Development of a Nonintrusive Refrigerant Charge Indicator

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ABSTRACT

The most common problem affecting residential and light commercial heating, ventilating, and air-conditioning (HVAC) systems is slow refrigerant leaks. Equipment users are usually not aware of a problem until most of the refrigerant has escaped. The concept of a nonintrusive refrigerant charge indicator was developed. The sensor, based on temperature measurements, appears to be inexpensive and easy to incorporate into existing heat pumps and air conditioners.

The design of the refrigerant charge indicator is based on the fact that when refrigerant starts to leak, the evaporator coil temperature starts to drop and the level of liquid subcooling drops. When the coil temperature or liquid subcooling drops below a preset reading, a signal can be activated to warn the equipment user that the system is undercharged. A further drop of coil temperature or liquid subcooling below another preset reading would trigger a second warning signal, such as a red warning light, to warn the equipment user that the unit now detects a leak and immediate action should be taken. The warning light cannot be turned off until it is re-set by a refrigeration repairman.

Temperature sensors are becoming very accurate and low in cost compared with pressure sensors. Using temperature sensors to detect refrigerant charge status is inherently nonintrusive, inexpensive, and accurate.

This paper provides laboratory test data on the change of indoor coil refrigerant temperature and subcooling as a function of refrigerant charge for a 2-ton off-the-shelf air conditioner and a 2-ton split heat pump system. The data can be used in designing the indicators for refrigerant loss.

INTRODUCTION

Despite advances made in the energy efficiency of systems used to heat, cool, and ventilate residential and commercial buildings in the United States, the primary energy consumption of these buildings continues to increase. From the period 1998 to 2000, primary energy consumption in residential buildings increased from 183 to 189 Mbtu/household; in commercial buildings, it increased from 251 to 254 kBtu/ft^2 (USDOE 1977). While much of this increase may be the result of growth in plug loads, it should be recognized that as plug loads increase, there is a corresponding increase in the energy needed for space conditioning (heating, ventilating, and air-conditioning, or HVAC), and it is, therefore, important to implement efficient HVAC equipment and keep it operating at design efficiencies. Efficient HVAC systems are available, and markets for them are growing; however, effective methods of making owners/occupants aware of decreases in system performance over the longer term are lacking. Even a poorly maintained HVAC system can continue to meet space conditioning loads, and often the occupant or building owner is unaware of a poorly performing unit. However, the operating efficiency of this poorly performing unit is decreased so that it consumes much more electrical energy than it did when it was first installed. The methods and means to ensure that the as-installed efficiencies of HVAC systems continue to be realized over the lifetime of the system are an area that has been generally ignored by the industry and by the user community. The fact that about 30% of peak electrical power consumption is due to HVAC equipment in buildings means that improvements in maintaining HVAC equipment at peak efficiency would have major benefits in terms of reduced national energy consumption.

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Refrigerant leak is the most common problem that causes chiller and air-conditioning systems to operate inefficiently. A real-time warning device for such problems in their early stages could warn equipment users to take action and thus save energy and reduce refrigerant leakage to the atmosphere. There is a need, in the continuous commissioning of HVAC equipment, for a simple, accurate, nonintrusive, low-cost device that can be integrated into all new air-conditioning and refrigeration equipment or retrofitted onto existing equipment for verifying the status of the refrigerant charge.

If equipment is undercharged because of a slow leak, capacity and efficiency may be greatly reduced, and the loss in efficiency could be 30% or more. However, most owners will not notice their air conditioners are not working properly until almost all the refrigerant has leaked out. Much of the difficulty stems from the time it takes to verify that the system is not properly charged, whether because the system was undercharged or because a leak has developed. An improper refrigerant charge is most obvious in window air conditioners, split-system air conditioners, and heat pumps for small buildings. A low-cost, nonintrusive charge indicator installed in the equipment has the potential to substantially reduce the impact of an improper charge by detecting it early, resulting in substantial energy savings. Environmental concerns associated with refrigerant leaking into the atmosphere will be mitigated as well.

The current technology for detecting a refrigerant undercharge or leak is to measure both the refrigerant liquid temperature and the suction superheat. Intrusion into the system is often required because refrigerant high-side and low-side pressure measurements are needed.

