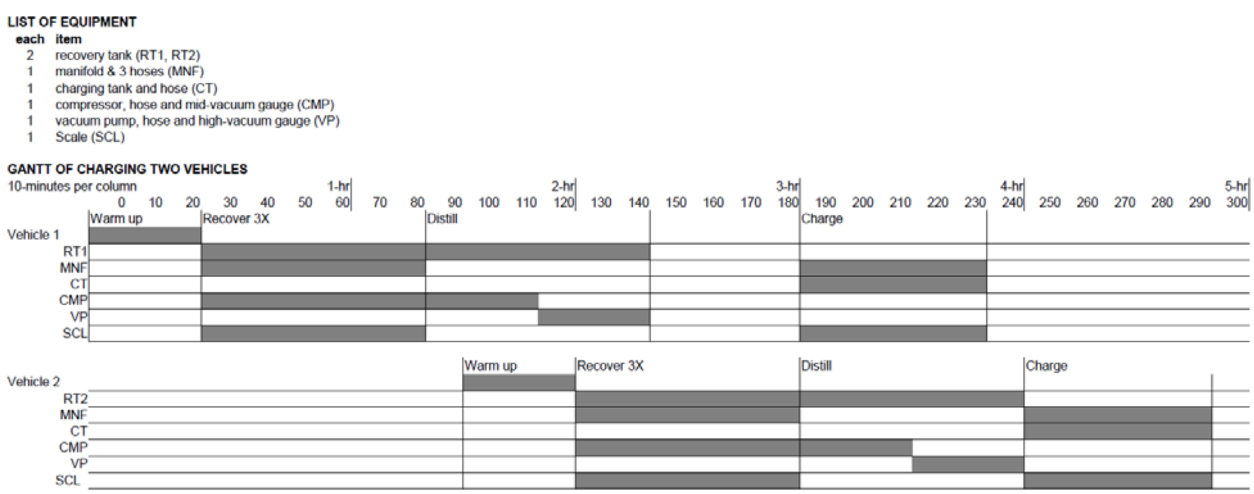
- Most MAC service equipment is not designed to hold the prolonged, extremely low vacuums called for in the sampling protocol. During evacuation of the recovery unit, hoses, gauges, and tanks the protocol requires pulling a vacuum to an absolute pressure of 20 Pascals or lower. This is in contrast to vacuums used during normal MAC maintenance which only pull to an absolute pressure of about 3,100 Pascals (over 150 times higher pressure than the protocol vacuum) and are hardly ever held for more than a few minutes.
- It was important to minimize refrigerant leakage whenever fittings were attached and unattached between the measurement system components and the MAC system.
- MAC maintenance equipment is not designed for this type of precise experimentation. MAC maintenance systems typically measure in tenths of a pound, while the protocol calls for measuring to tenths of a gram (a resolution over 450 times higher than normal MAC systems).
- MAC recovery systems and vacuum pumps are not typically designed to be used continuously, all day long. The vacuum pump was an especially high-wear item that typically ran 4 to 6 hours per day. These vacuum pumps are designed to last for years, but due to the extreme duty-cycles of the test protocol it was rebuilt once and ultimately replaced once during the project.

MAC equipment customizations included modifying the inlet manifold of the vacuum pump with a permanently plumbed vacuum gauge, having custom hoses made with on/off ball valves at each end and special fittings with metal gaskets to withstand the high torques required to stop fugitive leaks in the sampling system, and replacing the standard gauges on the MAC service gauge set to enable more accurate vacuum readings.

Extraordinary maintenance measures were required on recovery units, vacuum pumps and fittings due to the high usage rates required for this study. For example, vacuum pump oil was checked after every day of use. It was necessary to change the vacuum pump oil after about every five vehicles. Also gaskets for fittings were replaced frequently due to the extraordinary wear and extremely high levels of vacuum.

The procedure typically took from five to eight hours to conduct, depending mainly upon whether one or two vehicles were sampled at a time. A timeline of how two vehicles were sampled at a time is shown in Figure 6. The upper and lower sections of the timeline represent the two vehicles. Each row in the timeline represents a piece of equipment (see List of Equipment at upper left) and the grayed areas indicate when that piece of equipment was in use. Everything except the recovery tank (shown) and heating and temperature instruments (not shown) are shared between the vehicles, so most equipment could not be used on two vehicles at once.

Figure 6. Timeline for Sampling Two Vehicles Simultaneously



Personnel Conducting the Measurements

Field measurements were lead by an engineer and supported by EPA-certified MAC technicians who had been trained to perform the sample protocol by the engineer. The MAC technicians were identified through advertisements and targeted recruitment. The ERG field engineer interviewed technician candidates to determine if their background and skill levels (both technical and interpersonal) were appropriate for this research project. Ultimately three qualified MAC technicians were identified and contracted.

The technicians were trained on the job. The ERG engineer worked with the technicians through the first three or four days of sampling, making sure they understood the step-by-step standard operating procedure, the importance of properly completing the data sheets, the necessity of quality assurance steps, etc. Periodically during the study, the ERG engineer would visit the data collection site to review data forms and help as needed.

Sampling Plan

The study sampling plan called for obtaining vehicles from the Sacramento area to fill the seven equipment bins with as representative a cross-section of vehicles as possible. The practical constraints of actually finding fleets to participate, with appropriate vehicles and enough spare space available in which to conduct the measurements, greatly limited the number of participating fleets.

Candidate vehicles were identified from 12 fleets in the Sacramento area. The fleet sizes ranged from two to over 50 vehicles. Most fleets were identified as amenable to this type of research from previous projects for ARB. So recruiting most of the fleets was only a matter of calling previous contacts to verify their interest in participating in this project. Several fleets were not willing to participate due to the time and location requirements of this test method. Fleets with the flexibility of being able to spare two vehicles for an entire day while giving up two garage bays at the same time are not plentiful. Fleets who chose to participate were typically large (i.e. 30 or more vehicles total) and represented the electric utilities, garbage and waste collection, heavy construction, universities, municipal utilities, and public transport. Several new fleets were identified through other sources and personal connections. These were all smaller fleets, with typically fewer than five eligible vehicles.

Whenever possible, sampling took place at the garage locations of participating fleets. A few fleets did not have garages, but allowed ERG technicians to drive the vehicle to a suitable testing location. When a participating fleet was identified ERG's field engineer would visit the facility to assess the potential individual vehicles that would be most desirable to sample, and the locations in the facility that would accommodate conducting the procedure. Once candidate vehicles and locations were agreed upon, coordination of the fleet testing schedule and the MAC technician schedule was arranged between the fleet manager and the ERG field engineer.

At a minimum, the sampling location at the fleet facility needed to be sheltered from wind and rain, with ample electrical service. The capacity of the electrical utilities had to accommodate the significant current required to power heat lamps, heat blankets, a heat gun, a large (0.37 kW or 0.5 HP) vacuum pump, two refrigerant recovery units, and the electronic scale. Another major impediment to finding an appropriate location was that testing activities could not interfere with the normal activities at the facility. This final requirement was extremely difficult to satisfy, since garages tend to utilize most/all of their facility space at all times.

2.3.2 Fleet Maintenance and Refrigerant Consumption Data

During the course of the project it became apparent that certain types of diesel equipment in the Sacramento area do not typically use R134a refrigerant. This is especially true of transit buses. The only viable source of transit buses in the area (Sacramento Regional Transit) only had buses that use R22 refrigerant (chlorodifluoromethane – $CHClF_2$). Other area transit authorities either declined to participate or contracted their bus maintenance to a third party who was not willing to participate, or did not have appropriate facilities.[1] Therefore, it was decided to obtain R134a system servicing data from as many bus fleet operators in the state as possible to determine if such data could be used to estimate annual leak rates for these vehicle types.

With the assistance of ARB staff, ERG contacted transit fleet operators across California. Of the 11 fleet operators contacted, five responded and were willing to participate, with one in the Los Angeles air basin, one in the coastal region of northwest California, one in northern California (in-land), one in the Sacramento region, and one in the San Joaquin Valley. Some of the fleets requested that their identification not be disclosed in the report. At a minimum the following information was obtained from the participating fleets:

- The quantities and types of buses in the fleet;
- The age range of the buses;
- The type of refrigerant used in each type of bus, and;
- The consumption rate of R134a for the fleet.

Not all operators had, or were willing to provide, the same level of maintenance detail. For example, one of the fleet operators had collected the consumption rate of refrigerant for each vehicle in their fleet over the past several years. They were willing to share those data for the most recent year of operations (with the request that their data only be made public if identifying information is removed).

A shortcoming of using maintenance data to estimate leak rate is that fleets typically do not track refrigerant consumption data for each vehicle. So resolving any estimates down to the vehicle level is not possible. However, an advantage of this type of data is that, since it relies upon an overall consumption of refrigerant, it accounts for all leak sources, including technician practices, faulty service equipment, etc.

2.4 Data Analysis Methods

As described below, different analysis approaches were used for the two types of data collected in this study – directly measured leak rates for individual vehicles (the gravimetric method), and estimated fleet-average leak rates from MAC system maintenance information.

Estimating Accuracy and Precision of the Gravimetric Based Leak Rate Method

During the early stages of the project, the chosen measurement method was adapted for use in the field. The method was iteratively changed as it was tested on various vehicles. Although the field test method was adapted from a well-validated approach, it was implemented in different

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[1] In addition, even if suitable large transit buses had been identified, actual testing would have proven very difficult since the capacity of the MAC systems in large buses is four to five times that of other vehicles. As such, recovering all of the refrigerant from large transit bus MACs to the level required by the protocol could have easily taken more than 24 hours.

conditions than specified for the original method, and the changes from the original method were substantial enough that the precision and accuracy of the new method were not known. The accuracy and precision of the measurement method were estimated by charging a relatively new and obviously well-maintained MAC system with R134a, then recovering what had been charged as soon as possible to measure how much of the charged refrigerant was recovered. These quality assurance (QA) tests took from five to eight hours to complete. Assuming no significant leaks from the system between charging and recovering, ideally the method would recover 100% of what had been charged each time.

After the step-by-step procedure and the instrumentation and materials of the final method were decided upon, four vehicles were tested using the method to help estimate an expected level of accuracy and precision. The results of these QA tests are presented and discussed in Sections 3.1 and 3.2.

Description of Quality Assured Data Set

Quality assurance measures were in place during data collection to ensure the data from the field were of sufficient quality. For example, a step-by-step procedure was adhered to by following written instructions and filling out a data collection sheet for each vehicle. All field calculations were likewise spelled out explicitly in the instructions. Calibrated weights were used multiple times throughout the procedure to ensure that each mass measurement was accurate. Also the MAC technicians were trained to compare temperature and pressure gages to common sense estimates of what the values should have been to help identify data problems. For example, system pressures above those normally expected in a MAC system were investigated by using a redundant gauge set to measure the same value.

The data collection sheets were post-processed as soon as possible after completion to archive the data and to allow comparison with previous data to check for obviously inconsistent or missing information. Data from similar vehicles was compared to screen for transcription errors. All such errors were readily corrected. Ultimately none of the data were rejected as a result of these basic quality assurance procedures. All raw data sheets have been archived by ERG.

Analysis of Maintenance Data

In some special cases, reasonable assumptions derived from normal fleet maintenance records should allow for the calculation of average refrigerant leak rates from some kinds of vehicles – especially in the case of fleets with a uniform type of vehicle. This tends to be the case with public transportation bus fleets. Refrigerant maintenance operations for large bus fleets vary a great deal from fleet to fleet, however. Some fleets maintain their own systems and others contract the maintenance to outside providers. Nevertheless, most transit bus fleets share several practices that permit the calculation of average leak rates, including:

- Accurate tracking of their R134a purchases;
- Recycling and re-use of as much R134a as possible;
- Tracking which vehicles use which type of refrigerant (e.g., R134a, R22, etc.).

By assuming that the average amount of R134a purchased yearly equals the net amount leaked from the fleet, and that all of the leaked R134a can be attributed to the fleet vehicles that use R134a (e.g., none was used in personal vehicles, etc.), an average annual leak rate per R134a vehicle can be calculated. Unlike the mass emissions measurement approach described above though, leak rate estimates derived in this manner necessarily include a variety of potential sources, such as losses during regular servicing and sudden losses from system failure. In the case where R134a use is tracked for each vehicle, it is possible to calculate average leak rates by vehicle type.

Five transit fleets participated in the study by providing information about their overall R134a use rate and their associated vehicles. The fleets were located across California. For each of those fleets ERG obtained an overall snapshot of the number and type of vehicles using R134a as well as an estimate of the amount of R134a refrigerant the fleet purchases annually. These data were then used to calculate a vehicle-average leak rate for each bus fleet. One fleet tracked refrigerant use for each of their vehicles, and had enough historical data to allow estimating the average leak rate according to the type of bus (i.e. cutaway shuttle bus versus 40-foot coach bus).

3.0 Results

The results from the measurement tasks for the study are discussed below.

3.1 Validation of the Test Method

During the early stages of the project a test method for measuring R134a leak rates was modified from a laboratory setting to a field setting that could be performed on a large number of heavy-duty vehicles in a reasonable amount of time and within budget.

The recovery efficiency of the original method has been demonstrated by Clodic to be ± 1 gram. Modifications were necessary to make the method practical for use in the field. These modifications generally resulted in increasing the recovery error. To set a limit on how large an acceptable recovery error could be for the purposes of this study, ERG consulted with peer reviewers and ARB technical staff. Varying the current state of the refrigerant leak inventory for heavy-equipment, test conditions in the field, time constraints on keeping participant vehicles, taking space in participant facilities, and equipment limitations were all considered. Therefore it was decided that a recovery error of 20 grams or less would be acceptable.

