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ABSTRACT

Vapor compression systems continuously leak a small fraction of their refrigerant charge to the environment, whether during operation or servicing. As a result of the slow leak rate occurring during operation, the refrigerant charge decreases until the system is serviced and recharged. This charge degradation, after a certain limit, begins to have a detrimental effect on system capacity, energy consumption, and coefficient of performance (COP). This paper presents a literature review and a summary of previous experimental work on the effect of undercharging or charge degradation of different vapor compression systems, especially those without a receiver. These systems include residential air conditioning and heat pump systems utilizing different components and refrigerants, and water chiller systems. Most of these studies show similar trends for the effect of charge degradation on system performance. However, it is found that although much experimental work exists on the effect of charge degradation on system performance, no correlation or comparison between charge degradation and system performance yet exists. Thus, based on the literature review, three different correlations that characterize the effect of charge on system capacity and energy consumption are developed for different systems as follows: one for air-conditioning systems, one for vapor compression water-to-water chiller systems, and one for heat pumps. These correlations can be implemented in vapor compression cycle simulation tools to obtain a better prediction of the system performance throughout its lifetime. In this paper, these correlations are implemented in an open source tool for life cycle climate performance (LCCP) based design of vapor compression systems. The LCCP of a residential air-source heat pump is evaluated using the tool and the effect of charge degradation on the results is studied. The heat pump is simulated using a validated component-based vapor compression system model and the LCCP results obtained using the three charge degradation correlations are compared.

1. INTRODUCTION

Every vapor compression system has an optimum refrigerant charge at which it achieves its designed peak performance. Over time, as the system is operated, a portion of this charge, up to 30% in supermarket refrigeration systems, leaks out of the system annually. This refrigerant leak causes a drop in system capacity, rated energy consumption, and COP. In order to restore the system's optimum performance, the vapor compression system is charged during servicing. However, in some cases, charging during servicing can lead to overcharging or undercharging of the system, both of which cause a drop in system performance. Therefore, it is important to study the effect of charge degradation or undercharging of vapor compression systems on system performance and its subsequent negative environmental impact.

The first part of this paper presents a literature review of previous experimental work on the undercharging and charge degradation of different vapor compression systems, especially those without a receiver. Since there is no current correlation for the effect of charge degradation on the performance of vapor compression systems, the second part of the paper presents the development of three such correlations for different systems, based on the studies presented in the literature review. Finally, these correlations are implemented in an open source tool for LCCP based design of vapor compression systems to determine the effect of charge degradation on the vapor compression system's environmental impact.

2. LITERATURE REVIEW

A limited number of studies reporting the effect of charge degradation on vapor compression refrigeration system performance can be found in the literature. The systems investigated include residential and mobile air conditioning, heat pumps (including air-to-air and water-to-water), and water chiller systems as well as walk-in coolers and freezers. While the focus of this paper is on residential air conditioning, all of the available charge degradation studies were investigated in order to obtain pertinent data related to charge degradation and system performance.

In 1976, the Trane Company tested an eight year old residential air conditioner which had a 10% reduction in its charge (Trane Co., 1976). They found that the efficiency of this system was 20% lower than that of a system with the optimum charge. Domingorena (1978) tested a low cost, three ton, air-to-air, split-system residential heat pump using R-22 as the refrigerant in the heating mode. The tested system had no accumulator and used a capillary tube as the expansion device. Domingorena concluded that the system performance was highly sensitive to refrigerant undercharging while being almost insensitive to refrigerant overcharging. Furthermore, system COP and capacity were found to decrease almost linearly with a decrease in the system charge. Subsequently, Domingorena and Ball (1980) tested a similar three ton, air-to-air, split-system residential heat pump using R-22 as the refrigerant in the heating mode. However, this unit had an orifice-type refrigerant flow control and one accumulator in the refrigerant suction line. Domingorena and Ball varied the charge from 63% to 127% of the rated charge while maintaining the outdoor and indoor air dry bulb temperatures at approximately 283 K and 294 K, respectively. Based on their work, it was found that using the accumulator in the second system helped to maintain the COP of the system at its rated value for more charge reduction (around 20%) as compared to the low cost system which had no accumulator. Moreover, the accumulator helped to limit the increase in superheat that is caused by the charge reduction in the system.

