STATEWIDE MEASURE PERFORMANCE STUDY
Final Report
An Assessment of Relative Technical Degradation Rates

Submitted To:

California Statewide Persistence Subcommittee

CADMAC

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Executive Summary

The Statewide Measure Performance Study is a project, sponsored by the CADMAC subcommittee on persistence, which examined the relative technical degradation of thirteen major DSM measures compared to the standard efficiency equipment which they replace. The project did not involve collecting new data, but instead focused on assessing existing information. There were two primary stages of work. The first stage involved performing an exhaustive search for existing information from published and unpublished sources and synthesizing this information into an engineering analysis of technical degradation rates. The second stage of the project involved developing research plans for assessing relative technical degradation for those measures where substantial uncertainty was found in stage one. This report provides the findings from both stages of the project.

Prior interim technical memos summarizing the work in each stage of the project were reviewed by the CADMAC subcommittee and this final report incorporates much of the feedback from project review meetings as well as formal comments submitted by some of the concerned parties.

Stage 1 - Degradation Analysis Findings

Proctor Engineering Group (PEG) and team members Energy Investment, Inc., and the Energy Systems Laboratory at Texas A&M University conducted a broad search for information concerning the relative technical degradation of the 13 DSM measures. The data collection process included the use of in-house expertise and resources combined with a broad literature search utilizing journal and periodical indexes, internet search facilities, and fee-based on-line search services. The project team also spoke with numerous manufacturers, industry associations, utilities, government agencies, national laboratories, and researchers.

As expected, existing data on performance changes over time were very limited. However, PEG was able to utilize the information that was available to develop a systematic engineering analysis of technical degradation for each measure. The goal of the engineering analysis was to identify, understand, and quantify the underlying mechanisms of technical degradation for each measure. PEG utilized this approach to estimate degradation rates and/or identify key uncertainties for each of the measures. The results of this analysis are summarized in Table 1.

The engineering analysis found that relative degradation is very unlikely for ten of the thirteen measures. Indeed, some measures (residential air conditioners and refrigerators) are likely to degrade less than their standard efficiency counterparts, resulting in increasing savings over time, or “negative” degradation. In one case, HID lighting, a small and quantifiable degradation was found. In three cases (occupancy sensors, optical reflectors, and adjustable speed drives), the potential degradation mechanisms were considered related to measure retention and further investigation would be best performed via retention studies. In two cases (commercial package air conditioners and oversized evaporative cooled condensers), the first stage analysis found that potentially significant relative technical degradation could occur and therefore research plans were developed to collect additional information.

While few measures were found to suffer from relative degradation, many measures are likely to experience absolute degradation (i.e. decreases in efficiency over time). In particular: air conditioners, refrigerators, fryers, and insulation may all suffer from absolute technical degradation. However, this degradation tends to lead to stable or increasing savings over time relative to the standard measure.

Table 1. Summary of Findings

Efficiency Measure	Baseline Technology	Relative Degradation
Residential Central A/C - high efficiency.	Standard SEER A/C	none or negative
Commercial A/C - Package DX	Standard efficiency unit	some possible
Oversized evaporative cooled condenser	Air cooled condenser	much possible
Refrigerator 10-30% better than std.	Standard efficiency refrigerator	none or negative
Electronic Ballast	Efficient magnetic ballast	none
T8 with electronic ballast	T12 w/efficient magnetic ballast.	none
Optical Reflector, delamp	Standard fixture	none (energy), some (light)
HID interior Metal Halide 250-400W	Mercury vapor 400-1000W	very little (<5%)
Occupancy Sensor	On/off switch	some possible, retention issues
Motor - high efficiency	Standard efficiency motor	none
Adjustable Speed Drive for HVAC Fan	Variable inlet vanes or dampers	none, retention issues
Infra-red Gas Fryer	Standard atmospheric fryer	unlikely
Residential ceiling insulation	Standard levels attic insulation	none

Stage 2 - Research Plans

Research plans for assessing relative degradation for the two measures identified in stage 1 were designed to balance the need to develop reliable answers in a reasonable time frame while not expending more effort than the answers are likely to be worth. The plans focus on assessing particular technical degradation mechanisms which were identified during stage 1. The research designs are adaptive, in that the results of early phases of the research may affect the level of, or need for, future phases. This approach was taken because of the unique nature of these projects and the associated uncertainty in the variances of the data being collected.

The air conditioner plan involves two stages. In the first stage, laboratory testing will be used to simulate a variety of heat exchanger fouling scenarios and measure performance impacts. This testing may find that no relative degradation will occur, and the research will be complete. If the testing indicates that a small amount of relative degradation may occur, then the involved parties may be able to agree to default estimates of degradation factors, avoiding more costly research. If the testing indicates that large relative degradation may occur, then a model which relates measurable fouling parameters to system efficiency will be developed and field testing will be used to collect data needed to quantify the relative degradation rate.

The evaporative cooled condenser plan involves a relatively large number of brief site visits to characterize the population and typical field conditions (including a visual assessment of fouling/scaling) with more intensive site testing and modeling of a selected sub-sample of these sites. A combination of test data, population characteristics, and engineering simulations will be used to quantify relative degradation.

Installation, Operation, Maintenance and Retention Issues

The performance and useful life of most efficient and baseline measures depends upon installation, operation, and maintenance (O&M) practices. The influences of these factors were included within this study to the extent that they were found to affect relative changes in measure performance over time. The scope of this study involved examining how performance may change over time *after* a measure is installed. Therefore, installation problems are only accounted for to the extent that they may lead to continuing performance changes over time. The immediate impacts of any initial installation defects are assumed to be accounted for in first year impact studies.

In most cases, the efficient and baseline measures are very similar and no relative degradation from installation or O&M practices should occur if they receive comparable attention. In some cases, the efficient measure is believed to be more tolerant of poor practices. In the case of reflectors, maintenance issues may affect light output, but not energy savings. For occupancy detectors, dust build-up may lead to occupants changing control settings or over-riding the system. For adjustable speed drives, operators may over-ride the system or adjust settings which compromise savings. For each of these three measures, the CADMAC subcommittee determined that these issues should be addressed through retention studies. For the two measures which need additional research, maintenance practices were identified as a key factor in degradation and are incorporated within the research plan.

Conclusions and Next Steps

The project results are quite encouraging. The analytical approach developed and employed in this study has proven to be quite successful in providing strong conclusions concerning relative technical degradation rates, even though empirical data were limited. Because of this success, the CADMAC subcommittee requested that PEG review lists of additional measures in order to assess the likely time and effort needed to perform a similar analysis on some of the major remaining measures. Many opportunities were found for leveraging the results of this project to help assess degradation rates. For example, some of the measures which would benefit from this study include other HID lighting applications, residential freezers, many other commercial gas cooking appliances, and insulation measures in all sectors. In addition, the current findings could be used to assess future year design variations in the measures covered.

1. Introduction

The objective of the Statewide Measure Performance Study was to estimate the changes in energy savings which may occur over time due to the relative technical degradation of energy efficiency measures compared to the standard measures which they replace. The study did not involve collecting new data, but was based on identifying, acquiring, and analyzing available data. As described in the project research plan, if currently existing data could be used to reliably assess net changes in performance for a particular measure, then the analysis and conclusions would be thoroughly documented. If existing data were insufficient for drawing reliable conclusions, then plans for future research would be developed for how to collect and analyze such data. This report provides the results from both stages of the project.

The data collection plan included an exhaustive search of available studies, papers and reports along with extensive efforts to locate unpublished “gray” literature from researchers and manufacturers. The information collected through these sources was used to develop an engineering framework designed to assess measure performance over time. The project research plan involved employing a combination of statistical and engineering analysis techniques as appropriate to maximize the value of existing information and develop reliable estimates of technical degradation rates and their associated uncertainties. For technologies where this analysis indicated large uncertainty in relative degradation, targeted research plans were developed to minimize this uncertainty as quickly, inexpensively, and reliably as possible.