Traditionally, there are three types of refrigerant leak-detecting technologies: corona discharge, heated diode, and ultraviolet (UV). The corona discharge method uses an electric current to detect leaks. Anytime something crosses that current and breaks the current, it sounds an alarm, thus detecting the leak. This technology is relatively inexpensive and can be reliable depending on the conditions under which it is used. The drawback to this technology is that it can give false readings. Heated diode technology is more refrigerant sensitive. This technology uses a sensor that is looking for a specific type of refrigerant component to set off an alarm. A pump is required to draw in the substance and, because it is controlled by heat, there is a certain amount of time required for warm-up. Among advantages of this technology, it is more accurate and more refrigerant specific. Among disadvantages, it is quite expensive and there is additional time required for warm-up. The ultraviolet light method for detecting leaks requires a special lamp designed for using ultraviolet or black light that is looking for an oil-based dye that is highly active when the light shines on the dye. It is a compressor oil-based dye that is injected into an air-conditioning system and circulated through the system via operation. If a leak is present, the dye will mist through at that point. Among advantages of this type of leak detection are that even hard-to-find leaks will be noticeable and the dependability is better (there is no highly sophisticated technology to break down). Among disadvantages, injecting the dye can be sloppy and create false leak impressions, and not all the original equipment manufacturers (OEMs) have approved the leak-detecting dyes for use with their components.

The aforementioned technologies, however, are used only when the users of equipment already know a leak has been developed. There is no warning in the early stage of leaks. One nonintrusive technology has been proposed (Collins et al. 1997) for continuously monitoring the charge status. The technology was based on the dynamic measurement of the evaporator outlet refrigerant temperature and correlates strongly with charge level. It was claimed that the measurement correlated well with the clutch cycling behavior. This technology was specifically developed for automotive application.

The technology ORNL developed is to measure the two-phase refrigerant temperature of the evaporator coil (for window air conditioners) and/or measure the liquid refrigerant subcooling (for split air conditioners and heat pumps) (Mei et al. 2003). Because temperature measurement is accurate and relatively low in cost, this technology could potentially cut the cost of detecting leaks and undercharge and could be incorporated into existing HVAC diagnostic sensors to expand their sensing functions.

DEVELOPMENT OF A REFRIGERANT CHARGE INDICATOR

The principle for detecting the system refrigerant charge is simply to measure the indoor coil refrigerant two-phase temperature. When the system is properly charged, the coil temperature (in the two-phase region) will be maintained at around 45°F to 50°F for summer operation. When the indoor coil temperature drops below 40°F, for example, the system is likely undercharged or possibly leaking. When the coil temperature drops sufficiently, a warning signal automatically turns on to alert the equipment user that the system has a problem. When the coil temperature drops to below 30°F (a point where about 20% of the refrigerant has been lost for a window air conditioner), the system is likely leaking, and the cooling capacity also drops substantially. The system is operating very inefficiently at that point. Another warning signal comes on to alert the user that the equipment has a leak. Immediate attention will be needed at this stage before all the refrigerant leaks to the environment. This proof-of-concept has been successfully demonstrated on an off-the-shelf air conditioner in the laboratory.

However, for systems not sensitive to slow refrigerant leaks, such as systems with thermal expansion valves (TXV) or split units with long liquid lines, the traditional liquid subcooling measurement is a viable way. The measurement of the evaporator coil's two-phase refrigerant temperature will still work, except that when the two-phase refrigerant temperature starts dropping, the majority of refrigerant has already been lost.

Figure 1 shows the test results for the evaporator's two-phase refrigerant temperature as a function of the refrigerant

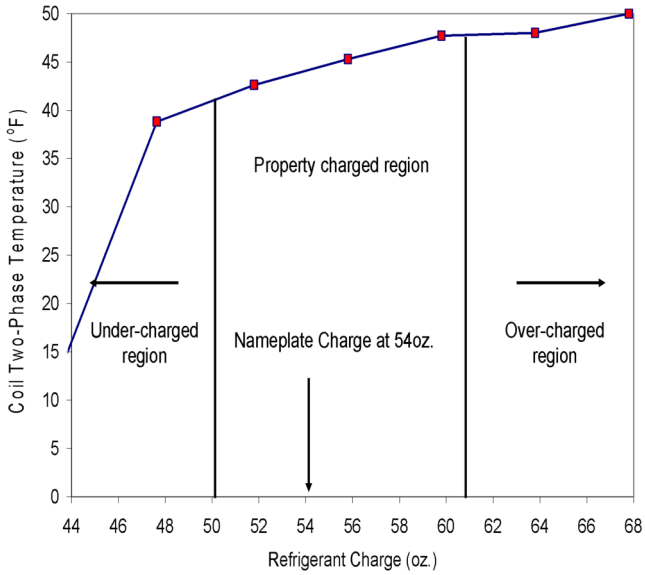

Figure 1 *R-22 charge versus evaporator coil temperature for an off-the-shelf air conditioner.*