A 1.5 ton split high efficiency air conditioning system was tested by Houcek and Thedford (1984) under steady state operating conditions for 23% undercharging and overcharging of the system at different outdoor temperatures ranging from 294 K to 311 K. They found that for the undercharging conditions, the capacity dropped by 23% at 301 K and 34% at 308 K. They also found that overcharging of the system caused an increase in the system's energy efficiency ratio (EER) while undercharging caused a decrease in the EER. However, the authors note that overcharging of the system caused an increase in the energy consumption as well as compressor flooding, which reduces the life expectancy of the compressor since it is not designed to pump liquid refrigerant. It was noted that increasing the ambient temperature amplifies the negative effect of charge reduction on system performance.

Farzad and O'Neal (1988) studied the effect of improper charging on the capacity, EER, energy consumption, seasonal EER (SEER), and COP of a residential three ton Trane air conditioner with capillary tube expansion and no accumulator during steady state and cyclic operation. The system was tested for an overcharging and undercharging of 5% to 25% as well as four outdoor temperatures (301 K, 305 K, 308 K, and 311 K). Similar to the previous studies, they found that the total capacity, EER, and SEER were more sensitive to undercharging than overcharging conditions. Farzad (1990) then extended the analysis to compare the effect of refrigerant charging on the performance of the system for three expansion devices (capillary tube, thermal expansion valve (TXV), and short-tube orifice). The study was done for charge increments from -20% to +20% of the full charge and at outdoor dry bulb temperatures from 301 K to 311 K. Farzad concluded that the system using a capillary tube was more sensitive to the off-design charging than the system using either the TXV or the short-tube orifice. However, for the tested charge range, the performance of the system with the TXV and the short tube orifice was strongly dependent on the outdoor air temperature. These results agree with the results from Domingorena (1978) and Domingorena and Ball (1980), since the system with the accumulator in the latter also had an orifice expansion system which would be another reason that it handled up to 20% reduction in the charge before the COP started to decrease. Similar trends were obtained when this study (Farzad, 1990) was extended by Robinson (1993) to compare the performance of three blends of R-134a and R-32 with the performance of R-22 under off-design charging conditions and three different orifice diameters. Furthermore, Rodriguez (1995) extended the same study (Farzad, 1990) on the two systems using the short tube orifice and the TXV, to include outdoor temperatures up to 322 K and charge levels from -40% to +30% of the rated charge. The extended study showed that a charge reduction of more than 20% caused a sharp decrease in system capacity and EER while overcharging the system by more than 20% did not have much impact on system performance.

The performance of a 70-ton helical rotary screw, dual circuit, air-cooled chiller, utilizing R-22, and operating over a range of refrigerant charge from -60% to +15% of the nominal charge was studied by Bailey (1998). The author concluded that the chiller power per ton of refrigerating capacity is directly proportional to the outdoor air temperature and the refrigerant charge level.

Goswami et al. (2001) tested a 3 ton high-efficiency split residential air conditioning system with an orifice expansion device and using R-22 for charge reduction down to 50% of the optimum charge at an outdoor temperature of 308 K. They found that for a 10% reduction in charge, the capacity decreases by 3.5% while the COP increases by 2%. This increase in COP doesn't match the expected trend based on previous studies which can be due to uncertainty in the measurements. However, beyond a 20% undercharging the system capacity and COP drops sharply and ice starts to form on the evaporator coil because of the very low refrigerant temperature coming out from the expansion valve.

Choi and Kim (2002) compared the performance of a 3.5 ton water-to-water heat pump using an electronic expansion valve (EEV) and a capillary tube while varying the charge from -20% to +20% of the full charge in steady state, cooling mode operation. Similar to previous studies for the TXV and orifice tube, the performance of the system using the EEV was almost insensitive to the change in charge in the tested range while it was sensitive to the outdoor conditions. On the other hand, the performance of the system using the capillary tube was sensitive to both the charge and outdoor conditions with the capacity and COP decreasing for both undercharging and overcharging. Grace et al. (2005) investigated the performance of a small 1.14 ton (4 kW) nominal cooling capacity vapor compression water-to-water chiller equipped with plate type heat exchangers at charge levels ranging from 50% to 140% of the full charge. The refrigerant was R-404A and the system used a TXV as the expansion device. The authors found that the charge degradation had a slight effect on the system performance in the charge range from 75% to 125%. Further reduction in the charge caused a sharp drop in the system performance and at 50% charge reduction, the cooling capacity reaches 50% of its nominal value. A similar trend was observed by Kruse and Palmiter (2006) who tested a 3-ton economy model heat pump using R-22 refrigerant, suction-line accumulator in heating mode only with a charge range from 70% to 130% of the rated charge. Their measurements were performed with two different expansion devices: a short-tube orifice and a TXV and at 3 ambient temperatures (265 K, 275 K, and 281K). Furthermore, Shen et al. (2011), performed 150 steady-state performance tests, 18 cyclic tests, and 18 defrost tests on the same system and provided more detailed data on the effect of charge degradation on the system performance at indoor airflow rates ranging from 60% to 150% of the rated airflow rate.