1.1 Project Research Objectives

The Statewide Measure Performance Study is part of a multi-faceted approach to estimating the persistence of energy savings from DSM programs in California. This study focuses on one aspect of the persistence of savings -- Technical Degradation. Other aspects of savings persistence such as measure life, measure retention, and market effects are being examined through a number of other studies and projects. The general research question which this study is designed to help answer is:

> *How will DSM program savings be affected over time by changes in the technical performance of efficient measures compared to the standard measures they replace?*

More specifically, the project seeks to quantify the annual changes in energy savings which can be expected over the effective lives of specific measures due to any differences in the technical degradation rates of the efficient measures compared to the baseline measures.

The focus of the project is on longitudinal changes in the energy usage associated with the measures. The analysis timeframe is from the period covered by the first year impact evaluation (defining the base level of performance) through the end of the measure’s useful lifetime (as determined in the California evaluation protocols or by another CADMAC study). Changes in energy usage which are due to operating conditions, product design or human interaction are included within the scope of the project. Types of degradation which do not affect energy usage, but only level of service are discussed where applicable but are not the focus of this project and have not been subject to the same level of research and analysis.

1.2 Study Measures

Measures were selected for inclusion in this project by the sponsoring utilities on the CADMAC subcommittee based on the measures' contribution to overall DSM program resource value. The final list of efficient and baseline technologies selected for the study are shown in Table 2.

Table 2. Study Measures

Efficiency Measure	Baseline Technology
Residential Central A/C - high efficiency.	Standard SEER A/C
Commercial A/C - Package DX	Standard efficiency unit
Oversized evaporative cooled condenser	Air cooled condenser
Refrigerator 10-30% better than std.	Standard efficiency refrigerator
Electronic Ballast	Efficient magnetic ballast
T8 with electronic ballast	T12 w/efficient magnetic ballast.
Optical Reflector, delamp	Standard fixture
HID interior Metal Halide 250-400W	Mercury vapor 400-1000W
Occupancy Sensor	On/off switch
Motor - high efficiency	Standard efficiency motors
Adjustable Speed Drive for HVAC Fan	Variable inlet vanes or damper
Infra-red Gas Fryer	Standard atmospheric fryer
Residential ceiling insulation	Standard levels attic insulation

Several of the measures encompass a wide variety of specific products with differing characteristics. For example, higher efficiency air conditioner designs may involve changes to evaporators, condensers, compressors, refrigerant metering devices, and fans. In order to focus the research on the most applicable design characteristics, considerable effort was expended to identify the particular products that were most representative of the California market. In some instances, PEG had to acquire and analyze program databases to calculate market shares for specific products and then interview dealers and distributors to identify comparable baseline products.

1.3 Data Collection

The project team sought all available information concerning performance degradation characteristics of the measures. The data collection process included identifying and utilizing in-house expertise, published and unpublished reports and studies, manufacturers' literature and product specifications, and data sets available at our firms. A general literature search was carried out utilizing journal and periodical indexes, internet search facilities, and fee-based on-line database search services. The project team also spoke with numerous manufacturers, industry associations, utilities, government agencies, national laboratories, and researchers. Specific data collection activities are described further for each measure. As expected, existing empirical data on performance changes over time was limited for most measures.

1.4 Analytical Approach

The overall analytical approach to this project is based on the assumption that there would be little data available concerning measure degradation and that any available data was likely to represent only certain measures or technologies, operating conditions, and time frames. To help overcome the lack of available data, PEG performed a systematic engineering analysis of technical degradation for each measure to act as an analytical framework for the project. (A more detailed description of the approach is contained in the project research plan.)

The goal of the engineering analysis was to identify, understand, and quantify the underlying mechanisms of technical degradation for each measure. Once the physical causes for changes in performance of a measure are understood, then existing information can be fully and appropriately utilized in assessing any technical degradation. The analysis plan involved employing a combination of engineering and statistical techniques to estimate degradation rates and / or identify key uncertainties. PEG also anticipated that engineering analysis alone may be able to determine or put bounds on degradation rates for some measures.

If the result of the above process indicated substantial uncertainty, then the engineering analysis would be utilized to help develop optimal research and sampling plans for estimating relative performance changes. By identifying the key performance factors and sources of uncertainty, the analysis would allow these plans to focus on just one or two factors which are amenable to quick laboratory tests or simple spot measurements over time instead of expensive long-term monitoring.

1.5 Findings

The findings from the literature search and engineering analysis are provided in detail in section 2 of this report. Brief summaries of these findings are also provided for each measure in Appendix A.

1.6 Installation, Operation, Maintenance and Retention Issues

The performance and useful life of most efficient and baseline measures depends upon installation, operation, and maintenance practices. These factors were included within this study to the extent that they were found to influence relative changes in measure performance over time. For example, if an air conditioner is improperly installed, any reduction in its initial efficiency is not within the scope of this project but should instead be captured in a first year impact study. However, if installation defects lead to continuing declines in efficiency over time, then those effects are within the scope of this project.

The potential impacts and interactions of operation and maintenance practices with measure performance were considered in the analysis of relative degradation. In most cases, the efficient and baseline measures are essentially two variations on the same equipment and therefore maintenance requirements are identical or very similar (e.g., lamps, ballasts, air conditioners, motors, refrigerators, fryers, insulation). The degradation analysis assumes that maintenance would be comparable for such comparable products. In a number of cases, the efficient version of the measure is believed to be more tolerant of poor practices or adverse conditions. However, for commercial package air conditioners, maintenance issues were identified as a key aspect of potential relative degradation.

For several measures, the efficient and baseline technologies are very different and require differing maintenance and operating procedures (e.g., evaporative vs. air cooled condensers, reflectors, occupancy sensors, adjustable speed drives). These differences were considered in the degradation analysis. In the case of evaporatively cooled condensers, maintenance is a key issue and a focus of the research plan. In the case of reflectors, maintenance issues may affect light output, but not energy savings. For occupancy detectors, dust build-up may lead to occupants changing control settings or over-riding the system. For adjustable speed drives, operators may over-ride the system or adjust settings which compromise savings. For each of these three measures, the CADMAC subcommittee determined that these issues should be addressed through retention studies.

The retention issues briefly described above are discussed further under each measure in this report and should be communicated to any parties performing retention studies on these measures. In particular, retention studies for reflectors need to measure light output, studies for occupancy detectors need to record control settings, and studies for adjustable speed drives need to examine control settings and sensor calibrations.

1.7 Conclusions and Next Steps

The project results are quite encouraging. The analytical approach developed and employed in this study has proven to be quite successful in providing strong conclusions concerning relative technical degradation rates, even though empirical data were very limited. Because of this success, the CADMAC subcommittee requested that PEG review lists of additional measures in order to assess the likely time and effort needed to perform a similar analysis on some of the major remaining measures. Many opportunities were found for leveraging the results of this project to help assess degradation rates. In particular, the current study findings would be useful in developing degradation assessments of:

- residential freezers and newer designs of residential refrigerators;
- additional types, wattages, and applications of HID lighting;
- other residential, commercial and industrial applications of insulation;
- other commercial gas cooking appliances; and,
- other small residential and commercial air conditioning systems.

In addition, the current findings could be used to assess future year design variations in the measures covered. More detailed results of this measure review and leveraging assessments were provided in a separate memo to the CADMAC subcommittee.

2. Analysis of Relative Technical Degradation

This section provides the detailed findings from PEG's analysis of relative degradation. Appendix A provides a brief summary of these findings for each measure.