Having set a maximum limit on measurement error ERG modified the test method as needed to obtain at least that level of precision. Through consultation with Dr. Clodic and an iterative process of trial and error we determined that the measurement system should have several design features to minimize the leakage of refrigerant during the measurement process, as discussed below.

<u>Make as many equipment connections permanent as possible</u>: Many MAC maintenance systems come with quick connect and other types of couplings that are simple to change. However, these types of non-permanent connections do not hold the deep vacuums required by the measurement method. So wherever possible we replaced connections sealed by o-rings or flared fittings with threaded connections sealed by PTFE (e.g., Teflon®) tape. For example, we permanently attached a vacuum gauge transducer to the vacuum pump instead of storing the transducer separately, as would be done during normal usage.

<u>Use only the highest quality flexible MAC service hose and metal flared couplings with heavy-duty crimped, barbed hose fittings</u>: Toward the beginning of the project we purchased many system components based upon price. Some of these items, especially hoses and fittings, turned out to be of lower quality than required for holding a high vacuum. High quality hose tends to cost more, but holds a vacuum better. Also, when changing connectors on hose ends, "do it yourself" barbed hose fittings that use screw-tightened hose clamps are not as durable and leak-tight as those crimped with heavy duty clamps that require high pressure crimping tools to attach properly.

<u>Properly valve the ends of system plumbing</u>: Many components of MAC maintenance systems come with openings to the atmosphere that cannot be closed, or with inadequate valves for the purposes of this program. For example, MAC service manifold hoses either have relatively leaky Schraeder valves or no valves at all on their free ends. For this effort we installed or replaced all hose ends with heavy on/off ball valves adjacent to the free end connector. These

valves were always closed before the hoses were disconnected from any other system component so that any R134a still in the hose was retained for measurement instead of leaking to the atmosphere.

3.2 Results of Accuracy and Precision Tests

As previously described, four vehicles were tested a single time using the charge-recover method to help estimate the expected level of accuracy and precision for the procedure. The vehicles were tested throughout the project, with the first QA vehicle tested on April 10, 2009 and the final QA vehicle tested on April 9, 2010. Table 3 summarizes the results from the QA vehicles. Note that the procedure used on the first vehicle was preliminary, and was not identical with the procedure applied with the others, which may have contributed to the larger measured difference.

Table 3. Results from Tests to Estimate Accuracy and Precision of Method

Vehicle ID	Model Year	System Capacity (g)	Charge (g)	Recovered (g)	Difference (g)	% Difference	Note
Util2-01	2007	907	907.6	871.7	35.9	4.0	Draft Procedure
Garb2-02	2006	1,190	1,217.9	1,214.2	3.7	0.3	Final procedure
Priv4-1	2002	1,080	1,104.7	1,094.1	10.6	1.0	Final procedure
Priv5-1	2003	1,758	1,784.4	1,769.8	14.6	0.8	Final procedure

Ideally, if there was no error in the measurement, the differences between the "charged" and "recovered" amounts would be zero. The actual differences for these QA tests ranged from about 4 to 36 grams, with three of the four QA measurement errors below 15 g, that is, at or below 1% of the originally charged amount. During the regular measurements (discussed in section 3.3 below) we observed several "negative" losses, demonstrating that some recoveries do not remove 100% of the refrigerant. (In other words, the system was charged with a precisely measured amount of R134a while some refrigerant was still in the system from the original recovery.)

Since the measurement variability seems relatively large (as discussed in section 3.3 below) compared to the differences observed in the QA tests, there do not seem to be enough QA data points to treat these results with statistical rigor. However, consistent with what was previously decided regarding precision targets, it appears that a reasonable estimate of measurement error would be within 15 to 20 grams. So, for the sake of the following analysis, it is assumed that if the measured loss from a given vehicle is greater than 20 grams (or 2% of the original charge, whichever is larger), the result is deemed an actual loss and cannot be attributed to random error in the measurement.

3.3 Mass Based Leak Measurements

Once the method had been finalized, the gravimetric leak data collection began. Measurements started in January 2009 and continued through April 2010. A total of 65 vehicles were sampled, three of which experienced failures or other problems that invalidated their result. One failure was the seizing of the MAC compressor, which resulted in the destruction of the MAC drive belt and made the system unrecoverable. The two other problems had to do with servicing the vehicle's MAC during the testing period. As a result a total of 62 samples had valid results.

The vast majority of these vehicles were powered by diesel engines and had factory or assembler installed MACs. Almost all of the MACs had belt driven, piston type compressors, however, three of the newer medium-duty trucks and one tracked loader (heavy construction) had sealed, electric compressors which have inherently low leak rates. All of the MACs sampled used standard PAG oil of various viscosities. Three of the vehicles (all 1993 model year or older) had been converted from an R12 (Freon) system to an R134a system.

As previously described, the sample bins were determined in accordance with CARB technical staff. Within each of the bins ERG attempted to distribute the samples over a range of model years and system capacities. Table 4 shows the sample counts within each sample bin, as broken down by model year and Table 5 shows the same data broken down by the MAC manufacturer's recommended charge capacity.

Table 4. Sample Counts by Sample Bin and Model Year

Sample Bin	1	2	3	4	5	6	7
Model Year							
1989			1				
1990				1			
1991			1	1			
1993				1			
1995				1			1
1996			1				
1997		1					
1998		1	1	1			
1999			1	3	1	1	1
2000		2	1	2	2		
2001				2			
2002			1	1		1	1
2003		2	1			1	
2004		1	2	2	1	1	
2005			2	1		1	
2006			1		3		
2007			6	2	1		
2008				1	1		

<u>Sample Bin Key</u>
1 – Full-Sized Transit Buses
2 – Shuttle Buses
3 – Medium-duty Trucks
4 – Heavy-duty Tractor Trucks
5 – Other Heavy-duty Trucks (e.g., waste haulers)
6 – Construction Equipment
7 – Agricultural Equipment

Table 5. Sample Counts by Sample Bin and MAC Capacity

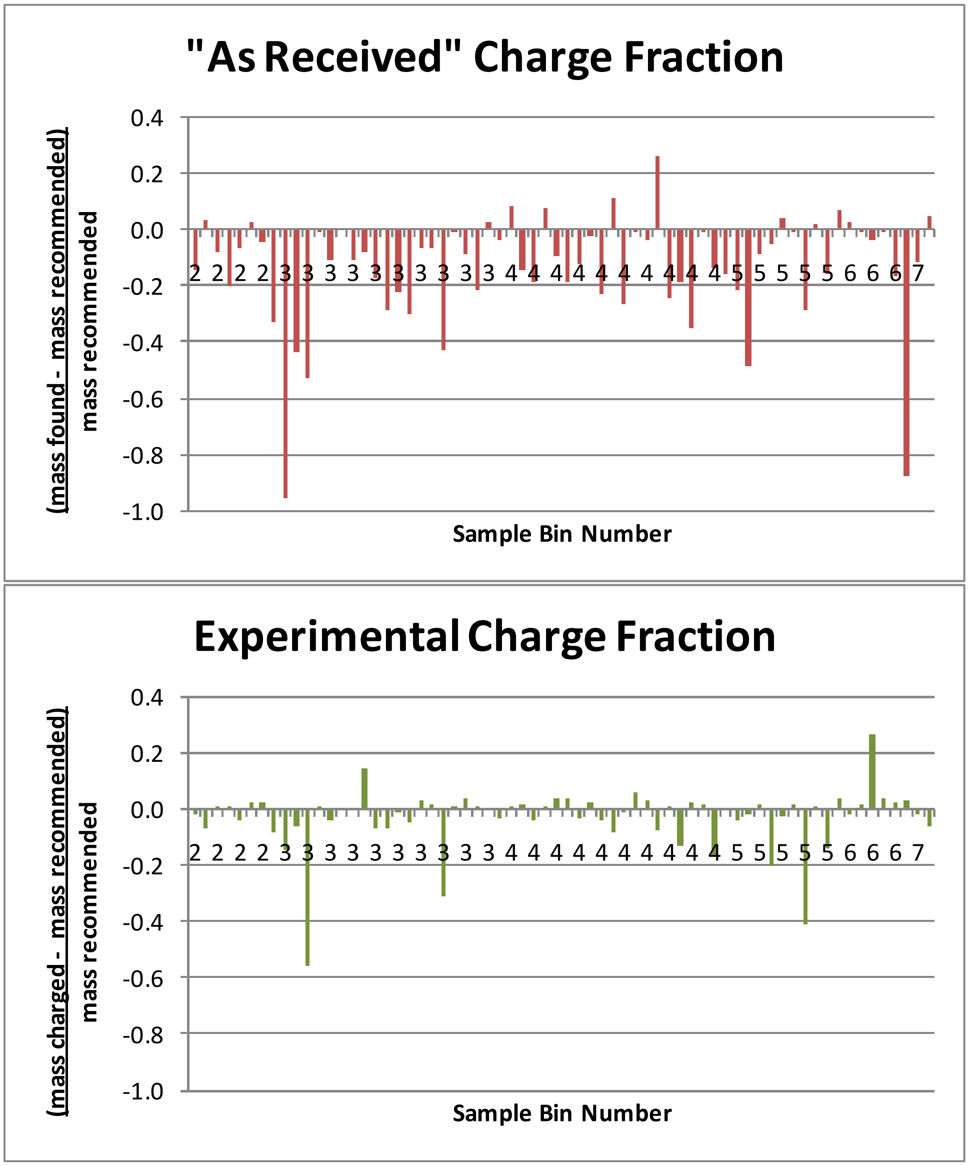
Sample Bin Capacities (g)	1	2	3	4	5	6	7
650		1					
907			1		1		
1080			4	2			
1134		1	1	2	1		
1190		1	3		2	1	
1247			1				
1280			1				
1310			5	5	2	2	2
1360		1	1	2	2		1
1400						1	
1474			2	6			
1700						1	
1950				2	1		
2495		3					

<u>Sample Bin Key</u>
1 – Full-Sized Transit Buses
2 – Shuttle Buses
3 – Medium-duty Trucks
4 – Heavy-duty Tractor Trucks
5 – Other Heavy-duty Trucks (e.g., waste haulers)
6 – Construction Equipment
7 – Agricultural Equipment

As indicated in the two graphs in Figure 7, there is a tendency for vehicles to be undercharged when received for service. These graphs compare the amount of R134a in the system "as received" versus the amount charged by ERG technicians. The MAC systems were consistently received with less R134a than the system capacity. This tendency seems to support the conclusion (as discussed later) that there may be significant leakage occurring from MAC systems in-use.

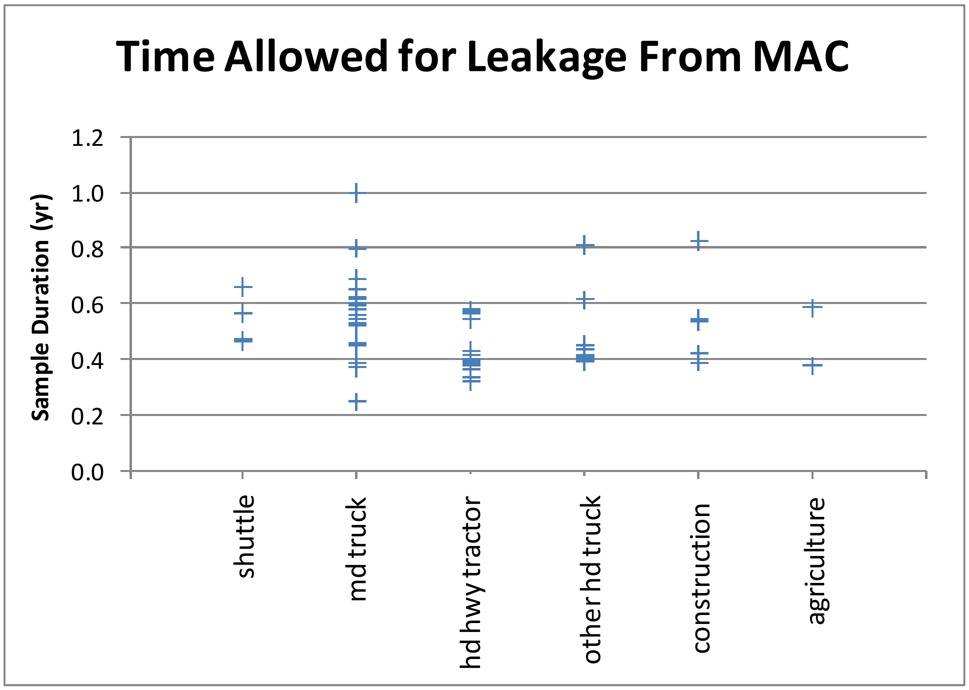
Also note that some of the systems were somewhat undercharged during the project as a result of technician error (e.g., a misreading of the recommended capacity label) but were retained in the sample, as reliable leak rates were still obtainable through the test protocol.