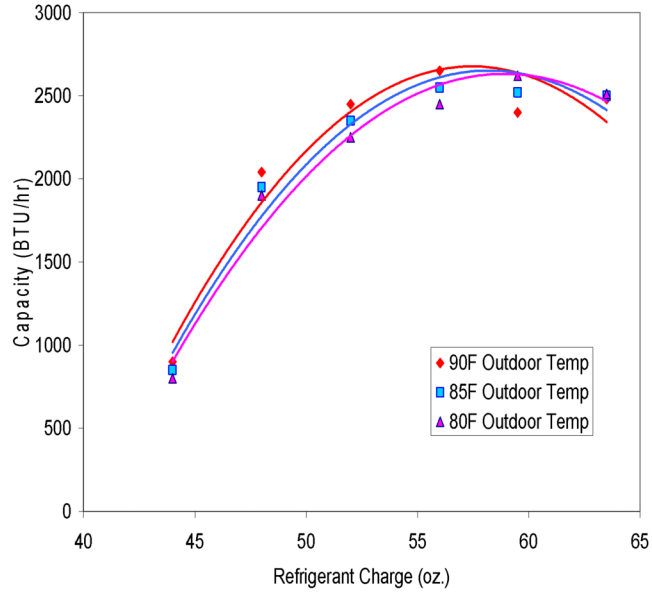

Figure 2 *Cooling capacity as a function of outdoor temperature and refrigerant charge.*

charge of an off-the-shelf air conditioner. Figure 2 shows the cooling capacity as a function of both the outdoor temperature and the refrigerant charge. Figure 2 also shows the importance for window air conditioners of keeping the proper refrigerant charge. A 20% leak will cause the cooling capacity to drop from 24,000 Btu/h to 10,000 Btu/h. In addition, it shows that the evaporator coil's two-phase refrigerant temperature is a strong function of the refrigerant charge and a weak function of the outdoor temperature. Additional test data on the same air conditioner indicate that the evaporator's two-phase refrigerant temperature is also a weak function of indoor air temperature. Therefore, there is a real possibility that the refrigerant charge status can be determined by measuring only one temperature (at the evaporator coil). Measuring both coil and ambient temperatures will improve the accuracy, and adding the indoor temperature will provide further improvement. Measuring pressures could be much more expensive, and the error is usually higher. Moreover, pressure measurements require penetration of the refrigeration circuit, opening up the potential for refrigerant leakage from what was a sealed, reliable system.

Based on the test data for the window air conditioner, an engineering refrigerant charge indicator was built and tested. Figure 3 shows the pre-prototype charge indicator. The indicator performed as expected; when the evaporator coil's two-phase refrigerant dropped to below a preset temperature, a warning light went on to indicate a low charge. A further drop of the coil temperature triggered another warning light, which indicated that the unit had a leak.

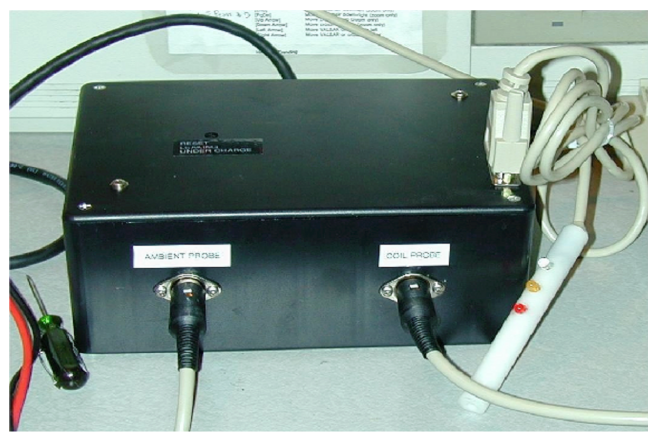

Figure 3 *Pre-prototype charge indicator with analog technology.*

On the other hand, split heat pump systems, because of their long liquid lines, are less sensitive to slow refrigerant leaks. Systems with TXVs are also insensitive to slow refrigerant leak. The coil temperature measurement approach will still work for these systems, as shown in Figure 4, but only when most of the refrigerant has already leaked out.