2.1 Air Conditioners D/X - Residential and Commercial

The baseline residential air conditioner was defined as a "builder's model" with a SEER of 10. The high efficiency units are defined as having a SEER of 11 or higher. The commercial air conditioners are package units divided into three size categories corresponding to federal minimum efficiency classes. Baseline smaller capacity (<=5 tons) units have a SEER 10 rating, medium size units (6-12 tons) have an EER of 8.9, and larger units (13-20 tons) have an EER of 8.5. The efficient commercial units have efficiencies of at least SEER 11, EER 9.2, and EER 8.9 respectively. Because of the many design variations and potential approaches for improving air conditioner performance, PEG focused on the most common baseline and high efficiency units. Databases of rebated air conditioner makes and models were analyzed to identify market leading units. In addition, distributors and manufacturers were contacted to confirm this analysis and identify the most popular standard efficiency models. Product specifications were acquired for the units to identify design differences.

For residential units, SEER 12 units dominated. The most consistent design modification to achieve high efficiency was a dramatic increase in the condenser face area. This improvement was usually accompanied by slightly increased condenser air flow and reduced fan power. The most popular units coupled this with a scroll compressor. Other units incorporated increased evaporator face area and fins per inch, and used TXV instead of fixed orifice refrigerant metering. For commercial package units, face area increases tended to be smaller (due to cost and design considerations). Carrier increased the number of condenser rows and both Carrier and Trane increased the number of evaporator rows in most units. Condenser fan flows tended to stay about the same. Carrier used scroll compressors in some of the small and mid-sized units.

The first data collection efforts on air conditioner degradation focused on locating any direct measurements of overall system efficiency over time. Manufacturers stated that they generally perform no performance degradation tests and that any accelerated aging and / or long-term tests are only used to establish system reliability, not efficiency. A contact at ARI stated that they tested a clean, well maintained unit over seven years and found that efficiency declined by less than 1% early in the test due to oxide film on the condenser and then remained constant. No long term studies of air conditioner field performance were found in the literature or through research contacts. Therefore efforts concentrated on performance degradation of system components with a particular focus on the design differences between the standard and efficient units. The primary potential sources of system performance degradation were identified as evaporator and condenser fouling, compressor efficiency degradation, and refrigerant charge changes caused by leaks or mischarging by service personnel.

2.1.1 Heat Exchangers

The predominant design modification for higher efficiency air conditioners is increased heat exchanger effectiveness through greater overall heat exchange area. Air cooled heat exchangers are widely known to be subject to degradation due to fouling of the coils.

Evaporator coils are subject to dust, particulates, and vapors from the indoor environment, most of which will pass through or around a typical filter (20-30% particulate arrestance). The coils tend to trap particulates because of the tight fin spacing and the "sticky" nature of both the coil (due to condensation) and the indoor air (cooking and / or tobacco smoke). The rate of dust build up will depend on the amount of air passing through the coil; the indoor environment; the amount and environment of return duct leakage; the filter design, location (filter grille vs. at air handler cabinet) and maintenance; and the coil fin spacing, geometry, and number of rows. The dust may load throughout the coil providing an insulating layer over the fins, or it may primarily build up on the face, reducing the effective coil size. The impacts of this fouling are reduced air flow through the coil and a reduced heat transfer coefficient. These changes will reduce system capacity while also reducing indoor fan power draw and compressor power draw. The overall efficiency is reduced because capacity is reduced at a greater rate than power draw, but connected load will tend to decrease from evaporator fouling.

Condenser coils are exposed to the outdoor environment and are subject to fouling from dust and dirt much like evaporator coils. On residential units, condenser coils are also exposed to common yard debris such as grass clippings and may be located near clothes dryer exhaust. In general, the coil fin spacing is tighter than on the evaporator but the surfaces are less sticky (i.e., they are dry and generally subject to fewer aerosols such as smoke and grease). Condensers are also subject to corrosion from salt and pollution which can be a substantial problem in coastal areas (manufacturers tend to use special anti-corrosion coatings or materials to minimize corrosion). Condensers are generally more accessible and therefore easier to maintain than evaporator coils, but field experiences indicate that such maintenance is rarely performed. Condenser coils may also suffer from reduced air flow over time due to growth of surrounding plantings. A dirty condenser coil will increase compressor power draw and slightly reduce outdoor fan power draw. The overall effect is to reduce system capacity and efficiency while increasing power draw.

Specific information on rates of fouling and impacts on overall system efficiency were sought through the literature search and contacts with manufacturers and researchers. Little empirical data or theoretical analyses were found.

Manufacturers stated that they perform no tests of heat exchanger fouling. In addition, they noted that there are no standards for testing conditions (e.g., dust levels) and so results would be difficult to interpret. The information located on air conditioner heat exchanger fouling includes:

- Two ASHRAE papers on indoor coil fouling were published by an engineer from Honeywell, which makes electrostatic air cleaners (Krafthefer et al. 1986 and 1987). The analysis estimated that typical levels of dust will cause coil pressure drops to double in about 7.4 years (at 3167 hours per year of operation) and reduce system efficiency by 20% over that time frame. Higher and lower assumed dust levels change the time for this degradation to about 5 and 10 years respectively. The analysis was based on limited empirical data concerning dust levels in houses, filter and coil particulate arrestance rates, and a heat pump simulation model. The general approach is sound, but the specific assumptions are questionable, particularly the high estimated particulate arrestance rates for the coils (40%-78%) and fairly high dust levels (.05-.2 mg/m^3).

- A study by Oak Ridge National Labs used computer simulations of air conditioner performance under a variety of conditions representing dirty evaporators, condensers and filters (Jung 1987). The estimated energy use impacts ranged from 20% for a dirty evaporator or condenser to as much as 79% from a dirty evaporator, condenser, and filter accompanied by significant condenser air flow reduction. The simulations did not consider fan power changes under these conditions (which would reduce the impacts as the fans moved less air, particularly for the indoor unit).
- Trane provided data from an experiment performed in the 1970's where two air conditioners were operated continuously with condensers exposed to a very dirty factory environment for 18 months, equal to perhaps 4-8 years worth of typical operating hours (Trane 1990). Performance measurements at the end of the test indicated that the air conditioner with the standard plate fin coil had lost 17% of its capacity and 27% of its efficiency. The manufacturer's new spine fin coil reduced these losses to 8% of capacity and 10% of efficiency. This test provides evidence that condenser fouling may have substantial effects, but is difficult to generalize from. Even after cleaning, efficiency was still reduced by 9% for the plate fin coils and 3% for the spine fin coils.
- An ASHRAE paper noted considerable capacity problems in two 20 ton chillers caused by dirty condensers (Braun 1986). The static pressure across the coils was measured at 2.5 times greater than design after 8 years. Cleaning was not very effective at improving capacity or reducing pressure drop. The author noted that it is extremely difficult to clean a coil more than two rows deep and that coils with tighter fin spacing will tend to foul more quickly.

Several reports and papers were located which assessed coil cleanliness and/or measured energy savings from coil cleaning in residential and small commercial air conditioners. Unfortunately, coil cleanliness ratings are quite subjective and the energy savings studies all included additional maintenance activities (often adjustments in charge as well as cleaning of both the evaporator and condenser coils).

- PEG has performed several studies on residential air conditioner performance (Proctor et al. 1990, 1991, 1995, Blasnik et al. 1995). One study in PG&E's service territory found dirty evaporator coils in half of the houses. Savings of about 8% were predicted from coil cleaning and other air flow improvements. A study in SCE's service territory found that 65% of the evaporator coils were dirty. The average age of systems with dirty coils was 10 years, while systems with clean coils were 7 years old on average. There was no relationship between coil cleanliness and levels of servicing.
- A study of problems with air conditioners in the Phoenix area found that 75% of condenser coils and 55% of evaporator coils were dirty (see Neal 1992).