Figure 7. "As Received" Charge Versus Experimental Charge



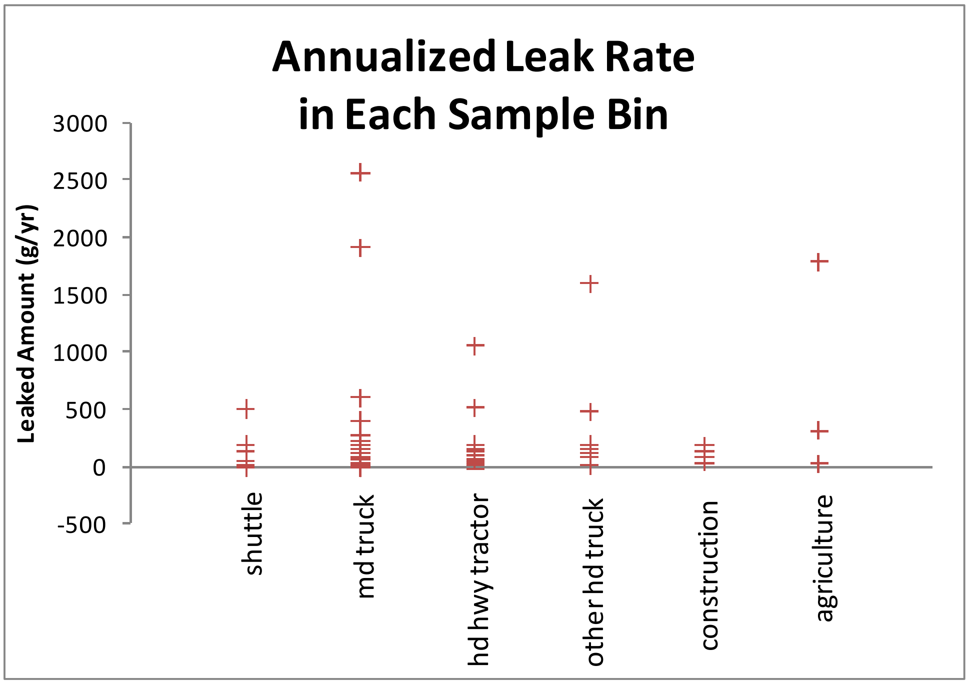
The charged systems were allowed to operate for a minimum of three months (i.e. 0.25 years) before being recovered. Figure 8 shows the length of time for each sample, grouped by sample bin. The longest sample time was 12 months, with the remaining times less than 10 months.

Figure 8. Length of Sample Time, Grouped by Sample Bin



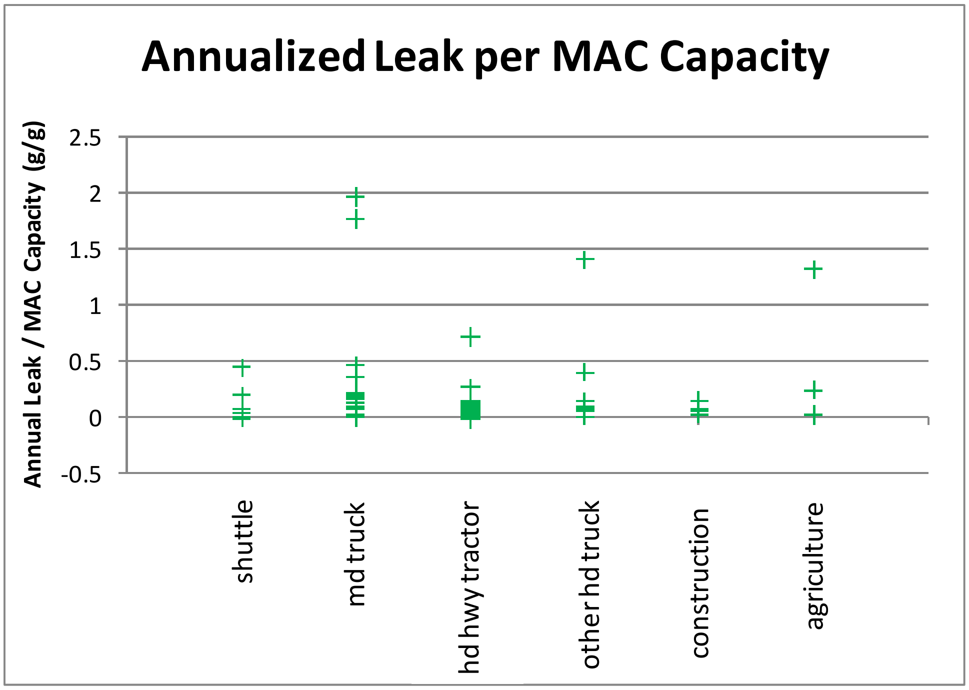
ERG attempted to identify trends in the measured leak rates by grouping the data in various ways. Figure 9 shows the annualized leak rate measured for each sample grouped according to sample bin. The annualized number is a projection of what would have been measured if the sample time had been 12 months. This estimate was calculated using a linear interpolation of the data from the actual sample time (i.e. 3 to 9 months) to a 12-month period. However, linear interpolation may result in an over-estimate of annual emissions because leak rates will be reduced as the system pressure decreases due to lower and lower charge levels. This error would be especially evident in MACs with high leak rates. Linear interpolation may also mask leak rate impacts of different MAC use rates during different seasons of the year. These and other such issues are discussed in later.

Figure 9. Annualized Leak Rate Projected for Each Data Point, by Sample Bin



Leak rates can also be expressed as a fraction of the capacity of the MAC system to gauge the reasonableness of the linear projection to an annualized rate. Dividing the manufacturer's recommended capacity (expressed in grams) by the annualized leak rate (in grams per year) yields the data in Figure 10. As previously discussed, these results may be an overstatement of the actual leak rate because of linear interpolation. For example, four of the linear projections result in annual leaks that exceed the capacity of the MAC. Taken at face-value, this finding indicates these vehicles would need to be refilled multiple times each year, especially since MAC system performance would deteriorate rapidly, well before the system approaches an empty state. Although it is unlikely that vehicle owners would tolerate such high leak rates for more than a season or two, temporary leaks of this magnitude seem feasible.

Figure 10. Annualized Leak Rate as a Fraction of Recommended Charge, by Sample Bin



ERG analyzed the final data for trends that might indicate a dependency of leak rate on the capacity of the MAC, the annual usage of the vehicle, the age of the vehicle or the type of vehicle. The only parameter with a possible indication of correlation with leak rate was the age of the vehicle. Although it is quite possible that other MAC system features will eventually be found to correlate with leak rate (as is assumed in SAE J2727), given the size of this data set and the inherent variability of the measurement process, it is not surprising other such correlations were not readily identified.

The annualized leak rate data are presented by model year in Figure 11. When the data are visually inspected, there appears to be a trend of increasing emissions with age. However, the trend is not obvious. Taken as a whole, the spread of the data are reminiscent of a log-normal distribution, where the majority of data points are aggregated near the low-end of the distribution and a few extreme outlier data points – 5 to 10-times larger than the bulk average – probably represent a large portion of the emissions from the fleet. In vehicle exhaust emissions studies, these types of "outlier" samples are commonly called "gross emitters" because they stand apart (with much higher emissions) from typical vehicles. This is similar to on-road exhaust emissions from vehicles as measured using vehicle remote sensing instruments.(8) An example of a lognormal distribution curve is shown below in Figure 12.

Figure 11. Annualized Leak Rate Projected for Each Data Point, by Model Year

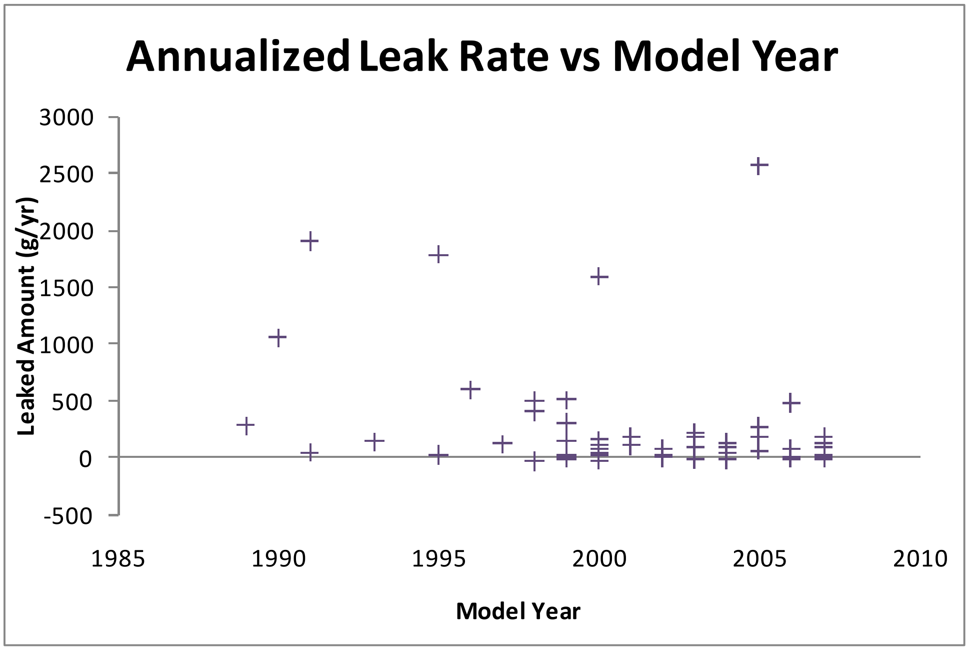
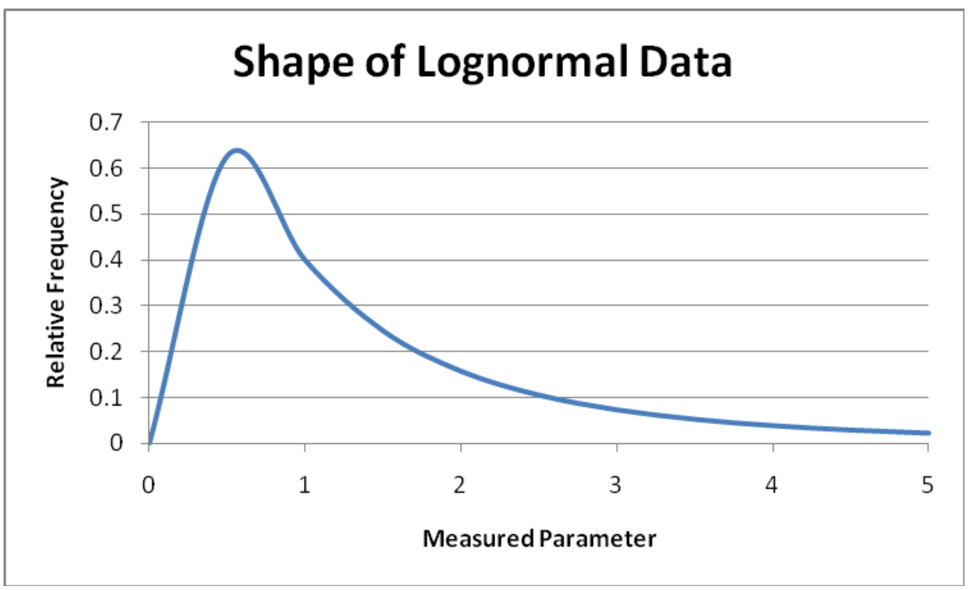


Figure 12. Example of Lognormally Distributed Data



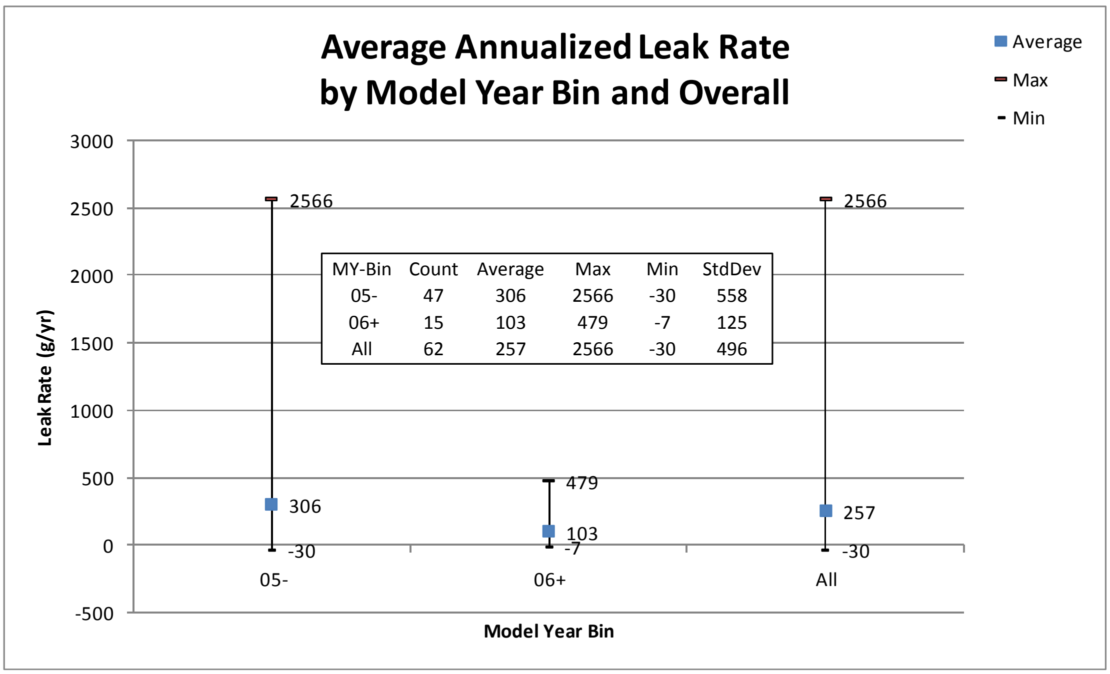
Comparing the example distribution above (Figure 12) to the data in Figure 10, one can see that the data for each of the vehicle types approximately follow this distribution. For example, most of the leak rate data for medium duty trucks are clustered near the low end of the measurement range, which is bounded by zero (approximately). The data at the upper end of the measurement range, which is (in theory) not bounded, become increasingly sparse, but can have a disproportionately large effect on the overall paramter average, because of their large distance from the bulk of the data points.