Figure 5 shows that even when the evaporator coil temperatures are constant; the liquid subcooling continues to drop when refrigerant leaks slowly. Measurement of the liquid subcooling can be used to determine the status of the system's refrigerant charge. It is anticipated that this approach can be used for heat pump heating mode operation, too.

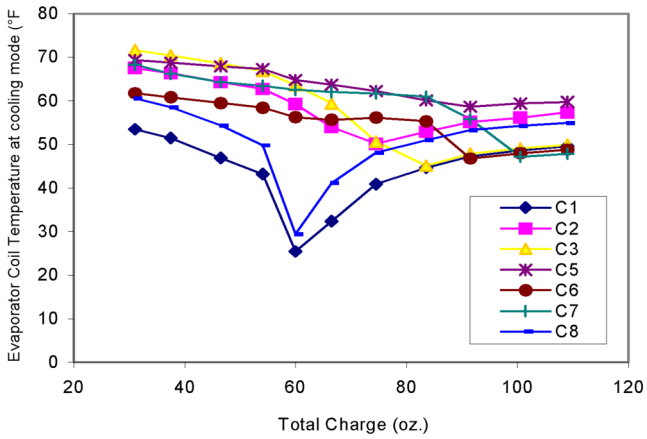

Figure 4 *A typical case of heat pump indoor coil temperature as a function of refrigerant charge in cooling mode with 82°F ambient, 800 cfm indoor airflow at 80°F and 52% RH. C1...C8 represent C section of coil (each evaporator has A, B, C, and D sections of coils).*

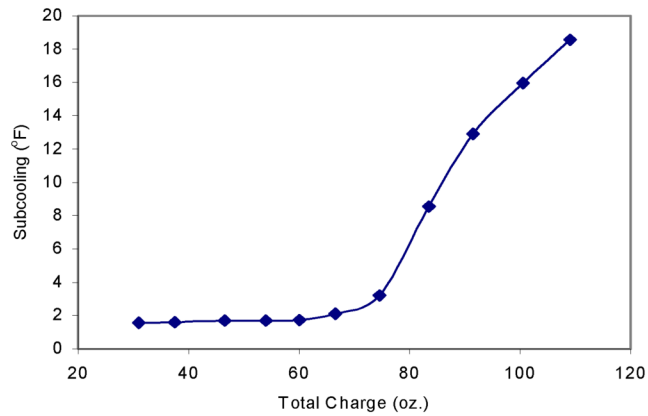

Figure 5 *A typical case of liquid subcooling as a function of refrigerant charge at 82°F ambient, 800 cfm, and indoor air at 80°F and 52% RH.*

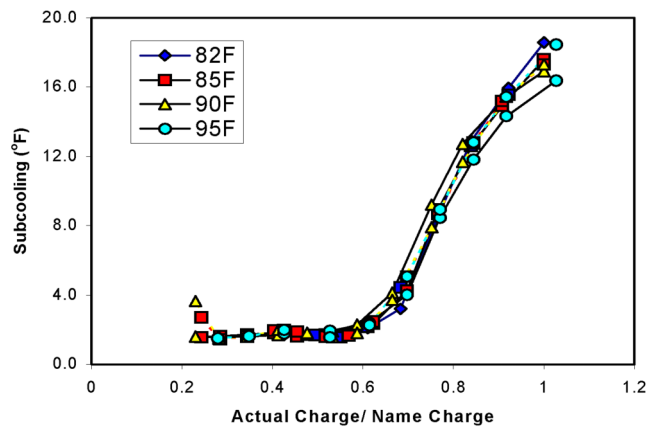

Figure 6 *Liquid subcooling as a function of refrigerant charge (orifice plate).*

HEAT PUMP LABORATORY TESTS

It is interesting to study the performance of an under-charged heat pump system. A 2-ton split heat pump system was tested. Both the indoor and the outdoor heat pump units have orifice plates as the expansion devices. However, the outdoor unit was later retrofitted with a thermal expansion valve (TXV) and tested again. The tests were performed with the refrigerant fully charged at the beginning and as baseline data. The refrigerant was slowly bled back into the tank to simulate a slow leak. The amount of refrigerant charge was used as the base of the system performance. Cooling and heating mode tests were performed.