Wichman and Braun (2008) studied the effect of charge degradation on vapor compression systems used for walk-in coolers and freezers. R-22 and R-404A were used as the refrigerants in the cooler and the freezer, respectively. Both systems were equipped with a TXV and a liquid line receiver. Similar to the other vapor compression systems reported above, it was found that a TXV helped to maintain system performance until the charge reached 80% of its nominal value. A further decrease in charge caused a sharp decrease in the capacity, reaching 75% of the rated capacity at 50% of the charge. Kim and Braun (2010) performed an extensive study on six different residential air conditioning systems with different components and utilizing two different refrigerants (R-22 and R-410A) at different outdoor temperatures. The study included units tested in the laboratory and using some data obtained from manufacturers. They concluded that for systems with a fixed expansion orifice (FXO), the accumulator had little impact on the charge degradation effect on the capacity. As for the systems using the TXV, they found that below a charge limit of 70% of the nominal charge, the TXV starts to operate similar to the FXO as the TXV becomes wide open.

Finally, Huyghe (2011) presented a study on the impact of low system charge on a mobile air conditioning system used in a mid-size sedan. The system utilized a TXV as the expansion device and it was tested using two refrigerants: R-134a and R-1234yf. Huyghe found that, in general, the system performance began to significantly decrease when the refrigerant charge dropped below 70% of the nominal charge.

To sum up, various experimental studies have been done on different types of vapor compression systems to determine the effect of undercharging (down to -75%) or overcharging (up to +50%) on their performance. The systems investigated include residential and mobile air conditioning, heat pumps (including air-to-air and water-to-water), and water chiller systems as well as walk-in coolers and freezers. The primary refrigerants tested include R-22 (most common), R-134a, R-32, R-404A, R-1234yf, and R-410A. The general trends observed with a drop in the system's charge include a decrease in system capacity, COP, and energy consumption, as well as an increase in the system's superheat. Three main factors were found to affect the sensitivity of system performance relative to charge degradation. These factors include the ambient temperature, whether or not an accumulator is used, and the type of expansion device used in the system. As for the latter, the common expansion devices tested and compared are the capillary tube, orifice device, TXV, and EEV. Systems with a capillary tube are very sensitive to a decrease in refrigerant charge, as opposed to the other three types of expansion devices which withstand some decrease in charge (in some cases up to 30%) before a decrease in system performance begins to be noticeable. The comparison between systems with and without an accumulator confirms that the accumulator helps to maintain the system performance at its rated value for a charge reduction of up to 20%. On the other hand, the ambient temperature affects the sensitivity of the system to the charge degradation for all systems and expansion devices used. Although many experimental studies were performed to determine the effect of charge degradation on the performance of different vapor compression systems, no correlation exists in literature that can be used to predict the performance of a vapor compression system at different charge values without doing an entire system simulation. Thus, in the following section, several correlations will be developed to predict the performance of a vapor compression system at different charge values based on the information presented in the studies discussed above.

3. CORRELATION DEVELOPMENT

As concluded from the literature review, there are three factors that affect the sensitivity of vapor compression system performance to the change in refrigerant charge, including the ambient temperature, whether or not an accumulator is used, and the type expansion device used in the system. The latter two factors affect the charge degradation limit below which charge degradation will begin to affect the system performance. However, different studies presented shows that below this charge limit, the charge degradation effect starts to have the same trend with some slight differences. Furthermore, since it was found that ambient temperature affects the sensitivity of the system to charge degradation regardless of system configuration, its effect must be included in the correlations. Hence, the correlations developed in this paper will predict system capacity and power fractions (ratio of the capacity and power to full capacity and power, respectively) in terms of the charge fraction and the ambient dry bulb temperature.