Given the large variability of the data and relatively small size of the data set compared to what would be required for a statistically rigorous analysis, ERG averaged the data in two model year groups for application to the state fleet. Vehicles with a model year of 2005 and older are in one group and vehicles with model year of 2006 and younger are in the other. This split corresponds roughly to the adoption of new voluntary IMAC standards by manufacturers, intended to improve the integrity of on-road MAC systems and decrease R134a leak rates.(5) Since off-road systems were not initially intended to participate in the IMAC standards, we assumed that on average, off-road MAC systems emit at the same rate as the 2005 and older on-road systems.

Figure 13 shows the calculated average results for older (pre-2006), newer (2006+) vehicles, and for all vehicles combined. The older vehicles are estimated to leak at an average rate of 306 g/yr (0.674 lb/yr), the newer vehicles at a rate of 103 g/yr (0.227 lb/yr). The maximum and minimum data points that contribute to each average are also shown to give an indication of the data variability. Standard deviations of the data in each average are also indicated in the data table on the graph to give an indication of the variability in the data used to calculate these averages.[2]

Given the small size of the sample, splitting the data set according to the above model year grouping may ultimately prove to be unjustified. Accordingly, ERG also calculated average annual leak rates for the aggregated data set as a whole, resulting in an estimate of 257 g/yr or 0.566 lb/yr (with summary statistics also indicated in Figure 12). As discussed in Section 4, utilizing this aggregated average rate does not substantially alter emission inventory estimates, however.

Figure 13. Average Results by Age Group and for All Vehicles Combined



[2] As discussed elsewhere, the measurements do not appear to follow a normal distribution, but rather a log-normal distribution. Accordingly, standard deviations only provide a qualitative indication of the level of noise in the data.

3.4 Refrigerant Leak Estimates from Maintenance Data

Five transit bus fleets participated in the study by providing information about their overall R134a use rate and their associated fleet characteristics. The fleets were operated all across California, with one in the Los Angeles air basin, one in the coastal region of northwest California, one in northern California (in-land), one in the Sacramento region, and one in the San Joaquin Valley.

The data from these fleets was analyzed as described in section 2.4. The maintenance data indicate the overall leak rates (e.g., including those due to maintenance errors, leaking maintenance equipment, accidentally opening refrigerant cylinders, etc.), in addition to leaks from the MAC itself. As another point of comparison, according to public transport fleet manager contacts, the nominal refrigerant charge for a large bus (e.g., 40 foot coach) averages around 6 kg while the range found in the gravimetrically analyzed vehicles with smaller capacity systems (the other heavy-duty vehicles described above) averaged around 1.3 kg. We briefly summarize analysis results of the maintenance information from these fleets in Table 6.

Of the 329 buses in these fleets that were 29 to 45 foot long coaches, 181 used R134a and the rest used R22 or R407c[3], or had no air conditioning. All of the shuttle/cutaway buses used R134a. The fleet-average leak rate, including all types of buses using R134a was 1,340 grams per year. These results are sample-weighted, meaning that data from large fleets have more influence on the average than data from small fleets. Again, this result includes types of refrigerant leaks, not just those from the MAC systems.

Since seven shuttle buses were tested using the gravimetric method, we can compare the more comprehensive leak estimates shown in Table 6 to the leaks measured directly from the MACs in other shuttle buses. Fleets 3 and 4 reported maintenance data that allowed the estimation of leak rates for shuttle buses. The weighted-average leak rate from the shuttle bus maintenance data from those two fleets was 2,500 g/yr. The average annual leak rate directly from MACs in the seven shuttle buses from the gravimetric measurements was 123 g/yr. ***So, according to this extremely limited sample of shuttle buses, over 20-times more R134a was released into the atmosphere from servicing shuttle buses than was emitted due to in-use leaks from the MAC system itself.*** At least in the public transport sector, this may point to a significant gap in any emissions inventories that do not account for leaks due to servicing MACs.

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[3] R407c is a mixture of 23% difluoromethane (R-32), 25% pentafluoroethane (R-125), and 52% 1,1,1,2 tetrafluoroethane (R-134a).

Table 6. Bus Fleet and R134a Maintenance Data Summary

Fleet	Location	Peak Month Avg. Daily High	Avg. Annual R134a Purchase	R134a Fleet	Estimated R134a Leak Rate (per vehicle)	Notes
Fleet 1	LA Basin	32°C (90°F)	27 kg (60 lb)	40-ft coaches: 170 total; 51 use R134a, 119 use R407c	540 g/yr (1.2 lb/yr)	Approx. 180 lb of R134a used in 3 years for 51 buses. 150 lb purchased, 30 lb already in stock.
Fleet 2	NW CA	18°C (64°F)	2.0 kg (4.3 lb)	40-ft coaches: 33 total; 5 w/o AC, 28 use R134a	68 g/yr (0.15 lb/yr)	30 lb cylinder of R134a purchased 7/18/2006. About ½ used so far.
Fleet 3	N CA	37°C (99°F)	55 kg (120 lb)	Shuttle buses: 23 total; all use R134a	2,400 g/yr (5.2 lb/yr)	Purchase approx. 120 lb R134a per year for shuttle buses
Fleet 4	Sacramento region	34°C (93°F)	Not provided	40-ft coaches: 22 total; all use R134a	1,100 g/yr (2.4 lb/yr)	Maintenance records: average of 103 lb R134a per year total for 40-ft coach buses
Fleet 4	Sacramento region	34°C (93°F)	Not provided	Shuttle buses: 21 total; all use R134a	2,700 g/yr (5.9 lb/yr)	Maintenance records: average of 138 lb R134a per year total for cutaway buses
Fleet 5	San Joaquin Valley	34°C (94°F)	180 kg (390 lb)	Shuttle buses: 32 total; all use R134a. 29 ft to 45 ft coaches: 104 total; 80 using R134a, 24 using R22.	1,600 g/yr (3.5 lb/yr)	Projected "year to date" use as of Nov 4 (325.7 lb R134a & 147.1 lb R22) to end of year.
Five-fleet-average R134a leak rate					1,340 g/yr (2.9 lb/yr)	
Total buses of each type				29 to 45 ft coaches with R134a: 181 29 to 45 ft coaches without R134a: 148 Shuttle buses with R134a: 76 Shuttle buses without R134a: 0		

4.0 Analysis and Discussion

4.1 Emission Inventory Projections

By using default assumptions from California's EMFAC and OFFROAD models, the above estimated leak rates can be projected for a rough estimate of the overall R134a heavy-duty emissions statewide. However, given the limited scope of this study, such projections are highly uncertain. For example, the sample size of the study is relatively small and vehicles were chosen based upon their availability and the willingness of the owner to participate. So the representativeness of the sample for projecting results to the state-wide fleet is not fully understood. Also, it was learned during this study that a significant fraction of refrigerant leaks likely occur due to service methods and the service equipment itself, especially in the public transport sector, where the ability of the MAC to cool the passenger compartment is critical (i.e., service intervals are more frequent and are intended to prevent poor cooling performance rather than to correct a performance problem that has already developed). Finally, as previously noted, the annualized leak rates for each MAC in the sample was calculated using a linear projection. In actual practice, leaks will tend to slow as refrigerant charge decreases due to a decrease in maximum working pressures. Therefore, annualized leaks calculated from MAC systems with high leak rates are probably somewhat over-stated. So by simply projecting leaks directly from vehicle MACs of unknown representativeness, and not accounting for other, related leaks from servicing the MACs, significant, unquantified errors may exist in the R134a emission inventory.

Conducting additional surveys to better understand the impacts of MAC service on the inventory was beyond the scope of this project. We did, however, prepare initial assumptions for such an inventory. In preparing for a future inventory, researchers can review these numbers to note which gap filling assumptions can most effectively be augmented with additional data.

The basic method for developing an emissions inventory is to estimate annual emissions by multiplying an activity-based emission factor by an activity level for the fleet in the inventory. In the case of this project, the emission factors developed are average annual leak rates per vehicle by vehicle/equipment type. So the applicable "activity level" is simply how many vehicles/equipment pieces are operating in the state, by category. The following provides an estimate of the state-wide population of such vehicles in 2010.

The two mobile source emission factor models used by California apply to on-road (EMFAC) and offroad (OFFRAOD) fleets. Both models have default data on the numbers of different types of vehicles in use in California for a given year. ERG then estimated what fraction of these vehicles have MAC systems. By multiplying the estimated fraction with a MAC by the total population of each type of vehicle, an initial estimate of the number of each vehicle type with MAC systems in California can be made.

The on-road sources applicable to this project are medium-duty and heavy-duty vehicles. For the purposes of an initial estimate of R134a leakage from these vehicles, it is reasonable to assume that 100% of these have MAC systems except for "other" and "urban" buses. Based upon interviews with the public transport fleet managers that provided maintenance data for this study, it was estimated that 55% of "other" and "urban" buses in California use R134a.

The default 2010 population numbers from EMFAC for medium to heavy-duty on-road vehicles in California (rounded to the nearest 1,000) are shown in Table 7. The populations shown for "other" and "urban" buses have been multiplied by 0.55, so this table represents our estimate for vehicles with R134a MAC systems.

Table 7. Estimate of 2010 On-road Vehicles with R134a MAC Systems in California

EMFAC Vehicle Category	Pre-2006 Count	2006+ Count
04 - Medium-Duty Trucks (T3)	1,722,000	746,000
05 - Light HD Trucks (T4)	239,000	188,000
06 - Light HD Trucks (T5)	119,000	49,000
07 - Medium HD Trucks (T6)	188,000	70,000
08 - Heavy HD Trucks (T7)	179,000	51,000
09 - Other Buses	9,000	3,000
10 - Urban Buses	7,000	1,000
12 - School Buses	23,000	4,000
13 - Motor Homes	198,000	61,000
Total	**2,684,000**	**1,173,000**

The OFFROAD model includes a wide range of engine-powered equipment in California that are not registered for on-road use. For the purposes of estimating R134a leakage, ERG reviewed the complete list of equipment types in the OFFROAD model, and based on our familiarity with these equipment types, identified those categories that may have enclosed cabs capable of utilizing a MAC system. The following provides a listing of these equipment categories.

- Rollers
- Trenchers
- Cranes
- Rough Terrain Forklifts
- Rubber Tire Loaders
- Tractors/Loaders/Backhoes
- Skid Steer Loaders
- Other Construction Equipment
- Forklifts
- Sweepers/Scrubbers
- Other General Industrial Equipment
- Other Material Handling Equipment
- Agricultural Tractors
- Combines
- Balers
- Sprayers
- Swathers
- Other Agricultural Equipment
- Cargo Tractor
- A/C Tug, Narrow Body
- A/C Tug, Wide Body
- Air Conditioner (GSE)
- Baggage Tug
- Bobtail
- Fuel Truck
- Lavatory Truck
- Maintenance Truck
- Passenger Stand
- Sweeper
- Service Truck
- Catering Truck
- Hydrant Truck
- Scrapers
- Excavators
- Graders
- Off-highway Trucks
- Rubber Tire Dozers
- Crawler Tractors
- Off-Highway Tractors
- Skidders
- Fellers/Bunchers
- Other GSE
- Other Workover Equipment
- Drill Rig
- Military Tactical Support Equipment
- Dredger
- Other Dredging

ERG then assumed that only larger equipment would have enclosed cabs with an A/C option, defining "large" as equipment greater than or equal to 50 hp. OFFROAD was then queried to obtain the statewide equipment population ≥ 50 hp for these categories for the 2010 calendar year. According to this assumption, the total number of such equipment in California (rounded to the nearest 10) in 2010 is 316,600.

Combining the estimated populations above with the estimated emission factors we can estimate a 2010 inventory for in-use R134a emissions (i.e., leaks directly from the MAC system under normal operation) from these vehicles. For example, the emission estimate for pre-2006 on-road vehicles is calculated as:

2,684,000 vehicles x 306 g/yr = 821 Mg/yr

The calculations for each estimate are indicated in parentheses within Table 8 below.

As shown in Table 8, the emissions inventory estimate for heavy-duty on and offroad vehicles using R134a in California is a total of 1,039 million grams (1,145 short tons) per year, using pre-2006 and 2006+ emission factors. Estimates for Other types of R134a leaks (some possibly quite significant) are not accounted for in this estimate. These additional types of leaks include those from servicing MACs and from catastrophic damage (e.g., cutting a hose) that causes all refrigerant to escape the MAC. This assumes that the off-road equipment is assumed to all have MACs that meet the leak-tightness of on-road systems from the 2005 and older model years.

Table 8. Estimate of 2010 Emissions of R134a directly from MAC leaks

EMFAC Vehicle Category	Pre-2006 Mg/yr (short ton/yr)	2006+ Mg/yr (short ton/yr)	All Model Years Mg/yr (short tons/yr)
On-Road Equipment [Pre-2006: 2,684,000*306=821 Mg] [2006+: 1,173,000*103=121 Mg] [All: 3,857,000 * 257=991 Mg]	821 (905)	121 (133)	991 (1,089)
Off-Road Equipment [Age Basis[4]: 316,600*306=97 Mg] [All: 316,000*257=81 Mg]	97 (107)		81 (89)
Grand Total	**1,039** **(1,145)**		**1,072** **(1,178)**

Note: These estimates account only for in-use leaks directly from the MAC. Leaks from other sources, such as maintenance procedures, are not included and are probably significant for certain vehicle types.