Cooling Mode Tests

Indoor airflow rate was at 800 cfm and indoor dry-bulb temperature was 80°F. Outdoor ambient was at 82°F, 85°F, 90°F, and 95°F. The system was fully charged, 110 oz, at the beginning of the operation. The refrigerant was slowly drained back to the tank, 5 oz each time, until the coil temperatures, or subcooling, started to drop sharply. Each test drained about 70% of the charge.

Heating Mode Tests

1. Indoor airflow rate was 800 cfm and indoor dry-bulb temperature ws at 70°F.

   Outdoor ambient was at 47°F, 42°F, and 37°F.

2. The outdoor orifice plate was replaced with a 2-ton TXV and tested again.

TEST RESULTS AND DISCUSSION

Orifice Plate—Cooling Mode Operation

Figure 6 shows liquid subcooling as a function of refrigerant charge at various ambient temperatures with indoor conditions maintained at 80ºF and 52% relative humidity. It is clear that the liquid subcooling kept dropping even when the coil temperatures were maintained at a normal operating level (see Figure 4). It is evident that split heat pump systems, because of the long liquid lines, should use liquid subcooling to indicate their charging status. It is interesting to note that liquid subcooling is a strong function of refrigerant charge but a weak function of ambient temperature. Further tests indicated that it is also a weak function of indoor air temperature.

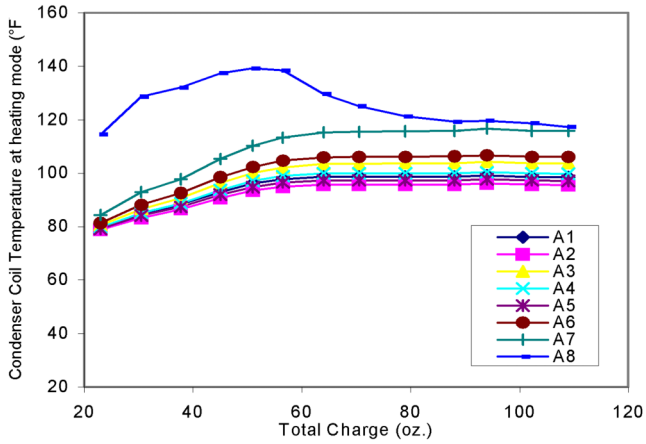

Figure 7 *Condensation coil temperature (section A coil) as a function of refrigerant charge at 47°F ambient (A1...A8 represent "U" bends at "A" section of coil; each evaporator has A, B, C, and D sections of coils.*

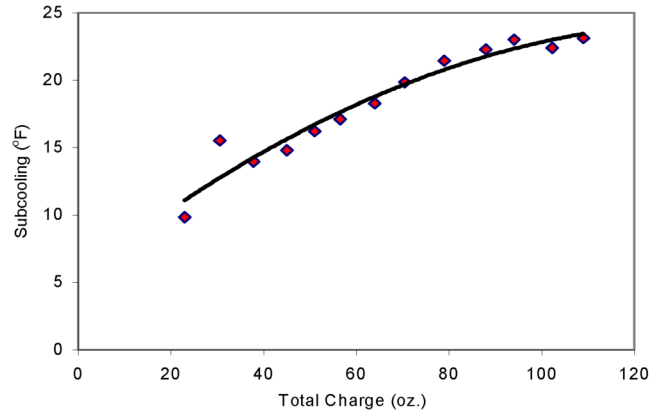

Figure 8 *Liquid subcooling as a function of refrigerant charge at 47°F ambient.*

The steep drop of liquid subcooling is a good indication of refrigerant loss. When the subcooling drops to 8°F to 9°F, a slow leak has likely been developed.

Orifice Plate—Heating Mode Operation

Figure 7 shows typical test data with coil temperatures. Clearly the system performance was not affected by the refrigerant leak until 25% of the charge had leaked out, and then other parts of the coil dried out and the temperature of one coil, which still has refrigerant in it, started increasing. This was not surprising because the system was overcharged to start with for heating mode operation. Figure 8 shows a typical liquid subcooling measurement as a function of ambient temperature and refrigerant charge. At low refrigerant level, the heat pump performance became unstable because of frost accumulation on the outdoor coil. As in cooling mode operation, the effect of ambient temperatures is relatively small.