- Trane found a 20% savings from cleaning both coils and adjusting charge in an 8 year old air conditioner (Trane 1976).
- A study of 18 commercial package systems in New England found that about half of the evaporator coils were dirty but all of the condenser coils were clean (Hewett et al. 1992). They cleaned coils, adjusted charge and TXV settings, and performed other maintenance and measured savings of about 6%-11% on average.
- EPRI is currently monitoring some commercial systems to analyze the impact of maintenance on system performance. No results are available yet.

The limited data above suggest that heat exchanger fouling is common and may be responsible for reductions in efficiency of 20% or more over extended periods under adverse conditions. However, savings from cleaning coils are unlikely to average that high. This discrepancy may be due to the difference between average field conditions versus more extreme conditions tested (or assumed) and may also be due to the difficulty in properly cleaning coils. There is substantial uncertainty in estimating absolute efficiency degradation rates for air conditioners due to heat exchanger fouling. However, the key issue for this project is estimating *relative* technical degradation rate.

For condensers in residential systems, the design difference is face area and air flow, not fin geometry or spacing or number of rows. The efficient systems have about twice the face area and 20%-50% greater air flow, leading to 25%-40% lower coil face velocities. There are two reasons why the larger coil units should experience less efficiency degradation than the smaller coil units.

First, the amount of heat exchanger fouling should be approximately proportional to the amount of fouling material potentially in contact with each unit area of coil, and therefore proportional to air velocity through the coil. While a lower air velocity will tend to increase particulate arrestance rates, the overall decrease in the amount of air passing through the coil per unit area should lead to less fouling. PEG explored this issue further by developing a simple model of relative coil fouling based on first principles and available data. The model accounts for the impact of air velocity on the overall exposure to pollutants for each unit area of coil and the potential impact of velocity on arrestance rates per unit area (with a functional form developed from measured data on electrostatic filters). The increase in arrestance rate due to lower velocity was varied over a wide range of values (up to four times the impact found with electrostatic filters) and no relative increase in fouling rate was found under any scenario for the larger coil with lower velocity. In addition, a lower velocity may reduce fouling caused by larger debris such as leaves and grass which can become entrained in higher velocity air streams.

Second, even if the two condensers experienced the same relative reduction in effective surface area and heat rejection capacity, the impact on system efficiency would be smaller for the larger coil. This smaller impact is due to the non-linear relationship between condenser heat transfer capacity and system efficiency. Figure 1 shows the relationship between condenser face area and normalized efficiency (based on air conditioner simulations performed by PEG using the Oak Ridge National Laboratory PUREZ model).

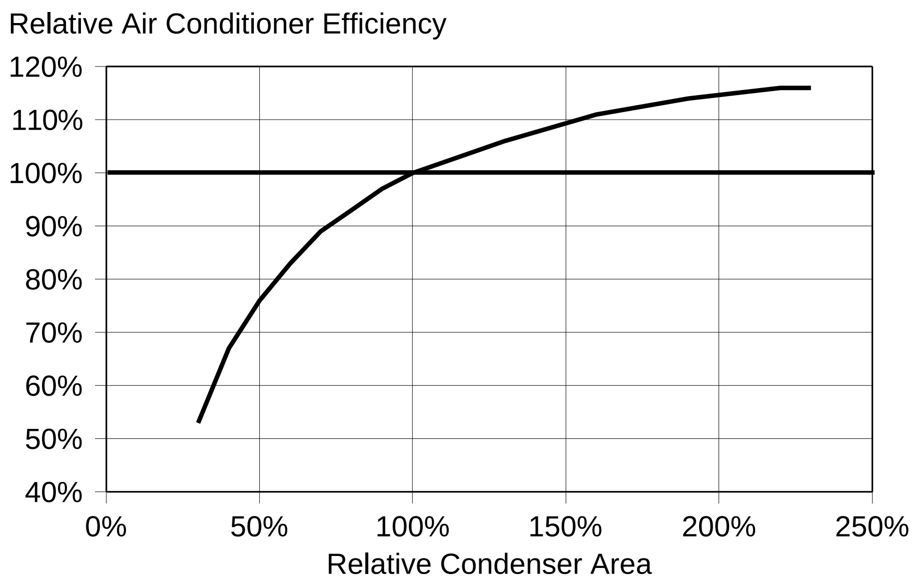

Figure 1. Impact of Condenser Area on System Efficiency

The condenser area and efficiency are both normalized in the figure (i.e., expressed as percentages relative to a baseline system). The figure shows that a 60% increase in the effective heat exchange area of the baseline unit improves efficiency by about 11%. A 120% increase in area only improves efficiency by about 5% more. The nature of this relationship has important implications for assessing fouling impacts because fouling may be viewed as a decrease in effective heat exchange area (although the actual effects may be reduced air flow, lower surface heat transfer rates, and reduced area).

One could estimate the impacts of a given amount of fouling on the efficiency of systems with differing condenser sizes by expressing the fouling rate in terms of a percentage change in effective area. For example, if fouling reduced effective area by a third each on systems with standard and doubled condenser areas, then the effective normalized areas after fouling would be .67 and 1.33, respectively. The efficiencies of these systems would change from 1.00 to 0.87 for the standard system and 1.14 to 1.07 for the efficient system. Therefore, percent savings would increase from 12.3% to 18.7% and kWh savings would increase to 21.5% of the baseline system's initial usage. Energy savings increase from equal fouling percentages because the system with the oversized condenser is less sensitive to changes in effective area than the system with the standard sized condenser -- the efficiency curve is flatter with a larger condenser (which is why the efficient units need to have double the condenser area in order to increase efficiency by about 10%-15%). Therefore, relative degradation will only occur if the relative rate of fouling for the efficient unit's heat exchanger is significantly greater than the standard unit's rate.

> *PEG concludes that differences in condenser coil face areas should produce no degradation in energy savings over time and may actually lead to increases in long-term savings.*

Many commercial units increase condenser and evaporator capacity by adding more rows to the heat exchanger. One would expect a greater rate of fouling in a heat exchanger with more rows because it would act as a better filter. However, if fouling is primarily through loading at the coil face then the additional rows may not increase particulate arrestance, although the impact of this equal fouling would be greater. Heat exchangers with more rows are also more difficult to clean (Schwed 1992, Braun 1986). It is not known whether the potential increase in fouling would create a greater proportional decrease in heat exchanger effectiveness for units with more rows. If the decreases are not more than proportional, then no relative degradation should occur (for the same reasons described in the face area discussion).

> *PEG concludes that differences in the number of condenser and evaporator rows may produce some degradation in energy savings over time.*

The most popular Trane high efficiency residential units increase evaporator face area and the number of fins per inch. The increase in face area should not cause savings degradation for reasons similar to those described in the condenser discussion. The evaporator air flow is the same so the face velocity will be lower in the units with greater face area. However, the tighter fin spacing (14 fpi instead of 12 fpi) will make the evaporator a better filter and could lead to an increased rate of fouling. Similar to the case of more coil rows described above, it is not known whether this tighter spacing will lead to a large enough increase in fouling rate that savings will decline over time. Some manufacturers mentioned tighter fin spacing as a potential source for relative degradation in efficient units employing this approach.