To calculate a CO_2-equivalent emission (CO_2E) for the above total, a greenhouse warming potential (GWP) factor can be used to ratio the tons of R134a to an equivalent tonnage of CO_2. ARB assumes a GWP for R134a of 1,300 as per IPCC guidelines.(1) Multiplying the 1,145 short ton/yr of R134a estimated above by the ARB accepted GWP results in a 2010 inventory

[4] Assumes offroad MAC systems emit at the same rate as pre-2006 on-road systems.

estimate of 1.35 million metric tons of CO_2E emissions per year due to R134a leaks from heavy equipment in California. Or, utilizing the average emission rate estimate for all model years, the inventory estimate comes to 1.39 million metric tons of CO_2E emissions per year.

4.2 Sources of Uncertainty

In general the data from this project indicate that R134a leak rates from MACs in medium-duty and heavy-duty equipment are significant. But a statistically rigorous analysis of these leak rates would require more data.

First, while the measurement procedure is well documented the actual noise resulting from the measurement process (operator variations, equipment wear, instrument noise, etc.) has not been firmly established. Measurement error could be better determined with further study by including more quality assurance tests that repeat the measurement within a few hours of the R134a recharge. Also, projection of the measurement results to annual losses assumes that loss rates are linear over time. In normal engineering practice one would assume loss rates decrease with system pressures, unless the MAC is frequently "topped off" as soon as a significant amount of refrigerant is lost. This linearity assumption will likely overestimate leak rate estimates because reduced MAC performance is not typically noticed until the system has lost a relatively large fraction of its refrigerant, which can often be after several seasons of use.

In addition, as noted above the calculated leak rate from the gravimetric method only accounts for in-use operation. Other probable significant sources of leaks include MAC maintenance equipment design (leaky hose valves, gaskets, etc.), MAC system failure (such as the compressor failure we experienced in the project) and inconsistent MAC technician practices. These other sources could easily be significant in the overall inventory.

Even diligent adherence to accepted practice when servicing MAC systems will likely lead to significant refrigerant losses that are not currently accounted for. For example, high use systems such as those in public transport vehicles must periodically replace system parts, such as the receiver/dryer. Typical service intervals for these components are every 24,000 miles. This requires emptying the MAC of refrigerant, cleaning and replacing the receiver/dryer, then recharging the MAC system. The recycling systems used to draw refrigerant from the MAC do so quickly enough to cause MAC lubricant to solidify, trapping any dissolved refrigerant in the lubricant itself and in interior system crevices the solidified refrigerant surrounds. As the MAC components are being serviced, the system remains open to the atmosphere, allowing the trapped refrigerant to escape as the lubricant liquefies after warming to ambient conditions. From our knowledge of the experimental method used in this project, we estimate this common service could result in the loss of 20 to 50 grams of refrigerant per 24,000-mile service event in the systems we measured (which hold from 1,000 to 2,500 grams total of refrigerant each).

Certain MAC system designs may also contribute significantly to the leaks from maintenance service. For example, the maintenance-related leaks from shuttle buses and cutaway buses seemed consistently higher than from the larger, 30-foot to 45-foot transport buses. This could be due to the dual systems often used in the shuttle and cutaway buses. One system comes with the bus chassis for cooling the driver cab and the other system is installed for cooling the passengers when the passenger portions of the bus are installed. Since these systems often have double the number of MAC components, the service-related leaks could also be increased due to the increased service steps required for these systems.

Regional differences in how MAC systems are used are probably important as well. North coastal areas most likely only use MAC systems for defrost. This application can be accomplished at much lower refrigerant levels, so topping off is probably less frequent and (based upon the interview data from a coastal operator) refrigerant consumption seems lower. This could be the pattern in all areas with cold winters and cool summers.

Finally, note that the effects of the measurement process itself on the system being measured, especially on older or compromised MACs, are not fully known. The procedure subjects the MAC systems to vacuums significantly more prolonged and intense than they would normally encounter. During the course of this study a MAC on an F550 medium-duty truck was found to be untestable as it began in-leaking air when a vacuum of lower than 15 inches of mercury was applied. This was in spite of the fact that the system appeared to be operating normally, with an apparently normal amount of R134a when the vehicle was received. Although the MAC system on this vehicle appeared to return to a normal operating state upon completion of the test and the effect was not apparent in other vehicles, it may be that other, less robust MAC systems could develop sustained leaks under such test conditions. (It should be noted however that Dr. Clodic has not experienced any such "false positive" results in similar studies he has conducted.) For this reason the effects of the measurement itself on older or impaired MAC systems are a source of uncertainty regarding the long-term emission rates for these vehicles.

4.3 Related Studies

During the past decade a body of research has been developed estimating leak rates from MAC systems. Some of the more quoted researchers in the field are Dr. Denis Clodic of the Paris School of Mines and Dr. Winfried Schwarz of Öko-Recherche in Frankfurt, both of which have peer reviewed this report.

As previously described, Dr. Clodic has developed a well regarded method for directly measuring refrigerant leak rates. Several of his studies have relied on this method utilizing a "bottom up" approach to emissions inventory that uses the measured leak rates to estimate total emissions. Dr. Schwarz has used an alternative, though also well regarded method for estimating refrigerant emissions. This approach is often called "top-down" since it uses estimates of remaining refrigerant as compared to the assumed full charge of the system when the vehicle was first registered for use. Unfortunately, the published study data do not seem directly comparable to the results from this study without significant research and possible recalculation. For example, it would be important to determine which of their estimates are limited to in-use MAC operation, and how to separate others from estimates for catastrophic system losses (e.g., vehicle crashes), maintenance, etc. However, in general it appears that Dr. Clodic's measured results tend to fall below those measured in this study while those from Dr. Schwarz tend to fall above.

5.0 Summary and Conclusions

The study described in this report provides a first-of-its-kind, mass-based measurement of R134a emissions from heavy-duty MAC systems. This groundbreaking effort also collected key information regarding the characteristics of these systems, and provides a foundation for improved emission inventories and for continued reduction of GHG emissions from the heavy-duty vehicle sector in both California and throughout the United States.

A number of observations have been gleaned from the study results, and are presented below.

1. Older MAC systems appear to leak more than newer systems. One reasonable model year grouping between higher and lower leak rates are before and after the 2005 – 2006 transition for the voluntary IMAC system integrity guidelines. This study resulted in an emissions inventory estimate for heavy-duty vehicles using R134a in California totaling 1,039 million grams (1,145 short tons) per year. This equates to an estimated 1.35 million metric tons of CO_2E emissions per year. (Utilizing average leak rates for all model years aggregated together results in similar inventory estimates, at 1.39 million metric tons of CO_2E emissions per year.)

2. Four quality assurance tests conducted to estimate the method's accuracy and precision indicate that measurement error (from all sources) can account for from 0.3% to as much as 4% of the MAC system charge. For the sake of this analysis it was assumed that if a measured loss from a given vehicle was greater than 20 grams, or 2% of the original charge, whichever was larger, the result was deemed an actual loss and not attributable to random measurement error.

3. Vehicles "as received" were usually low on charge. The average deficit was between 15% and 20% below the manufacturer's recommended charge. It was not determined how long these systems had operated since their last refill, but many of the newer systems had obviously never been serviced.

4. Projection of the gravimetric results to annual losses assumes that the MAC would be immediately topped off as soon as a significant amount of refrigerant is lost. This assumption probably errs on the high side of the actual leak estimate because reduced MAC performance is not typically noticed until the system has lost a relatively large fraction of its refrigerant, which can often be after several seasons of use.

5. Measurement error is not well established and could be better determined with further study.

6. Regional differences in how MAC systems are used may be important. For example, north coastal areas only use it for defrost. This seems to allow using the system effectively at much lower refrigerant levels. So topping off is less frequent and refrigerant consumption seems lower.

7. The distribution of the measurement results cannot be firmly established, but it appears to resemble a log-normal distribution, with most results being grouped at the low-end and a few, "gross emitters" standing out as several times higher than the rest of the data. These gross emitters have a disproportionate effect on the overall emission inventory.

8. Other types of R134a leaks (some possibly quite significant) are not accounted for in this estimate. Other probable sources of leaks include MAC maintenance equipment design (leaky hose valves, gaskets, etc.), servicing MACs, and from catastrophic damage (e.g., cutting a hose) that causes all refrigerant to escape the MAC. In particular, diligently following accepted practice when servicing MAC systems can still lead to significant refrigerant losses that are not currently accounted for. This is especially true for MAC systems in public transport vehicles (e.g., buses) where the MAC systems are larger than other types of vehicles and are serviced much more frequently than for other vehicles. Estimates based upon the sample of shuttle busses indicate that emissions from maintenance could add significantly to the emission inventory from vehicles used for public transport.

9. Of the 329 buses in these fleets that were 29 to 45 foot long coaches, 181 used R134a and the rest used R22 or R407c, or had no air conditioning. The fleet-average bus leak rate, including all types of buses using R134a was 1,340 grams per year. This result includes types of refrigerant leaks, not just those from the MAC systems.

6.0 Recommendations

ERG has developed a list of recommendations for utilizing and building upon the findings of this study, as described below.

- Survey large fleet operators and certified technicians to find obvious sources of leaks other than during typical MAC system operation. Variations in technician procedures, over-maintenance (transport systems) and design of MAC maintenance equipment are probable sources. Compare the results to MAC system leak rates measured in this study. Use the results to prioritize further research on R134a leak sources.
- Model the decline in leak rate as the refrigerant level (and average MAC working pressure) falls.
- Consider duty-cycle, which may correlate to the installation and history of the system. For example, if a system was converted from using R-12 to using R-134a refrigerant, that means the system was opened and modified, which may influence leak rate. Alternatively, if a system was installed using after-market equipment (after the vehicle was manufactured), its duty-cycle (and deterioration rate) may be different than a factory installed system.
- Consider accounting for other effects on the emission factors to be developed in the future. For example, the amount of time a MAC system is used may influence the average refrigerant leak rate from that system. This is due to refrigerant permeation from the high-pressure side of the system, which is about 150% higher than permeation from the low-pressure side when the MAC system is operating. SAE standard J-2727 assumes the typical system is operational about 6% of the time, but this figure could vary widely in California, especially for heavy-duty fleets that operate in a given area. (3) For example, we expect that fleets which operate exclusively near the coast will use their MAC much less frequently than those operating only in the Central Valley.[5]

[5] Compressor on-time could be estimated using the predictive algorithms in EMFAC, given appropriate information on ambient conditions for local fleets. Weather station data could be obtained to represent operating conditions for local fleets depending on geographic location and the time period between refrigerant measurements. Such information likely will not be available for fleets operating over large geographic areas with diverse ambient conditions.

References

1. Intergovernmental Panel on Climate Change Fourth Assessment Report, 2007.
2. California Air Resources Board, Initial Statement of Reasons for Proposed Regulation for Small Containers of Automotive Refrigerant, December 5, 2008, p. 4.
3. SAE standard J-2727: HFC-134a Mobile Air Conditioning System Emissions Chart, January 29, 2007.
4. US EPA Climate Protection Partnership, Mobile Air Conditioning, http://www.epa.gov/cppd/mac/, last verified 7/27/10.
5. Personal communication with Gary Hansen, Red Dot Corporation, April 2008.
6. W. Schwarz, Establishment of Leakage Rates of Mobile Air Conditioners in Heavy-Duty Vehicles – Part 1: Trucks, prepared for the European Commission (DU Environment), January 27, 2007.
7. D. Clodic, "Research Study on the Definition of the Implementation of a Method of Measurement of Annual Leak Flow Rates (LFRs) of MAC Systems", ACEM/Armines Contract, January 2006.
8. Spectroscopy Applied to On-Road Mobile Source Emissions, D.A. Burgard, G.A. Bishop, R.S. Stadtmuller, T.R. Dalton and D.H. Stedman, Applied Spectroscopy, 60:5:135A-148A, 2006. http://www.feat.biochem.du.edu/assets/publications/Applied_spectroscopy_60_5_2006.pdf, last verified 7/27/10.

Glossary of Terms, Abbreviations, and Symbols

°C: Degrees Celsius

CARB: California Air Resources Board

CO_2E: CO_2-equivalent

EPA: United States Environmental Protection Agency.

ERG: Eastern Research Group

°F: Degrees Fahrenheit

GHG: Greenhouse Gas

GWP: Global Warming Potential

HP: Horsepower

IMAC: Improved Mobile Air Conditioning (Cooperative Research Program)

IPCC: Intergovernmental Panel on Climate Change

kW: Kilowatt

MAC: Mobile air conditioner. Commonly refers to air conditioner systems in vehicles

MT: Metric Tons

PTFE: Polytetrafloroethylene, commonly referred to as Teflon®.

QA: Quality assurance. Refers to practices that ensure the quality of data (precision, accuracy, resolution, quantity, etc.) meets the levels required to achieve project goals.

R134a: HFC-134a (1,1,1,2-tetrafluoroethane), a refrigerant commonly used in modern and converted MAC systems because it has a low potential for harming tropospheric ozone.

R22: Chlorodifluoromethane ($CHCIF_2$). Refrigerant commonly used in applications that require colder temperatures systems than R134a can provide.

R407c: Refrigerant mixture of 23% difuoromethane (R-32), 25% pentafluroethane (R-125), and 52% 1,1,1,2 tetrafluroethane (R-134a).