By analyzing the data obtained from the literature, it can be found that, in general, the trends for the effect of charge degradation on system capacity, COP, or rated energy consumption fit well to a second degree polynomial. This curve fit applies only to that portion of the data where the effect of charge degradation is noticed (i.e. after the charge limit where there is slight or no change in the system performance with change in charge). By accounting for the effect of the ambient temperature, the proposed charge degradation correlation takes the following form:

$$z = a + b*x + c*y + d*x^2 + f*y^2 + g*x*y \qquad (1)$$

where *z* is the fraction of capacity, rated energy consumption, or COP; *x* is the ambient temperature in K; *y* is the charge fraction; and *a, b, c, d, f* and *g* are curve fit coefficients.

Table 1 gives correlation coefficients for three system types (heat pump, water-to-water chiller and air conditioner) based on data obtained from some of the experimental work presented in the literature.

Table 1: Charge degradation correlation coefficients for capacity (C) and power (P)

Correlation	System / Expansion Device		a	b	c	d	e	f
Shen et al. (2011)	Heat Pump / TXV	C	-1.62E+0	1.68E-2	6.07E-1	-3.22E-5	-3.16E-1	5.02E-4
		P	8.42E-1	3.21E-3	-6.18E-1	-1.10E-5	-4.80E-2	2.81E-3
Grace et al (2005)	Water to water chiller / TXV	C	2.33E-4	3.56E-2	-1.27E+1	-1.27E-4	-1.57E+0	5.38E-2
		P	2.00E-5	3.06E-3	1.31E+0	-8.14E-7	-9.28E-2	-3.43E-3
Farzad and O'Neal (1988)	Air Conditioning / Capillary Tube	C	-2.83E+1	1.26E-1	1.78E+1	-1.48E-4	-3.95E+0	-3.05E-2
		P	-1.38E+0	-1.26E-2	8.41E+0	4.95E-5	-1.35E+0	-1.79E-2

Fig. 1 shows a comparison of the charge degradation correlation (Eqn. 1) to data from Grace et al. (2005) for the effect of the charge degradation on system COP at two different ambient temperatures. The dashed lines represent the COP predicted by the correlation while the solid lines are the experimental data from Grace et al (2005). It can be seen that the correlation fits the data well at both ambient temperatures. The calculated R-squared value for this fit is 0.997 and the average percentage difference between the actual and fitted COP values is 0.45%.

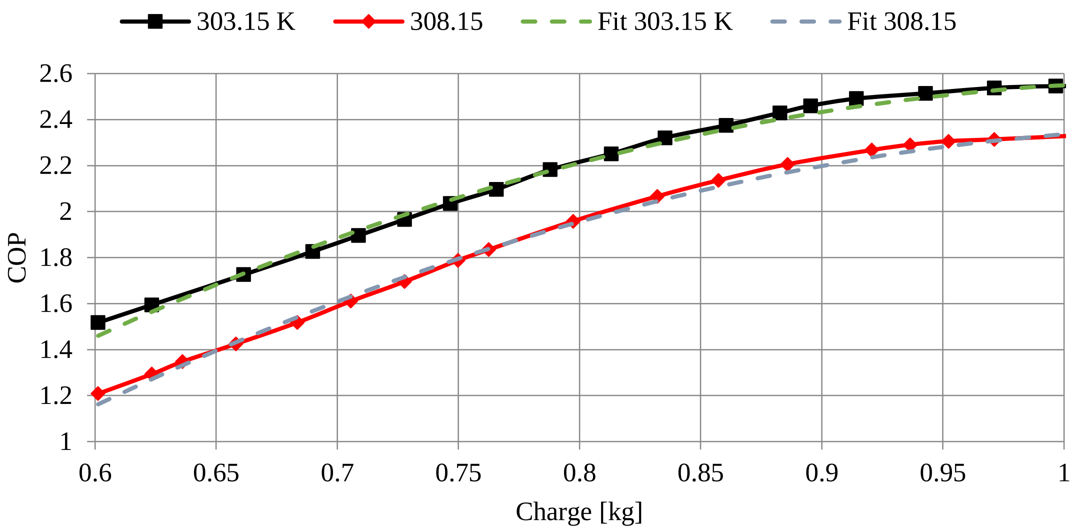

Figure 1: Comparison of experimental and correlated charge degradation data at different indoor temperatures