> *PEG concludes that differences in evaporator face area should not produce a degradation in energy savings over time, but differences in fin spacing are cause for concern.*

2.1.2 Compressors

About 40% of the high efficiency residential air conditioners use scroll compressors instead of reciprocating compressors. Scroll compressors are considered more reliable and better at maintaining efficiency because they have fewer parts, no pistons, and the primary surfaces are self-polishing (Beseler 1987). The fundamental design produces less wear and tear than a reciprocating compressor is likely to experience. Some information on the degradation of compressors over time was found from manufacturers. One system manufacturer stated that they run a 16 week test on their compressors (reciprocating) which simulates five years of use and that there is no change in efficiency. A major compressor manufacturer stated that they perform tests which simulate 40,000 hours of operation (equivalent to about 10 years of heavy use) and that if capacity or efficiency degrades by more than 5% it is considered a failure. They also stated that scroll compressors improve slightly in efficiency after a short period of running as the surfaces “wear in, not wear out”. Reciprocating compressors are also believed to be more likely to fail under adverse conditions caused by improper refrigerant charge or severely fouled heat exchangers, but no data on in-field efficiency changes over time was found. While available data are limited, all evidence indicates that the scroll compressors are unlikely to degrade in performance at a greater rate than reciprocating compressors and may actually better maintain their efficiency.

> *PEG concludes that the use of scroll compressors in some efficient units should produce no degradation in energy savings over time.*

2.1.3 Metering Device

Some of the efficient residential units use a positive shut-off thermal expansion valve (TXV) instead of a fixed orifice for refrigerant metering. TXVs can suffer from sticking and hunting problems, but no data on the efficiency impacts of these problems was found. One study which adjusted TXVs to prevent hunting found no noticeable impact (Hewett et al. 1992). TXVs respond better to adverse conditions than fixed orifice metering. Laboratory testing has shown that TXVs are better able to maintain system efficiency when refrigerant charge is incorrect (Farzad and O'Neal 1993). Since a number of field studies have found that many air conditioners in the field are improperly charged and charge may change over time due to refrigerant leaks or improper servicing, one could expect systems with TXVs to suffer less degradation in efficiency over time. However, in units with extreme charge problems, systems with fixed orifice metering will be more likely to fail and receive repairs while TXV systems will continue to operate longer with degraded performance. In summary, TXVs should experience no relative degradation in most units, some "negative" degradation in units with moderate charge problems, and some "positive" degradation in some of the small fraction of units with severe charge problems. Based on the information available, it appears that the net average effect will be small.

> *PEG concludes that the use of TXVs in some efficient units may lead to some changes in energy savings over time, but the direction of this change is uncertain and the magnitude is likely to be small.*

2.1.4 Common Degradation Mechanisms

The actual in-field performance of an air conditioning system depends upon several factors in addition to intrinsic unit efficiency. Some of the key performance factors include: air flow across the evaporator coil (Palani et al. 1992), refrigerant charge (discussed above), and distribution system losses.

Evaporator air flow may be too low due to coil fouling (described previously), dirty filters or improper duct design. Low air flow should have a comparable impact on units at both efficiency levels.

System refrigerant charge may be incorrect due to improper initial charging, improper servicing, or refrigerant leaks. Studies have found that refrigerant leaks severe enough to lead to a service call occur in about 5% of units each year (Karger and Carpenter 1978, Lovvorn 1989). The impact of incorrect charge on system performance strongly depends upon the type of metering device, which differs for some of the efficient units as described in section 2.1.3. Other design differences between the efficient and baseline systems are unlikely to lead to differences in the performance impacts of improper charge.

Numerous studies have shown that duct leakage can have a large impact on system efficiency. This leakage may increase over time due to tape failure and disturbances. However, the amount of leakage and impact on efficiency should be the same for both levels of efficiency (for single speed units). The system efficiency impact of a given level of duct leakage would only vary if the systems had different indoor coil temperature drops.

2.1.5 Air Conditioner Conclusions

While there are many unknowns in air conditioner performance over time, there is sufficient information to draw reasonable conclusions for residential units. The primary design differences between the efficient and standard residential air conditioners are unlikely to lead to an overall degradation of energy savings over time. Increased condenser and evaporator face areas, and scroll compressors are all likely to lead to stable or increasing energy savings over time when compared to standard efficiency counterparts. Potential degradation due to TXVs and tighter evaporator fin spacing on a minority of units is unlikely to overcome the improvements in long term average system performance expected from these other features. For commercial units, degradation over time may occur because of the more widespread use of increased rows in condensers and evaporators. This design is subject to potentially greater fouling and more difficult maintenance. New research is needed to assess potential degradation.

> **PEG concludes that energy savings from high efficiency residential air conditioners are unlikely to degrade over time and may actually increase due to a lower degradation rate than standard efficiency designs. Energy savings from high efficiency commercial package air conditioners may degrade over time. Insufficient information is currently available to draw reliable conclusions. A research plan for this technology is in section 3.1 of this report.**

2.2 Oversized Evaporative Cooled Condenser

The baseline technology is a supermarket refrigeration system with an air cooled condenser. The efficient measure is the same system with an oversized evaporative cooled condenser. Evaporative cooled condensers (ECC) use a water spray to take advantage of the difference between wet bulb and dry bulb temperatures and reduce condenser temperatures thereby improving system efficiency. The ECC can provide the same heat transfer capacity in a much smaller area. Oversized units provide a large heat transfer area and are designed to operate with a very low “approach” temperature (difference between condenser temperature and wet bulb temperature), providing improved efficiency over standard ECC designs.

The energy savings of an ECC depend on the improved heat transfer rate and reduced operating temperatures of the condenser compared to an air cooled unit. The key degradation issue is whether this improved heat transfer is maintained over time. Both types of condensers are subject to degradation caused by fouling.

Air cooled condensers can have dirt and dust buildup on the fins and may suffer from corrosion, particularly in coastal areas. Issues about air cooled condenser fouling are described in more detail in section 2.1 on air conditioners. Available information about fouling rates and impacts is very limited, but system efficiency losses of 20% or more may occur in some units. No data specific to supermarket refrigeration applications are available, but industry sources indicate that fouling is common (particularly for first and second stage condensers in multi-stage systems) and salt corrosion in coastal areas is a significant problem.

ECCs primarily suffer from scaling and biological fouling. The heat exchanger is made of a tube bundle and has no fins. While some level of biological fouling is reportedly common, sources indicate that scaling is the biggest issue.

2.2.1 Causes of Scaling

Oversized ECC’s operate at lower condenser temperatures than standard ECCs and therefore are less likely to scale (the solubility of the primary scale component increases at lower temperatures). However, scale can quickly build up on any ECC under the right circumstances. To avoid scale the spray water must be properly treated, spray and bleed rates must be properly adjusted, and spray patterns must be even. Virtually all ECCs receive regular service from water treatment companies. Typical services include treating the water and occasionally adjusting bleed rates and cleaning the condensers as needed. Because the water spray acts as an efficient air cleaner, the water becomes contaminated easily, particularly in areas with high levels of air pollution. Ventilation and heating equipment exhaust systems may also contribute to water contamination and condenser fouling (Ramsay 1993). Water treatment companies often attempt to reduce the bleed rate to a minimum in order to reduce the amount of chemicals needed. However, some industry sources reported that these rates are often set too low and problems occur. Spray nozzles become partly clogged or obstructed leading to uneven spray patterns which promote scaling. In some cases this situation is not rectified and condensers may not be cleaned until a performance problem arises (i.e., the refrigeration system capacity is inadequate to meet loads).

2.2.2 Frequency of Scaling

Manufacturers and other industry sources had widely varying opinions about the frequency and extent of scale problems. One contact suggested that about 20% of all units have substantial scale problems, 40% have moderate uneven scale buildup, and the remaining 40% have little or no scale but many of those have some biological fouling. Another contact believed that those numbers may be a little optimistic and that, in older units, partly plugged or even missing nozzles are very common and scaling is widespread. The same source said that some performance degradation occurs in virtually all units over the first couple of years. But any major problems are usually resolved by the manufacturer during this period. After the initial period, performance may start to level out with a smaller percentage of units experiencing additional degradation at any time. Degradation may increase again over time as miscellaneous problems such as nozzle clogging are more likely. In contrast, other sources contacted claimed that scaling is rare and is only a problem in units which are poorly maintained. In those units, scaling will occur rapidly and then system performance will be so severely degraded that refrigeration capacity will be insufficient and a service call will resolve the problem. The same sources also pointed out that air cooled condensers tend to receive less service and attention than the ECCs. No empirical data on actual scaling rates or changes in performance over time were found and no sources were aware of any such studies.