SAE: Society of Automotive Engineers

Appendix 1
Standard Measurement Procedure

ARB AC Refrigerant Leak Pilot Testing SOP

(updated 2009.05.14)

Overall Process:

- Charge a heavy-duty vehicle Mobile Air Conditioning (MAC) system with a precisely measured quantity (mass) of R134a refrigerant.
- After 4 months of use, recover and measure the mass of the refrigerant from the MAC system at the same conditions under which it was originally charged.

Notes:

The processes for the initial test (referred to as "initial") and the test conducted 4 or more months later (referred to as "final") are essentially identical. These steps, including vehicle preparation, recovery system preparation, refrigerant recovery process, distillation process and recharge process are each listed in detail in the instructions for the initial process. But these detailed instructions are not repeated for the final process. Only deviations or additions are specifically noted for the final test.

The data collection form has separate sections for data collection of both the initial test and the final test.

All mass measurements should be made and recorded to the 0.1 (tenth) of a gram. Since the balance is so sensitive, it is important that it be on a solid base and well shielded from air drafts, vibrations, etc. The graphic at the end of this document shows how to set up the wind-break and base for the balance. The bottom sandbags are optional when the floor is uneven. The photo next to the graphic shows an example of the actual set-up.

Each test cycle (vehicle prep, recovery system prep, refrigerant recovery, distillation, and recharge) are intended to be conducted sequentially without time delays between the steps.

In general, an evacuated a/c system is drawn down to an absolute pressure of 20 kPa absolute (-81 kPa gauge), but an evacuated recovery system is drawn down to a pressure of 20 Pa (-101305 Pa gauge).

The following reference chart provides comparison of pressure units at different pressures in both the absolute and gauge scales. Notice that the vacuum level we take the a/c system to (to remove only refrigerant) is 1,000 times higher pressure than the vacuum level we take the recovery system to in order to remove both oil and refrigerant.

vac. level for recovery system	20 (-101,305)	0.02 (-100.98)	0.00290 (-14.6971)	0.000197 (-.999803)

The system we use to recover and recharge refrigerant is composed of refrigerant tanks, a vacuum pump (for high vacuums), a refrigerant compressor (for lower vacuums and to transfer refrigerant), a scale (to measure mass), a high-vacuum gauge, a medium vacuum gauge, a refrigerant manifold with a high-pressure gauge and a low-pressure gauge, hoses (some with shut-off valves),

To make the vacuum pump work better (FASTER) and last longer, **keep the oil clean** by doing three things:

1. **When starting to evacuate the system, open the brass vacuum relief valve** on top of the pump 1/4 turn **for the first 2-minutes**. This helps keep refrigerant out of the oil.
2. **Before turning off the pump, relieve the vacuum** by re-opening the vacuum relief valve. This reduces internal surges and damage.
3. **Check the oil at the end of each day** to see if it's contaminated. Careful, it's hot! Drain a few drops onto paper and compare its color to fresh, high-vacuum oil. Green tinge is refrigerant dye (contamination). Check the vacuum level on just the hose with valves closed and no leaks. Best operation is 8 Pa-abs within 2-minutes and 6 Pa-abs within 6-minutes. Bad oil takes longer or won't even get down to 20 Pa-abs.

Do not contaminate the vacuum gauge sensor with oil. It will break and it is expensive to replace. Always either remove it or isolate it from the system (turn off the valve between it and the pump) before removing the vacuum from the system. This is to prevent oil from surging into the sensor as the system goes back to atmospheric pressure from extreme vacuum.

Vehicle Selection – Pre-Screen:

- Identify vehicle according to ERG’s sampling plan
- Discuss with the fleet manager/supervisor the MAC maintenance history of the selected vehicle during the prior two years. Obtain records or record summary in the “Summary of MAC Maintenance over Prior 2 years” section of the data collection form.

Vehicle Preparation:

- Ensure the vehicle is maintained at a minimum temperature of 70 °F for at least 12 hours prior to beginning process.
- Set up the two or more heat generator/space heaters to maintain the following temperatures:
    - ambient temperature of 70 °F in area surrounding vehicle
    - engine compartment temperature of 105 °F
- Set up vehicle with active exhaust ducting on exhaust outlet so engine may be run in garage.
- Install contact thermocouples on MAC suction line (near valve) and on compressor, as shown in the following images:

- Install a thermometer / temperature gauge on the vehicle's a/c condenser and also in one of the a/c cab vents.
- Use the refrigerant analyzer to determine the type of refrigerant present in the MAC. Record the types of refrigerant detected on the data forms. **If constituents other than R134a and moisture are detected, do not conduct any testing on the vehicle.** This will potentially contaminate the recovery equipment and other vehicles. Notify ERG contact for selection of an appropriate replacement vehicle.
- Using the sealant detector, determine if any sealant is present in the MAC. Record the results of the sealant detection test on the data forms. **If sealant is detected, do not conduct any testing on this vehicle**. This will potentially contaminate the recovery equipment and other vehicles. Notify ERG contact for selection of an appropriate replacement vehicle.
- Take digital photographs of the vehicle body, license plate, identifier used by the fleet, a/c compressor and lines/hoses, condenser, a/c service tag and any other noteworthy A/C equipment. Also, document and photograph any vehicle damage. Download photographs and rename using the vehicle test ID. [make not of this on the data forms and put a check box]

Recovery System Preparation:

- Perform scale tare and audit immediately prior to measuring system weights, record results in the "Recovery Prep, Part a" table. "Load" refers to highest anticipated mass to be weighed at one time (i.e., a recovery cylinder full of refrigerant, along with all the recovery equipment).
- Ensure the recovery cylinder to be used is empty. If none are empty, it may be necessary to empty one by transferring the contents to another cylinder that contains un-recycled R134a.
- Use the vacuum pump to evacuate the recovery cylinder to **20 Pa** (*not 20 kPa*) absolute, as shown in the following image. This removes all refrigerant and oil. Consider heating the tank to speed the process. Record the pressure of the evacuated recovery cylinder in the "Recovery Prep, Part b" table

- Weigh the evacuated recovery cylinder as shown below, record results in the “Recovery Prep, Part b” table

- Next, evacuate the service manifold, evacuation compressor, along with its inlet and outlet hoses, with the vacuum pump to **20 Pa** (*not 20 kPa*) absolute. The following images show the proper position of the compressor valves (red "open," blue "purge") and the evacuation of the compressor and hoses (service manifold is not shown in the image). Record recovery equipment pressure in the “Recovery Prep, Part b” table.

- Weigh the entire evacuated system (manifold, recovery cylinder, hoses and compressor) combined, as shown in the following image, record the measured mass in the in the "Recovery Prep, Part b" table.
- Weigh the manifold & hoses, the compressor & hose and record them in the next table. These will be used later to help calculate the amount of R134a in the components.

Refrigerant Recovery Process

1.1 First Recovery:

- After the 12-hour soak, measure and record the equilibrated ambient and engine compartment temperatures
- Using ASE-approved procedures, install the service manifold onto the a/c system, measure and record the pressure readings from the high and low service ports (with the vehicle's engine is still off).
- Start the vehicle engine, turn a/c to "on", set the a/c blower to "high", ensure vehicle windows are open, and air is set to on "fresh", (not "recirculate").
- Run the vehicle at idle for 20 minutes. At the end of the 20 minutes, measure and record the appropriate data in the "Recovery, Part a" table. Also note any compressor (or reed-valve) problems by watching gauges (high side too high, high side too low, low side too high, low side too low, dial flutter, etc.). This will give a baseline for health and performance of the system before we start our test, including providing info on pressures of the a/c system before we start evacuating it. Record any noteworthy info in the table.
- After the 20 minutes of operation, continue to run the engine but turn the a/c and blower motor off. Allow the engine to run for an additional 10 minutes.
- (Optional) Turn engine off

COMMON RECOVERY STEPS

- Continue to operate space and engine compartment heaters in order to maintain temperatures. Attempt to orient a heater to direct heat flow onto the a/c condenser because it will start to cool during recovery.
- In the "Recovery, Part b" table, record the beginning time (to the nearest minute) of the first recovery.
- Start the vehicle's engine (if already off), set blower motor to "high", leave a/c off
- Connect the recovery equipment to the service manifold and begin to slowly evacuate the system. Do not extract liquid. If temperature at LP valve drops quickly (more than 10 °F), liquid is flowing. Slow the recovery to allow only vapor to flow. Attempt to maintain a slow extraction rate (around 10 g/min) in order to eliminate any oil extracted from the system.
- Continue to evacuate the system down to 20 kPa abs and keep vacuum at this level for 10 minutes to let refrigerant boil out of oil in system.
- Once a system pressure of 20 kPa or so been achieved for 10-minutes (measured via mid-vacuum gauge on recovery compressor), record the recovery ending time
- Record the system pressure
- Close service manifold valves and turn off recovery compressor (Do not purge the compressor until after the final recovery and weighing!!)
- (Optional) Turn off the vehicle's engine
- Record post-recovery temperatures on data collection form

- Disconnect the recovery system (including service manifold and hoses) from the vehicle and weigh the complete recovery system (i.e., recovery cylinder, service manifold & hoses, and recovery equipment). Record this recovery weight in the appropriate location (Recovery Cylinder & Equipment Mass) in the "Recovery, Part b" table.

END OF COMMON RECOVERY STEPS

- Deduct the Recovery Cylinder & Equipment Empty Mass value (from "Recovery Prep, Part b") from the "Recovery Cylinder and Equipment Mass" value (from "Recovery, Part b") in order to determine the mass of refrigerant collected thus far. Write the result in the "Recovery, Part b" table.
- Calculate the initial recovery's extraction mass flow rate, record result on the next line in the table. This info may be used to help tailor extraction rates for subsequent tests.
- Leave the heaters on, warming ambient, engine compartment, and condenser

1.2 Subsequent Recoveries:

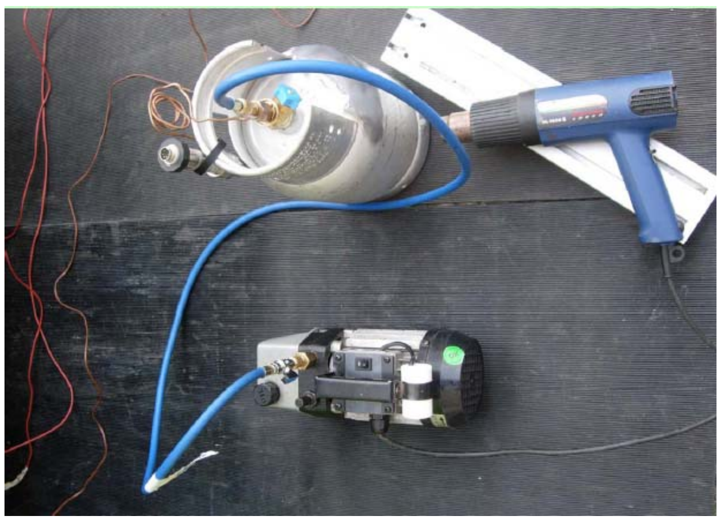
- Start engine (if already off), run for 30 minutes prior to performing second recovery (**blower motor on, a/c off**)
- Record the appropriate pre-recovery temperatures on the data collection form, call ERG manager if any temperatures are under 70 °F
- Measure and record the "system pressure before recovery" for the 2nd recovery in the "Recovery, part b" table.
- Repeat the "Common Recovery Steps" listed above, leaving at the system 20 kPa for 10 minutes each time.
- Calculate the mass of recovered refrigerant this time by deducting the initial recovery's "Recovery Cylinder & Equipment Mass" from the "Recovery Cylinder & Equipment Mass" just measured for second recovery, write result on data form.
- If the difference between the first recovery weight and second recovery weight is more than 1 g, perform a third recovery using an identical process. More than 3 recoveries are usually not needed. However, additional recoveries should be performed until the difference between the last two recovery masses is less than 1 g. Call an ERG manager if more than three recoveries are needed, as this may indicate a problem with a/c system.
- After the final recovery has been performed, disconnect the recovery cylinder from the recovery equipment, weigh the recovery cylinder (without the recovery equipment), and record the results in the bottom row of the "Recovery, Part b" table. Also weight the manifold/hoses and the compressor/hose individually before purging any of the recovery equipment. These masses will be needed later.
- Perform a post-recovery scale audit, record results in the "Recovery, Part c" table.