Fig. 2 shows the comparison between the three correlations in terms of the rated energy consumption fraction as a function of the charge fraction at 310 K. It is worth noting that for the Grace et al (2005) correlation, the charge limit (the level that the charge must be reduced to before system performance is affected as a percentage of the nominal charge) is 75% (Grace, et al., 2005). It can be seen that the Farzad and O'Neal (1988) correlation has a sharper drop in the rated energy consumption (similar trend for capacity and COP) with the charge reduction as it is developed for systems using capillary tubes.

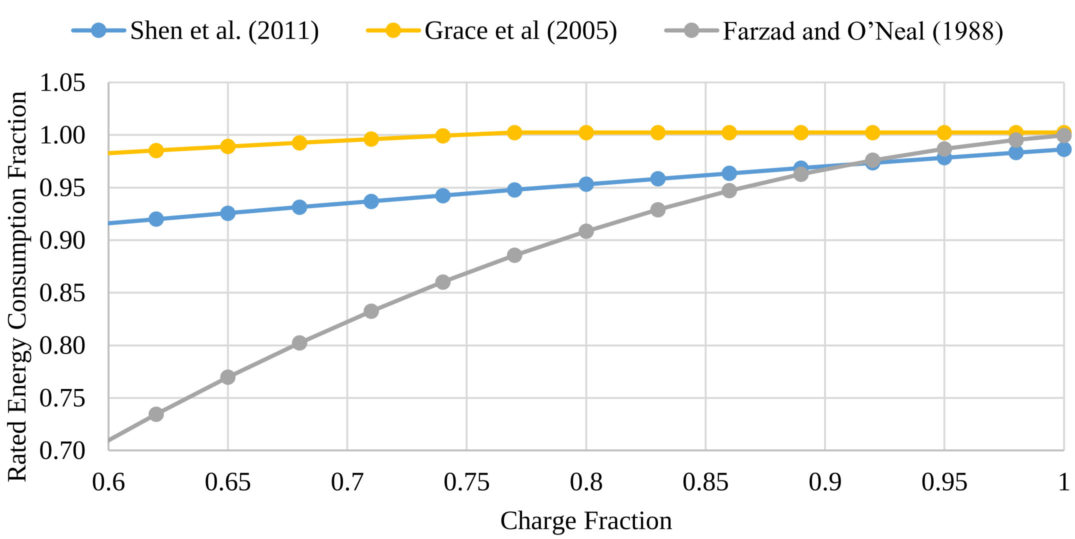

Figure 2: Comparison of the three correlations on energy consumption prediction

4. LCCP ANALYSIS

The aim of this section of the paper is to determine the effect of charge degradation on the annual energy consumption and, in turn, the environmental impact of a vapor compression system. The system investigated is a residential air-source heat pump system similar to the system experimentally tested in the AHRI low GWP AREP report #20 (Alabdulkarem, et al., 2013). The system was modeled in Chicago, IL and uses R-410A as the baseline refrigerant with a system charge of 4.54 kg. An open source modular life cycle climate performance (LCCP) based evaluation and design tool is used for the LCCP calculations (ORNL, and UMCP, 2013). The AHRI standard 210/240 (2008) is used for hourly load calculations. An in-house vapor compression system simulation tool (Winkler, et al., 2008), validated against the experimental data in the AHRI low GWP AREP report #20 (Alabdulkarem, et al., 2013), is used in the LCCP tool to perform energy consumption calculations.

The charge degradation is accounted for in the LCCP tool during the hourly energy consumption calculations. This will be based on the prescribed slow annual refrigerant leak rate, the charge limit (i.e. fraction) after which the charge degradation will begin to have an effect on system performance, and the two correlations for the capacity and power fractions in terms of the charge fraction and ambient dry bulb temperature. That is, when running the cycle, the LCCP tool runs the system simulation tool just once and then performs the charge degradation calculations on the outputs. The charge decreases by an amount equal to the annual slow leak rate based on the nominal charge for every year (e.g. if charge is 100 kg and leakage rate is 5%, then after the first year the charge is 95 kg, and after the second year it is 90 kg, and so on) until servicing is performed (at that point charge is restored to 100 kg). This is repeated over the lifetime of the system.