2.2.3 Impacts of Scaling

A paper on ECC performance was found which discussed several causes for reduced field performance including: scaling, piping, purging, placement, and wet bulb problems (Nugent 1994). Scaling and purging are the only two problems identified which are likely to cause changes in performance over time. The paper provided estimates of the relationship between scale thickness and condenser heat rejection rates based on limited test data and theoretical models. It also provided a variety of simple performance estimation aids. PEG applied the methods using assumptions appropriate for a typical supermarket application and the resulting energy impacts of different levels of scale were estimated. The results of this analysis are shown in figures 2 and 3.

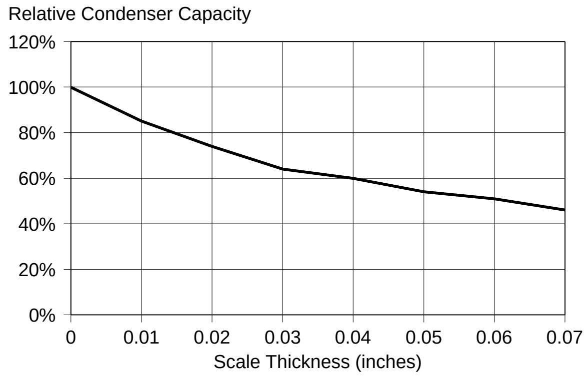

Figure 2. Scale Impact on Condenser Capacity

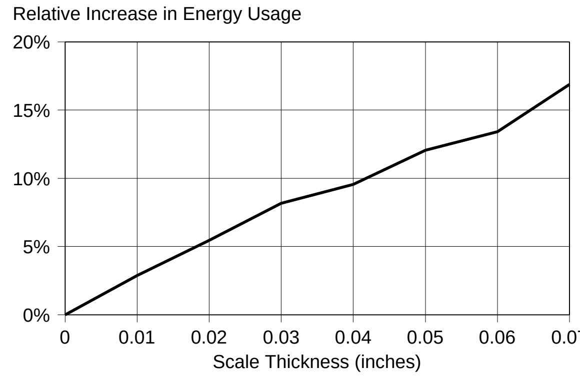

Figure 3. Scale Impact on Energy Usage

Figure 2 shows that condenser capacity may decline by more than 50% from a sixteenth of an inch of scale., This loss in condenser capacity is estimated to increase energy usage by about 17%, as shown in Figure 3. This loss in efficiency could nearly eliminate the energy savings for many applications if the air cooled condenser which it replaces would have suffered no degradation. However, the potential efficiency loss from fouling of air cooled condensers is often cited at a comparable level of impact. One ECC industry contact believed that the figures in the paper which this analysis is based upon understate the energy penalty from scaling and that energy usage could increase by a greater amount.

In order to quantify relative technical degradation for ECCs, the rates and amounts of fouling and their impacts on both the air and evaporative cooled condensers would be needed. This information does not exist. Available evidence indicates that both condensers can suffer substantial degradation. The actual frequency and severity of degradation in the field is unknown and additional data will need to be collected in order to make informed estimates.

PEG concludes that both evaporative and air cooled condensers may suffer substantial performance degradation in the field. Insufficient information is available to estimate relative degradation, but it may be significant in relation to the savings.

2.3 Residential Refrigerators

The baseline measure is a standard efficiency refrigerator which just meets the 1993 federal NAECA standard. The efficient measure is a refrigerator that exceeded the 1993 standard by greater than 15%. PEG acquired program databases to identify the specific refrigerators rebated under the 1994 PG&E refrigerator rebate program. Three classes of refrigerator efficiency were examined: 15-20% better, 20-25% better, and greater than 25% better than the 1993 standard. Six popular refrigerators were chosen as representative units, including the top model rebated in each of the three rebate categories and three other popular units. The refrigerators chosen represented 7%, 14% and 23% of their respective rebate categories. The sample units included four brands made by three leading manufacturers.

Baseline units of standard efficiency were identified by locating units in the 1994 AHAM directory (AHAM 1994) which were made by the same manufacturers and had identical characteristics (fresh food, freezer, and shelf areas and volume) but had higher rated energy usage. PEG contacted the manufacturers of the units to identify design and component differences between the baseline and efficient units. The manufacturers' responses were fairly uniform. The primary differences between the standard and efficient refrigerators are the compressor and motor efficiencies. Less common efficiency improvements included increased condenser coil area and a fuzzy logic smart defrost control system. The focus on compressors and motors instead of cabinet insulation or heat exchangers is sensible from production and cost perspectives since they are essentially "drop-in" replacements.

The major influences on refrigerator efficiency are: cabinet insulation, compressor efficiency, heat exchanger efficiency, fan motor efficiency, and the use of defrost and anti-sweat heaters. Potential sources of degradation were identified as insulation R-value degradation, door gasket deterioration, compressor performance degradation, heat exchanger fouling, motor degradation, refrigerant leaks, and control system failures. Given the common design differences identified, PEG focused research efforts on compressor and motor degradation. However, all degradation factors were examined to determine whether there may be interactive effects which cause relative degradation.

2.3.1 Compressors

Compressor efficiency improvements were the main approach manufacturers used to boost refrigerator efficiency. Increases in compressor efficiency create even greater increases in overall refrigerator efficiency because some of the compressor waste heat adds to the refrigeration load. Refrigerator and compressor manufacturers were questioned about the differences between compressors and potential degradation mechanisms and rates. All manufacturers representatives stated that there would be no difference in degradation between the two compressors and that neither would degrade. Compressor and refrigerator manufacturers stated that they use accelerated life-span testing on the compressors to ensure that they maintain their efficiency for at least 15 years. A common specification is that the compressor can not lose more than 5% of it's capacity or efficiency over the simulated life span and still be considered acceptable for production. All manufacturers stressed that they believe there is no degradation and that 5% is the upper limit. However, none were willing to share data generated from such tests.

One of the major compressor manufacturers stated that they periodically receive compressors that have been in operation for several years. They perform a calorimetric test on these compressors which determines operating characteristics including capacity and energy efficiency ratio at several operating points (a compressor “map”). The manufacturer stated that they have seen no discernible degradation of the compressors compared to the original specifications.

A study sponsored by Oak Ridge National Labs on a high efficiency refrigerator compressor tested capacity and efficiency of 50 compressors before and after 3000 hours of life-test stand operation (Middleton and Sauber 1983). They found no efficiency degradation (an average 2% improvement for one capacity and a 0.5% decline for the other capacity tested).

While the limited available information seems to support claims that compressor efficiency generally does not degrade, PEG analyzed specific design differences between the standard and high efficiency models to assess whether relative degradation may exist. The high efficiency compressors differ from standard efficiency units in three primary ways: motor efficiency, valve configuration, and oil viscosity.

Compressor motor efficiency improvements are due to more copper windings and higher quality copper and steel. As described in the analysis of motors, these efficiency improvements will not degrade over time.

The valve configuration change allows more compression during the upstroke of the piston (less dead space at the top of the cylinder). Manufacturers regard the specific technology used to obtain this efficiency increase as proprietary, but all involve reducing restrictions to flow on the suction side and reducing re-expansion of the compressed gas on the downstroke of the piston. The only way to accomplish both of these objectives is to increase the area of the inlet side of the cylinder and decrease the dead space at the top of the upstroke of the piston. A change of this type should not result in any specific efficiency degradation mechanism but could present a reliability problem.