Distillation Process (separating the oil/lubricant from the recovered refrigerant):

- Directly connect the suction port of the recovery cylinder to the discharge port of the distillation cylinder <u>with the hose valve at the distillation cylinder end</u>, as shown in the following image:

- Heat the recovery cylinder to 105 °F using a heat gun or thermal blanket
- Slightly open the valve to each cylinder, striving to minimize flow rate (in order to minimize oil transfer)
- Monitor valves and increase opening as refrigerant transfers and flow rate diminishes
- When flow from the recovery cylinder to the distillation cylinder ceases, pressure has equilibrated.
- Close all valves.
- Weigh the recovery compressor and hose. Install the recovery compressor in series between the two cylinders, drawing from the recovery cylinder and discharging to the distillation cylinder, as shown in the following image:

- Open valves and turn on evacuation compressor, monitoring pressure until 20 kPa (abs) is achieved. Hold that vacuum for 10-minutes.
- Record pressure and temperature in the “Distillation, Part a” table
- Close valves, turn off evacuation compressor, remove the heater and disconnect the evacuated recovery cylinder from the evacuation compressor hose.
- Weigh the recovery cylinder with hose and without hose, recording the results in the appropriate cell in the “Distillation, Part a” table
- Weigh the recovery compressor with hose.
- Next, remove the recovery cylinder from the scale, and reinstall the heater on the recovery cylinder to achieve a temperature of 105°F.
- Install the vacuum pump to the recovery cylinder, as shown in the following image:



- Open the valve on the recovery cylinder, and further evacuate the cylinder with the vacuum pump, monitoring the pressure until 20 Pa (abs) is achieved.
- Record the system pressure and cylinder temperature in the “Distillation, Part a” table
- Close the cylinder valve, turn off the vacuum pump, remove the heater, and disconnect the evacuated recovery cylinder from the vacuum pump hose.
- Again, weigh the recovery cylinder, recording the mass in the appropriate cell in the “Distillation, Part a” table
- Calculate the mass of oil as the difference between initial evacuation mass (performed with the evacuation compressor to 20 kPa) and the final evacuation mass (performed with the vacuum pump to 20 Pa), and record the results in the table
- Copy the “Calculated mass of extracted refrigerant (grams):” for the last recovery performed from the “Recovery, Part b” table into the “Distillation, Part a” table.
- Calculate the “Mass of extracted refrigerant after distillation” by subtracting the mass of oil from the mass of extracted refrigerant just copied, write results in the last row of the “Distillation, Part a” table. Also make sure to account for the

refrigerant/oil left in the manifold/hoses and the compressor/hose. Use the ratio of refrigerant-to-oil from the recovery cylinder to calculate an estimate of the refrigerant in the manifold/hoses and the compressor/hose.

Recharge Process:

- Add the appropriate amount and type of oil to the vehicle's a/c system. The amount to use (in grams) was determined during the distillation process just performed. Convert the amount in grams to ounces by multiplying grams by 0.0376 to obtain ounces (assumptions of SG = 0.9, density of water = 0.998 g/cc). Add the oil, and record the results in the "Recharge, Part b" table.
- Perform a scale calibration / audit, recording results in the "Recharge, Part a" table.
- Review Section 2 (Vehicle / Equipment Information) to determine the manufacturer recommended charge and also any deviation as requested by the fleet manager. Using this info, determine and record the in the "Recharge, Part b" table the target charge.
- Obtain a charge cylinder with sufficient refrigerant to charge the system (without having to change a cylinder). Refrigerant should be new or recycled to acceptable standards.
- Ensure the total mass of the charge cylinder (including the refrigerant) is less than the maximum scale limit (50 lbs / 25 kg).
- Ensure the charge cylinder is heated with a thermal blanket and maintained at a temperature of 105°F, record temperature in the "Recharge, Part b" table.
- Install a quick disconnect (self-sealing or valve-actuated) T-fitting somewhere along the charge hose / service manifold circuit.
- All mass measurements will include the charge cylinder, thermal blanket, service manifold, T-fitting, charge hose, and low and high pressure service hoses (with connectors).
- Connect the service manifold and hoses to the charge cylinder (but don't yet connect them to the vehicle), keep the charge cylinder valve closed, open the high and low service valves, and connect the vacuum pump to the T fitting.
- Turn on the vacuum pump, open the T-fitting valve (if necessary) and leave the vacuum pump running until the service manifold and hose assembly reach a pressure of 20 Pa (abs).
- Close the low and high service valves on the service manifold, close the T-fitting valve (if necessary) and disconnect the vacuum pump from the T fitting.
- Weight the assembly (including the charge cylinder, thermal blanket, service manifold, T-fitting, charge hose, and low and high pressure service hoses with connectors). Do not include the vacuum pump, vacuum gauge (on pump) or hose from vacuum pump to the T-fitting in the weight.
- Record the mass of the assembly in the "Recharge, Part b" table ("Mass of Charge Cylinder assembly before recharge")
- Prepare the vehicle's a/c system for recharge according to appropriate ASE procedures, including evacuating the a/c system with the vacuum pump for a period of time to extract as much moisture from the system as possible.

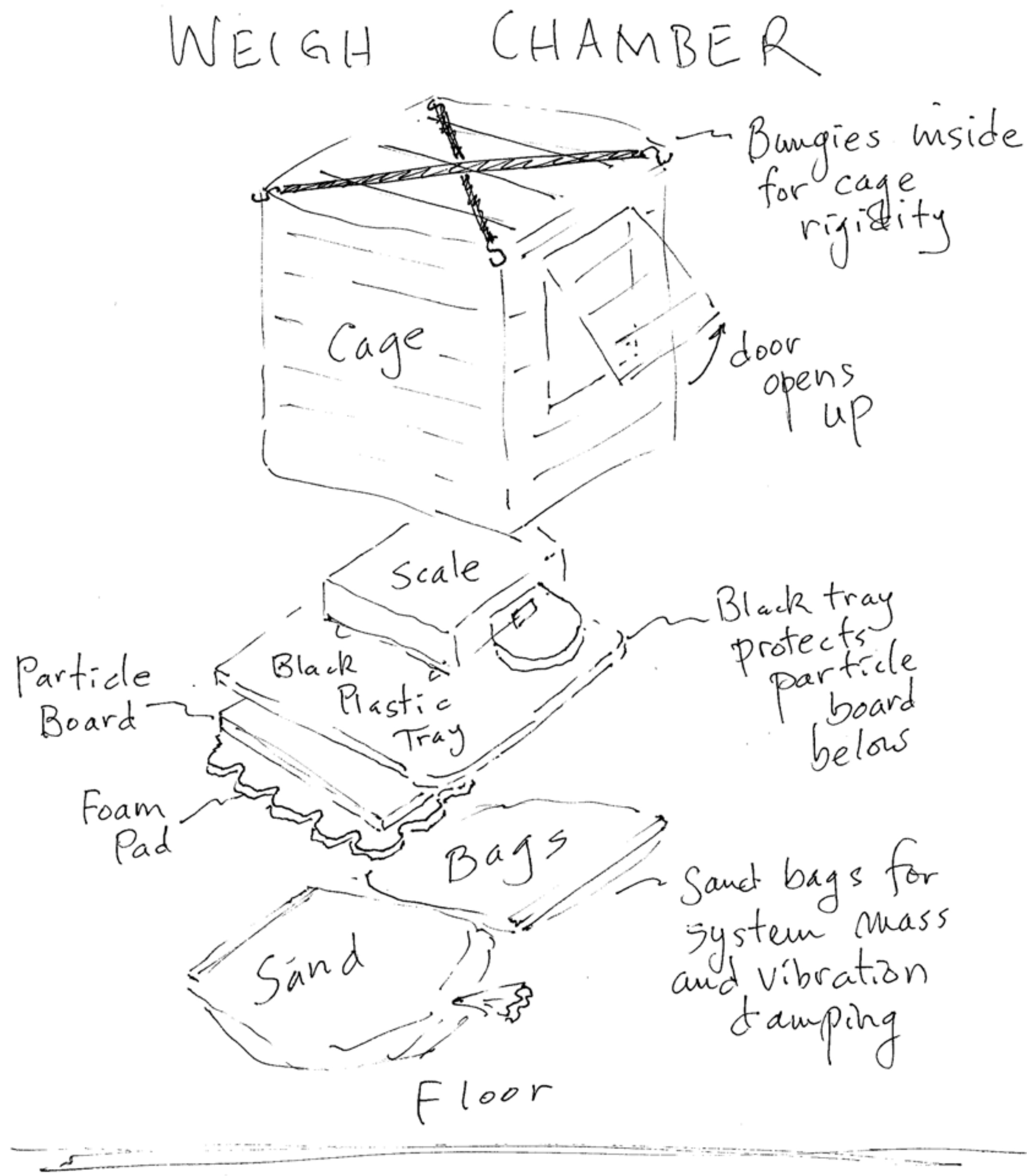
- Connect the high and low service manifold hoses to the vehicle's a/c system, and use ASE procedures to recharge the a/c system. Charge the system to the target mass by watching the display on the scale during the charge process.
- When the target mass is reached, close the charge cylinder valve, keeping the low pressure valve on the service manifold open in order to empty the manifold and hose system as much as possible (vehicle and a/c are running at this point)
- Close the low pressure valve on the service manifold (at this time, all valves are closed, but the service manifold and hoses are still connected to the a/c system)
- Measure and record system performance in the "Recharge, Part c" table (A/C functional stage)
- Disconnect the hoses from the vehicle, weight the assembly (including the charge cylinder, thermal blanket, service manifold, T-fitting, charge hose, and low and high pressure service hoses with connectors), and record results in the "Recharge, Part b" table
- Calculate the mass of R134a charged to the system and record in the "Recharge, Part b" table
- Record the ending time in the "Recharge, Part b" table
- Perform a post-recharge scale audit, record in the "Recharge, Part d" table
- Replace the dust caps on the a/c system service ports, and attach tags/labels near the high and low service ports of the a/c system stating: "ERG Study Vehicle - Please contact Andrew at 916-760-8474 before performing any AC service work".

<u>Final Test Process:</u>

The final test process is identical to the initial test process as previously described, with the obvious exception of removing the vehicle tagging at the end of the study. Prior to beginning testing, discuss with the fleet manager any performance issues that have been reported for the vehicle, and also discuss with the fleet manager any a/c service work that has been performed on the vehicle. Record results of the conversation with the fleet manager in Section 10 of the data collection form.

Record all final test results in Sections 11 through 17 of the data collection forms.

Schematic of Weigh Chamber



- Assemble in order above
- Wrap cage w/ tarp like a present but with front open for door. Clip.
- Put sand bag on top if necessary to hold cage steady

Appendix 2
Standard Data Collection Form

SECTION 1: OVERALL CONTACT INFORMATION (collected prior to initial test) (modified 2009 May 19)

******

START PREPING THE EQUIPMENT BEFORE FINDING VEHICLES, ETC. GET THE VEHICLE INFORMATION WHILE THE EQUIPMENT IS BEING VACUUMED OUT.

******

ERG Vehicle ID / Test ID:____

Date of initial vehicle selection:____

Name of Company / Fleet:____

Person to contact within company:____

Contact person's office number:____

Contact person's mobile number:____

Other contact information / notes:____

Address of Fleet:____

ERG MAC Testing address (if different):____________________________________

Vehicle identifier used by fleet to describe this vehicle:_________________________

Region where this vehicle / equipment is generally operated:____________________

____

Anticipated type and amount of usage (nonroad, offroad, highway, city, miles/yr, hrs/yr, etc)

____

____

License Plate (if any):____

Name of person who completed this page:___________________________________

SECTION 2: VEHICLE INFORMATION: (collected prior to initial test, much of this info may be provided by the fleet manager)

2a: Vehicle / Equipment Description:	
Equipment Type:	Compressor type (please circle): Electric (sealed), scroll, piston, other__________, unk
Manufacturer / Make:	A/C manufacturer:
Model:	Please circle: Factory Dealer Aftermarket Unknown
Model year:	A/C age (if aftermarket or dealer)___________years old
Engine Fuel Type:	Is system an R12 conversion? Yes No
Odometer (with units)	Mfr recommended MAC Capacity _______________ (lbs / kg)
Hour meter	Fleet mgr recommended MAC Capacity __________(lbs / kg)
Equipment VIN, PIN or serial number: ______________________________________ (please carefully photograph VIN label with camera set to "close-up")	# of service ports __________
	A/C system type: Orifice tube, Expansion valve
Equipment Comments:	Lubricant type: PAG POE / ester Other_______________

Summary of MAC Maintenance over Prior 2 years: (info provided by fleet manager)

SECTION 3: VEHICLE PREPARATION, INITIAL TEST
Vehicle Prep, Part a: Results of Sealant/Refrigerant Analysis:

Date:________________________

Type(s) of Refrigerant Detected:____

Results of sealant detection test:____

Note: if any system contamination is detected, vehicle must be rejected from study and replaced with an appropriate substitute

Please note below any pre-existing vehicle damage, document with photographs:

____

____

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____

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____

SECTION 4: RECOVERY SYSTEM PREP, INITIAL TEST

Recovery Prep, Part a, Pre-Recovery Scale Audit Results ("load" refers to full mass of system expected to be measured, including refrigerant, report to 0.1 g resolution)			
Date:________________________________		Time:________________________________	
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

Recovery Prep, Part b, Pressures and masses of recovery system prior to recovery	
Date:	Time:
5.1: Abs. Pressure of recovery cylinder after evacuation (Pa)	
5.2: Recovery Cylinder Initial (Empty) Mass (grams)	
5.3: Abs. Pressure of Recovery Equipment after evacuation (Pa)	
5.4: Recovery Cylinder & Equipment (Empty) Mass (weigh all together) (grams)	

System Component	Tare (before recovery) (g) A	After recovery (g) B	Difference (g) C
5.5: Compressor + hose			
5.6: Manifold + hoses			
5.7: Cylinder	5.2		
5.8: Total			

SECTION 5: RECOVERY PROCESS, INITIAL TEST

Recovery, Part a, Results of Preliminary A/C Functionality Test (perform after 12-hour soak in heated garage)	
Date:________________________________	Time:________________________________
"Soak" start date / time: ______________________	"Soak" end date / time: ______________________
AFTER SOAK, BEFORE STARTING ENGINE & A/C SYSTEM	
Ambient temperature ______________°F	Engine compartment temperature: ____________°F
High-side pressure:____________ PSI	Low-side pressure:____________ PSI
(Run engine at idle, windows open, A/C on, air on "fresh", blower on "max", run for 20 minutes) **AFTER 20 MINUTES OF ENGINE AND A/C OPERATION**	
High-side pressure max:____________ PSI	Engine Idle Speed (if available):
High-side pressure min:____________ PSI	Suction line temperature: ______________°F
Low-side pressure max:____________ PSI	Condenser temperature: ____________°F
Low-side pressure min:____________ PSI	Compressor temperature:_______________°F
	Air vent temperature:_______________°F
Below, please write down any noteworthy system characteristics such as abnormal pressure differential between high and low side, needle gauge flutter, or other signs that might indicate MAC problems.	