Fig. 3 shows the total indirect emissions and annual electrical energy consumption of the system when no charge degradation correlation is applied, as well as when each of the correlations given in Table 1 is used to account for the charge degradation. It can be seen that the energy consumption calculated using the Shen et al. (2011) correlation is slightly less than that when no correction is applied. However, the opposite behavior occurs with the other two correlations, with the Farzad and O'Neal (1988) correlation giving the highest energy consumption. It can be seen in Fig. 2 that the Farzad and O'Neal (1988) correlation has the highest sensitivity of energy consumption to charge reduction. The effect of the charge degradation on the LCCP results can be explained as follows. As the system charge decreases, the system's capacity, rated energy consumption, and COP decrease. When the load is lower than the system capacity, energy consumption, which is equal to the load divided by the system's COP, will increase. On the other hand, when the load is larger than the system's capacity, only rated capacity is delivered and thus the system's rated energy consumption will decrease with the charge reduction as discussed earlier. Thus, depending on the number of hours when the load will exceed the capacity and depending on the selected correlation, the annual energy consumption will either increase or slightly decrease.

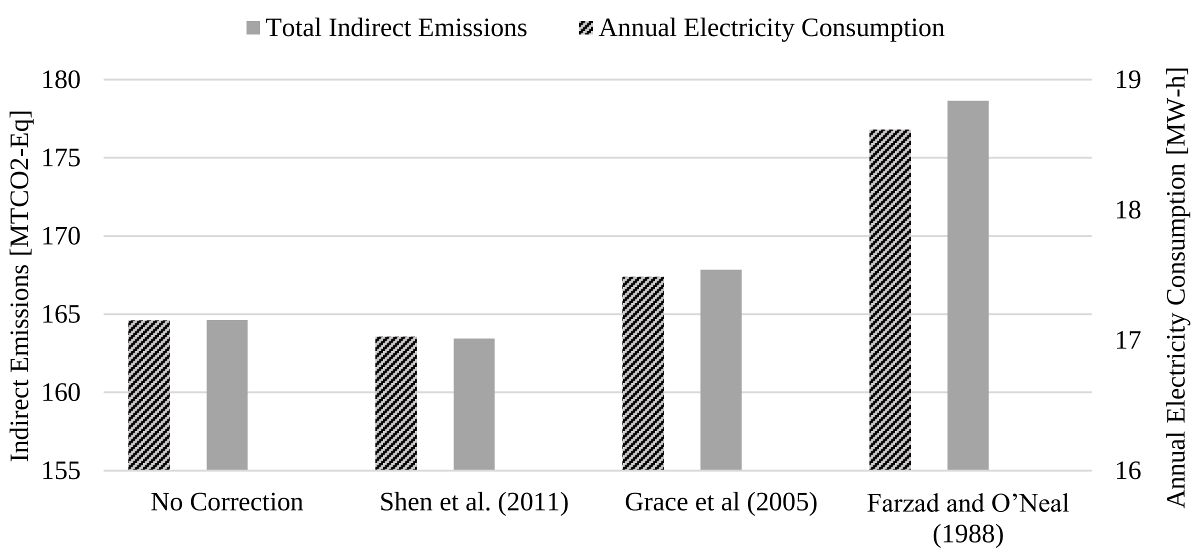

Figure 3: Indirect emissions and annual electricity consumption of the system

5. CONCLUSION

Previous experimental work investigating the effect of charge degradation on the performance of different vapor compression systems was reviewed. It was found that three main factors affect the sensitivity of system performance relative to refrigerant charge: the ambient temperature, whether or not an accumulator is used, and the type of expansion device. Three correlations for the capacity and rated energy consumption fractions as a function of charge fraction and ambient temperature were presented for three system types (heat pump, water-to-water chiller and air conditioner). These three charge degradation correlations were used in conjunction with an LCCP evaluation and design tool to analyze the effects of charge degradation on the performance of a residential air-source heat pump. It was found that the Farzad and O'Neal (1988) correlation gives the highest energy consumption since it was developed for systems with a capillary tube which causes higher drop in the system performance with the charge degradation.

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Supporting Information Available

The LCCP tool used in this analysis is available free of charge via the internet at: http://lccp.umd.edu/ornllccp/

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