Most manufacturers are running the more efficient compressors with an ester-based refrigerant oil which has a lower viscosity to improve efficiency. Research has shown that reducing the viscosity of the oil can increase efficiency by about 5% (Vineyard 1991). One might expect that lower viscosity oil could have a detrimental affect on compressor reliability, but all manufacturers stated that they complete the accelerated life tests with the lower viscosity oil and do not see any appreciable degradation or cause for concern about compressor reliability.

Based on the above analysis, PEG concludes that there is no evidence to suggest that higher efficiency refrigerator compressors should experience any greater performance degradation than standard compressors.

2.3.2 Fan Motors

All manufacturers indicated that the second most common efficiency increase is achieved through the use of higher efficiency evaporator and condenser fan motors (if used). The type of fan motor improvement varied by manufacturer and included use of electrically commutated motors, improved efficiency shaded pole motors for evaporators, and improved efficiency permanent split capacitor motors for condensers. As discussed in section 2.10 on motors, higher efficiency motors are unlikely to suffer from relative degradation.

2.3.3 Miscellaneous Design Differences

Changes in condenser coil area and defrost controls were made in some high efficiency units. The condenser coil design and fin and tube spacing are unchanged and therefore, based on the analysis provided for air conditioners in section 2.1, there should be no relative degradation from this change. The defrost control change on one unit is implemented with fuzzy logic using solid state circuitry that is not likely to suffer performance degradation.

Overall, the analysis of design differences between the standard and high efficiency units indicates that there should be no relative performance degradation in any of the higher efficiency components.

2.3.4 Absolute Performance Degradation - Common Factors

Although the higher efficiency components may not experience degradation relative to the standard components they replace, the design differences may cause the units to respond differently to other degradation mechanisms common to both units. Several data sources have indicated substantial absolute efficiency degradation for refrigerators. Some of these studies include:

- A paper soon to be published by ASHRAE reports on four refrigerators which were lab tested both before and after two years of usage in homes. Energy usage increased an average of 14 percent.
- A national lab reported on a test of a refrigerator when first bought and then tested again after 22 months (with the refrigerator unused). They found a 9% degradation in performance.
- A report analyzing potential savings from “greenplugs” summarized data on energy usage of refrigerators collected through various utility turn-in programs (LeBlanc et al. 1995). Their analysis of test data from two major refrigerator recyclers indicated that usage of these appliances averaged about 53% higher than rated consumption for one recycler and 29%-45% higher than rated for the other. The report also cited a study by SMUD which found usage levels 77% higher than ratings.

The first two sources in the list above provide some evidence of short-term degradation in a small number of newer units. The refrigerator turn-in program data sources indicate high degradation rates. However, these rates may not accurately represent typical degradation in the field. First, refrigerators which are turned in under utility programs are unlikely to represent a random sample of older units. Such samples are likely to over-represent units that don’t work well (due to refrigerant leaks, major compressor problems, serious gasket deterioration, badly fouled condensers, or other damage) and the owners are using the turn-in program to get rid of a lemon. Units may also be damaged during pick-up and transport (since they are being recycled, presumably few precautions would be taken to safeguard them). In addition, it is not clear whether all sources used standard DOE test procedures on the removed refrigerators or how reliable the "rated" consumption numbers are for refrigerators manufactured before the DOE test procedure was mandated. Therefore, while these results certainly indicate that significant degradation may be occurring in some older refrigerators, they do not establish what average rates may be.

In addition to the above data sources located, PEG analyzed hourly end-use metered field data from 128 new efficient refrigerators which was acquired by PEG during a project for PG&E in 1992 (Proctor and Dutt 1994). The metered refrigerators' rated usage rates were comparable to 1993 minimum efficiency standards. While the data only encompassed the first year of use for these new refrigerators, the large high quality data set was examined to look for degradation. A number of techniques were used to estimate degradation (including direct comparisons of usage by outdoor temperature bin by month of metering, analysis of residuals by month from a time-series cross-sectional regression model, incorporation of a time trend variable in such models, and analysis of within-refrigerator usage deviations summarized by month and by temperature bin). All approaches indicated that usage rates had increased by 5% to 9% over the course of 10 to 12 months. This finding is generally consistent with the two small studies of newer refrigerators described above.

Potential causes for the apparently significant degradation in newer refrigerator performance were examined. In addition to the components examined previously, four primary degradation mechanisms have been identified: insulation R-value degradation, door gasket deterioration, heat exchanger fouling, and refrigerant leaks. For the older units cited in the turn-in programs, all of these mechanisms may be at work (although many older refrigerators did not use much or any foam). However, only insulation and heat exchanger degradation seem likely to be able to cause the 5% to 15% early degradation found in newer units. The response of higher efficiency refrigerators may differ from standard efficiency refrigerators when exposed to these sources of degradation.

2.3.4.1 Foam Insulation

Manufacturers generally use 2-3 inches of injected urethane foam (CFC or HCFC blown) to insulate their cabinets. Due to the limitations of the cabinet dimensions that are acceptable to the consumer and production logistics, insulation increases were not used by manufacturers in their higher efficiency units. It is well known that urethane foam R-value degrades over time due to outgassing of the blowing agent and, more importantly, air components diffusing into the foam. This degradation may reduce the R-value per inch from an initial value of about 7 or 8 ($hr \cdot ft^2 \cdot {}^oF/Btu$) down to a fully aged value of 5 or 6. Some refrigerator manufacturers claimed that their foam does not degrade much because it is encased in the cabinet. However, an analysis of research on foam aging indicates that refrigerator liner and cabinet construction are unlikely to substantially affect foam degradation.

PEG analyzed the potential impact of R-value degradation on refrigerator energy usage. A paper on foam aging mechanisms and rates (Glicksman and Page 1992) was used to estimate typical 1inch foam aging rates, adjust these values for thicknesses used in refrigerators (degradation varies inversely with the square of foam thickness), and then develop an equation which estimates R-value as a function of time (based on an exponential functional form).

The impact of these R-value changes on refrigerator usage was modeled using the EPA's refrigerator simulation software (EPA 1993). Typical 1993 18 cubic foot top freezer model data were used as a baseline and then a series of simulations were run adjusting the foam R-value incrementally. The results of these runs were fit with a regression model relating foam R-value to energy usage. Energy use impacts by year were calculated by using the R-value degradation function with these simulation results. The resulting performance degradation curve estimated from this analysis is shown in figure 4.

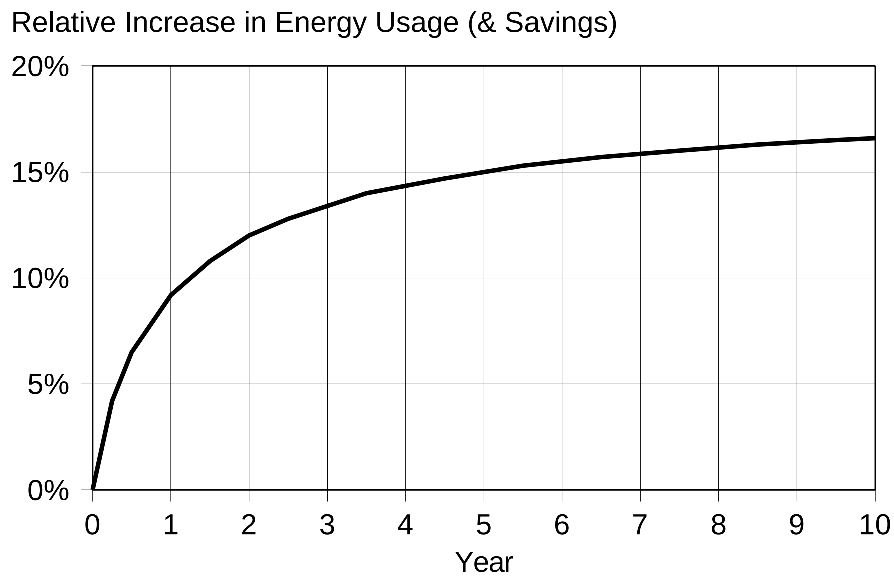

Figure 4. Refrigerator usage increase from foam R degradation

The figure shows that energy usage should increase by about 9% over the course of the first year and then eventually reach about 17% higher than initial levels over the life of the appliance. The 9% increase is generally consistent with the metered data analysis and the two studies described earlier.