Liquid subcooling measurement for heating mode operation is less sensitive to refrigerant loss, compared with cooling mode operation, because the system is charged for cooling mode operation, which is overcharged for heating mode operation to start with. However, it is still viable to indicate refrigerant loss. The accuracy of liquid subcooling measurement is becoming important, as only a 2°F drop in liquid subcooling could mean the loss of 20% or more of refrigerant, as shown in Figure 8.

Outdoor Coil with a Thermal Expansion Valve

The heat pump was modified with a TXV as the outdoor coil expansion device for tests in heating mode. Systems with TXVs can tolerate a higher level of refrigerant loss and still perform well. The only way to measure the refrigerant loss is to measure the liquid subcooling because subcooling is a function of charge regardless of the amount of refrigerant loss. Only the outdoor coil was retrofitted with a TXV to replace the original orifice plate expansion device. Figure 9 shows typical liquid subcooling measurements as a function of refrigerant charge at different outdoor ambient temperatures. Again, it is a strong function of refrigerant charge and a weak function of outdoor ambient temperature.

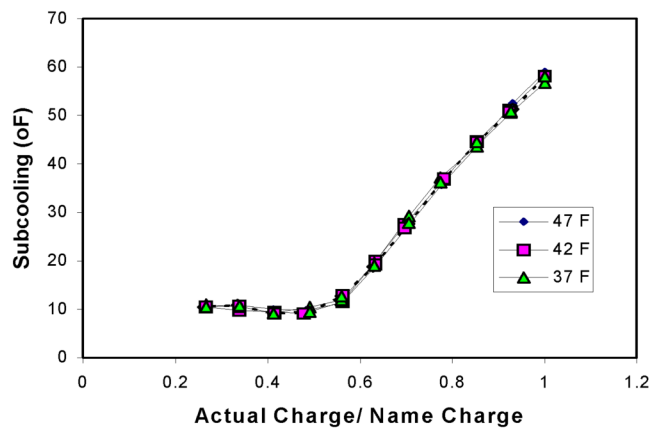

Figure 9 *Typical heating mode operation with a TXV on outdoor coil.*

CONCLUSIONS

A slow refrigerant leak is the most common problem associated with malfunction of an air-conditioning and refrigerating system. A low refrigerant charge could result in energy efficiency degradation of 30% or more. The traditional way of checking the refrigerant charge status of a system involves

measuring high-side and low-side pressures, along with ambient temperature. It requires the use of pressure gauges and at least one temperature sensor. However, most owners or users of HVAC equipment do not have the knowledge to interpret the results of the measurements, even if they have the proper measuring tools.

A method of checking a refrigerating or air-conditioning system refrigerant charge status by temperature measurements was conceived to resolve these issues. Temperature measurements are accurate, easy to implement, and inexpensive. The test data in this study prove that the concept of developing a refrigerant charge indicator by measuring temperatures on the heat exchanger coil is viable.

The data presented in this paper can be used to design a low-cost charge indicator with one or two warning lights. A pre-prototype charge indicator was developed, based on test data for a window air conditioner presented in this report. The indicator will send out a signal to the owner or user of the equipment that the system is at proper charge or at low charge or that a leak has developed. The indicator can send out a second warning signal that the system requires immediate service because the refrigerant charge is dangerously low. This approach can help the owner/user ensure that the system is always charged properly and operated at optimum system efficiency. The charge indicator will also be friendly to the environment because prompt repair action will reduce the leakage of refrigerant to the surrounding environment to a minimum. Most important, this method will not require that equipment owners be knowledgeable about equipment operation.

REFERENCES

Collins, C.D., N.R. Miller, and W.E. Dunn. 1997. An investigation of the feasibility of refrigerant charge loss detection using low cost measurements. SAE paper #970106, Society of Automotive Engineers, Inc.

Mei, V.C., F.C. Chen, and Z. Gao. 2003. Development of refrigerant charge indicator and dirty air filter sensor. ORNL/CON-489 report, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

USDOE. 1997. A look at residential energy consumption in 1997. DOE/EIA-0632 (97) report, Energy Information Administration, U.S. Department of Energy.