Recovery, Part b, Results of Recovery	1st Recovery	2nd Recovery	3rd Recovery	4th Recovery (if nec)
Beginning Time:				
Ending Time:				
7.3: Calculated Recovery Duration (minutes)				
7.4: System Abs. Pressure before recovery (kPa)	**N/A**			
7.5: System Abs. Pressure after recovery (kPa) (target = 20 kPa absolute or -81.3 kPa gauge)				
7.6: Recovery Cylinder & Equipment Mass (grams):				
7.7: Calculated mass of extracted refrigerant (grams): 7.6 - 5.4				
7.8: Calculated extraction mass flow rate (grams/minute): 7.7 / 7.3		**N/A**	**N/A**	**N/A**
7.9: Pre-recovery condenser temp °F	**N/A**			
7.10: Pre-recovery ambient temp °F	**N/A**			
7.11: Pre-recovery compressor temp °F	**N/A**			
7.12: Pre-recovery suction line temp °F	**N/A**			
7.13: Post-recovery condenser temp °F				
7.14: Post-recovery ambient temp °F				
7.15: Post-recovery compressor temp °F				
7.16: Post-recovery suction line temp °F				
7.17: Recovery Cylinder (without extraction equipment) Final (Full) Mass (grams): * Copy to page 8, line 2.				

NOTE: start heating recovery tank for evacuation and charge tank for charging the A/C system.

Recovery, Part c, Post-Recovery Scale Audit Results ("load" refers to full mass of system expected to be measured, including refrigerant, report to 0.1 g resolution)			
Date:______________________________		Time:______________________________	
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

SECTION 6: DISTILLATION PROCESS, INITIAL TEST

Distillation, Part a, Determination of Oil Collected During Recovery	
Date:________________________________	Time:________________
Mass of Compressor + hose before initial evacuation (g)	
Recovery Cylinder Final (Full) Mass (grams) (copy Recovery, Part b)	
Temperature of recovery cylinder during initial evacuation (F) measured near top	
Pressure of recovery cylinder after initial evacuation (kPa)	
Mass of Recovery Cylinder after initial evacuation to 20 kPa (grams)	(a)
Temperature of recovery cylinder during final evacuation (F)	
Pressure of recovery cylinder after final evacuation (Pa)	
Mass of Compressor + hose after initial evacuation (g)	
Mass of Recovery Cylinder after final evacuation to 20 Pa (grams)	(b)
Mass difference of compressor + hose (g). This is R134a & oil.	
Calculated Mass of oil (difference between initial evacuation mass of tank and final evacuation mass) (grams) (a - b from above)	(c)
Mass of extracted refrigerant before distillation (copy from the last recovery from the "Recovery, Part b" table)	(d)
Calculated Mass of extracted refrigerant after distillation (grams) (d - c)	
MAKE NOTES HERE ON HOW TO MAKE THIS BETTER. NEED TO ENTER MASSES BACK IN TABLE ON PG 5. TURN THIS INTO "A+B=C" FORMAT (LIKE IRS FORM). It's okay to estimate the mass of oil to replace before distillation so you can get started with recharging while you distill to find the true mass of oil.	

SECTION 7: RECHARGE PROCESS, INITIAL TEST

Recharge, Part a, Pre-Recharge Scale Audit Results ("load" refers to full mass of system expected to be measured, including refrigerant, report to 0.1 g resolution)			
Date:________________________________		Time:________________________________	
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

Recharge, Part b Recharge Results	
Start time:	
Amount of oil added to the a/c system (oz)	
Type of oil added to the a/c system:	
Target Charge for Vehicle (grams)	
Temperature of charge cylinder (°F)	
Mass of Charge Cylinder assembly before recharge (grams)	gauges + cylinder = total
Mass of Charge Cylinder assembly after recharge (grams)	
Calculated mass of R134a charged into system (grams)	
Ending Time:	

Recharge, Part c, Results of Recharge A/C Functionality Test (perform after recharge is completed. Run engine at idle, windows open, air on "fresh", blower on "max")	
Date:________________________________	Time:________________________________
High-side pressure max:____________ PSI	Engine Idle Speed (if available):
High-side pressure min:____________ PSI	Suction line temperature: ______________°F
Low-side pressure max:____________ PSI	Condenser temperature: ____________°F
Low-side pressure min:____________ PSI	Compressor temperature:_______________°F
Ambient temperature ______________°F	Air vent temperature:_______________°F
Below, please write down any noteworthy system characteristics such as abnormal pressure differential between high and low side, needle gauge flutter, or other signs that might indicate MAC problems.	

Recharge, Part d, Post-Recharge Scale Audit Results ("load" refers to full mass of system expected to be measured, including refrigerant, report to 0.1 g resolution)			
Date:___________________________		Time:___________________________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

SECTION 8: NOTES / COMMENTS, INITIAL TEST

SECTION 9: SUPPLEMENTAL SCALE AUDIT RESULTS, INITIAL TEST

Please recalibrate and audit the scale after any break in the test sequence, prior to resuming weighing

Where in the test process is this audit being conducted? (i.e., prior to initial recovery system prep, prior to final recovery process, etc.)**:**____

Date:________________________________		Time:________________________________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

Where in the test process is this audit being conducted? (i.e., prior to initial recovery system prep, prior to final recovery process, etc.)**:**____

Date:________________________________		Time:________________________________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

Where in the test process is this audit being conducted? (i.e., prior to initial recovery system prep, prior to final recovery process, etc.)**:**____

Date:________________________________		Time:________________________________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

SECTION 10: FLEET MANAGER INTERVIEW, FINAL TEST

Fleet mgr's description of performance issues, complaints______________________________

____

____

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____

____

Description of any A/C service that was performed: ______________________________

____

____

____

____

Was any refrigerant added to or removed from the system?: ______________________________

____

____

____

Region where this vehicle / equipment was generally operated:_______________________

____

Type and amount of actual usage (nonroad, offroad, highway, city, miles/yr, hrs/yr, etc)

____

____

SECTION 11: VEHICLE PREPARATION, FINAL TEST
Vehicle Prep, Part a: Results of Sealant/Refrigerant Analysis:

Date:_________________________

Type(s) of Refrigerant Detected:____

Results of sealant detection test: ____

Note: if any system contamination is detected, contact ERG manager before proceeding.

Please note below any vehicle damage, document with photographs:

____

____

____

____

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____

____

SECTION 12: RECOVERY SYSTEM PREP, FINAL TEST -- [RENAME?]

Recovery, Part a, Results of Preliminary A/C Functionality Test (perform after 12-hour soak in heated garage, run engine at idle, windows open, air on "fresh", blower on "max", run for 20 minutes and record the following info)	
Date:______________________________	Time:______________________________
"Soak" start date / time: ____________________	"Soak" end date / time: ____________________
AFTER SOAK, BEFORE STARTING ENGINE & A/C SYSTEM	
Ambient temperature _____________°F	Engine compartment temperature: ___________°F
High-side pressure:___________ PSI	Low-side pressure:___________ PSI
AFTER 20 MINUTES OF ENGINE AND A/C OPERATION	
High-side pressure max:___________ PSI	Engine Idle Speed (if available):
High-side pressure min:___________ PSI	Suction line temperature: _____________°F
Low-side pressure max:___________ PSI	Condenser temperature: ___________°F
Low-side pressure min:___________ PSI	Compressor temperature:______________°F
	Air vent temperature:______________°F
Below, please write down any noteworthy system characteristics such as abnormal pressure differential between high and low side, needle gauge flutter, or other signs that might indicate MAC problems.	

Recovery Prep, Part a, Pre-Recovery Scale Audit Results ("load" refers to full mass of system expected to be measured, including refrigerant, report to 0.1 g resolution)			
Date:______________________________		Time:______________________________	
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement (g)			
Second Measurement (g)			

Recovery Prep, Part b, Pressures and masses of recovery system prior to recovery	
Date:	Time:
Pressure of recovery cylinder after evacuation (Pa) (Target = 20 Pa absolute or -80 Pa gauge)	
Recovery Cylinder Initial (Empty) Mass (grams)	
Pressure of Recovery Equipment after evacuation (Pa)	
Recovery Cylinder and Equipment (Empty) Mass (grams)	

SECTION 13: RECOVERY PROCESS, FINAL TEST

Recovery, Part b, Results of Recovery	**1st Recovery**	**2nd Recovery**	**3rd Recovery**	**4th Recovery**
Beginning Time:				
Ending Time:				
Calculated Recovery Duration (minutes)				
System Pressure before recovery (kPa)	**N/A**			
System Pressure after recovery (kPa)				
Recovery Cylinder & Equipment Mass (grams):				
Calculated mass of extracted refrigerant (grams):				
Calculated extraction mass flow rate (grams/minute)		**N/A**	**N/A**	**N/A**
Pre-recovery condenser temp	**N/A**			
Pre-recovery ambient temp	**N/A**			
Pre-recovery compressor temp	**N/A**			
Pre-recovery suction line temp	**N/A**			
Post-recovery condenser temp				
Post-recovery ambient temp				
Post-recovery compressor temp				
Post-recovery suction line temp				
Recovery Cylinder (without extraction equipment) Final (Full) Mass (grams):				

Recovery, Part c, Post-Recovery Scale Audit Results ("load" refers to full mass of system expected to be measured, including refrigerant, report to 0.1 g resolution)			
Date:______________________________		Time:______________________________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

SECTION 14: DISTILLATION PROCESS, FINAL TEST

Distillation, Part a, Determination of Oil Collected During Recovery	
Date:_______________________________	Time:__________________
Recovery Cylinder Final (Full) Mass (grams) (copy Recovery, Part b)	
Temperature of recovery cylinder during initial evacuation (F)	
Pressure of recovery cylinder after initial evacuation (kPa)	
Mass of Recovery Cylinder after initial evacuation to 20 kPa (grams)	
Temperature of recovery cylinder during initial evacuation (F)	
Pressure of recovery cylinder after initial evacuation (Pa)	
Mass of Recovery Cylinder after final evacuation to 20 Pa (grams)	
Calculated Mass of oil (difference between initial evacuation mass and final evacuation mass) (grams)	
Mass of extracted refrigerant before distillation (copy from the last recovery from the "Recovery, Part b" table)	
Calculated Mass of extracted refrigerant after distillation (grams)	

SECTION 15: RECHARGE PROCESS, FINAL TEST

Recharge, Part a, Pre-Recharge Scale Audit Results ("load" refers to full mass of system expected to be measured, including refrigerant, report to 0.1 g resolution)			
Date:________________________________		Time:________________________________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)	226.8 (8 oz)	10,000	20,000
First Measurement(g)			
Second Measurement (g)			

Recharge, Part b Recharge Results	
Start time:	
Amount of oil added to the a/c system (oz)	
Type of oil added to the a/c system:	
Target Charge for Vehicle (grams)	
Temperature of charge cylinder (°F)	
Mass of Charge Cylinder assembly before recharge (grams)	
Mass of Charge Cylinder assembly after recharge (grams)	
Calculated mass of R134a charged into system (grams)	
Ending Time:	

Recharge, Part c, Results of Recharge A/C Functionality Test (perform after recharge is completed. Run engine at idle, windows open, air on "fresh", blower on "max")	
Date:________________________________	Time:________________________________
High-side pressure max:____________ PSI	Engine Idle Speed (if available):
High-side pressure min:____________ PSI	Suction line temperature: ______________°F
Low-side pressure max:____________ PSI	Condenser temperature: ____________°F
Low-side pressure min:____________ PSI	Compressor temperature:_______________°F
Ambient temperature ______________°F	Air vent temperature:_______________°F
Below, please write down any noteworthy system characteristics such as abnormal pressure differential between high and low side, needle gauge flutter, or other signs that might indicate MAC problems.	

Recharge, Part d, Post-Recharge Scale Audit Results ("load" refers to full mass of system expected to be measured, including refrigerant, report to 0.1 g resolution)			
Date:______________________________		Time:______________________________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)			
First Measurement(g)			
Second Measurement (g)			

SECTION 16: NOTES / COMMENTS, FINAL TEST

SECTION 17: SUPPLEMENTAL SCALE AUDIT RESULTS, FINAL TEST

Please recalibrate and audit the scale after any break in the test sequence, prior to resuming weighing

Where in the test process is this audit being conducted? (i.e., prior to initial recovery system prep, prior to final recovery process, etc.)**:**_______________			
Date:_______________		Time:_______________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)			
First Measurement(g)			
Second Measurement (g)			

Where in the test process is this audit being conducted? (i.e., prior to initial recovery system prep, prior to final recovery process, etc.)**:**_______________			
Date:_______________		Time:_______________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)			
First Measurement(g)			
Second Measurement (g)			

Where in the test process is this audit being conducted? (i.e., prior to initial recovery system prep, prior to final recovery process, etc.)**:**_______________			
Date:_______________		Time:_______________	
	Low Mass (5-10% full load)	Mid Mass (≅ 50% full load)	High Mass (≅ 110% full-load)
Calibration Weight (g)			
First Measurement(g)			
Second Measurement (g)			