To assess the impact of this R-value degradation on the energy savings from the high efficiency unit, PEG performed additional simulations which confirmed that the relative usage impacts of R-value changes are essentially independent of the compressor and motor efficiency. Therefore, absolute energy savings from the high efficiency refrigerator will increase over time as both units' usage levels increase by the same percentage. It is worth noting that any factor which increases cabinet loads over time should lead to increased savings ("negative" relative degradation) from the high efficiency units due to their more efficient compressors and motors.

If initial energy savings are estimated based on rated usage (and rated usage is accurate), then foam R-value degradation should lead to actual savings about 6% higher than predicted in the first year, climbing to about 15% higher by year 6 and reaching 17% higher by year 15. If initial savings were measured based on data from the entire first year (which includes a significant fraction of initial degradation), the analysis indicates that savings will be understated by about 4% for the second year, 6% for the third year, and eventually reach a 10% underestimate by year 14. All of these values are based on the assumed R-value degradation rates and the assumption that no other factors are changing over time.

2.3.4.2 Door Gaskets and Condenser Fouling

Door gaskets receive considerable stress over the life of a refrigerator. The average number of door openings per day in one study was 42 (Parker and Stedman 1992). It appears that long term deterioration is likely and significant energy usage increases possible. PEG used the Lawrence Berkeley National Laboratory residential infiltration model (Sherman and Grimsrud 1980) to estimate the potential impacts of gasket leakage on energy usage (of course, the wind speed was set to zero). The analysis indicated that a moderate gap (one sixteenth inch) around the entire perimeter of the door should increase energy usage by about 60%. A very large gap could cause the compressor to run continuously, more than doubling usage. The percentage impacts would be about the same for the baseline and high efficiency units, so energy savings would increase over time if both units experienced similar gasket deterioration.

Condenser fouling is another potential degradation mechanism. The coils are difficult to access for cleaning and therefore one could assume that they are rarely cleaned and likely to pick up dust and dirt over time.

While it would appear that these two factors could cause substantial degradation in performance over time, available data seems to indicate that the impacts are relatively small on average. Three studies were found on the energy impacts of performing refrigerator maintenance (see Meier 1993):

- A study by Rochester Gas and Electric found that replacing door gaskets and cleaning condenser coils on older refrigerators did not decrease energy usage (it actually increased by an average of 2.5%). A sample of 27 older refrigerators with an average age of 17 years were metered for a year before and after receiving maintenance. Twenty six of the refrigerators got new door gaskets (even if they were not needed) and ten of the refrigerators were found to have dirty coils that were cleaned. Only 3 of the 27 refrigerators showed a significant drop in energy usage, 2 experienced a clear increase in usage and the remainder of the refrigerators appeared to be unaffected.
- A study by SMUD measured savings from cleaning coils on 28 older refrigerators from a turn-in program. 70% of the condensers were considered dirty. They also noted that 18% had cabinet or gasket damage and 34% had improper refrigerant charge. Cleaning coils reduced usage by an average of 6% (150 kWh / yr. for these units) as measured by the DOE test procedure.
- A study of 5 refrigerators by PECo Energy found savings of about 5% from cleaning condensers on older refrigerators in low-income homes (based on two weeks of pre / post metering).

The available evidence suggests that coil cleaning may save only about 5% on average and that gasket replacements may not save any energy for most units. While air leakage around a door gasket can certainly increase usage (as calculated above), the actual leakage rates may be small and / or the replacement gaskets may not be very effective. Fouling of condensers does not appear to be a very large degradation mechanism and is highly unlikely to cause any greater degradation in high efficiency refrigerators than in standard efficiency units. Instead, those high efficiency units with larger condenser areas may be expected to suffer less degradation from this effect.

2.3.5 Refrigerator Summary

The analysis of refrigerator design differences found no evidence to indicate that any of the efficiency improvements will suffer from relative performance degradation. An analysis of common degradation mechanisms revealed that the high efficiency units should suffer less degradation than the standard units and savings may increase over time.

> **PEG concludes that the energy savings from high efficiency refrigerators will not degrade over time and may actually increase.**

2.4 Fluorescent Lighting - General Information

Three measures in this study involve changes in fluorescent lighting systems. Several aspects of these systems are common to the discussion of these measures. A fluorescent lamp produces light by discharging an electric arc through a tube filled with low pressure mercury vapor. The mercury vapor produces primarily ultra-violet radiation which is absorbed by a phosphor coating on the inside of the tube. The phosphors convert this energy to visible light. The phosphor composition of a lamp determines its color rendering qualities and affects lumen output. The lamp is started by a voltage kick (provided by the ballast) to cathodes at the ends of the tube which are coated with electron emissive material in order to initiate the voltage arc across the tube. The tube contains an atmosphere of inert gas, usually argon, to facilitate the starting of the arc. The lamp rapidly heats up to operating temperature which increases the mercury vapor pressure to an efficient level. The temperature and operating pressure are quite low in comparison to other gaseous discharge light sources and much of the mercury remains in a liquid state. Once the arc is initiated, the lamp resistance decreases as the current increases. Therefore a ballast is needed to limit current to the lamp while providing the proper operating arc voltage (typically 101 volts for standard 4 foot T12 lamps and 135 volts for T8 lamps). The normal end of life for a lamp is caused by depletion of emissive material from the cathodes.

2.4.1 Light Output and Efficacy

Typical lamp efficacy (lumens per watt) is about 77 lpw for standard T12 lamps. The efficacy of a fluorescent lamp may be increased by using improved phosphors, driving the lamp at high frequencies, using smaller diameter tubes (e.g., T8), and using longer tubes. The light output decreases as the lamp ages due to deterioration of the phosphor coating and, to a lesser extent, from end darkening (due to emissions from the electrodes). Manufacturers publish lamp lumen ratings which indicate initial lumen output (after 100 hours of operation) and mean lumen output (defined as lumens at 40% of rated life which usually means at 8000 hours). Typical rated lamp lumen depreciation rates range from about 10 to 20 percent and are primarily a function of phosphor composition (“deluxe” colors perform much worse) and current loading. The majority of lumen depreciation occurs before the midpoint of lamp life. The rated lumen depreciation values are based on ANSI-defined test conditions which do not necessarily represent field conditions. Lamp lumen depreciation in the field is affected by ballast electrical characteristics and other factors. The actual light output of a fluorescent system is lower than the rated lamp lumens because of ballast interactions (represented by the ballast factor), losses in the fixture, and dirt buildup on the fixture and room surfaces. The average maintained lumens of a system depend on these factors along with lamp lumen depreciation, re-lamping strategies, and maintenance practices. Lumen output and power draw are also affected by line voltage variations.

2.4.2 Temperature Effects

The light output and power draw of a fluorescent lamp are affected by the mercury vapor pressure in the lamp, which is primarily determined by the minimum bulbwall temperature (which affects how much mercury remains liquid). Changes in mercury vapor pressure affect the arc voltage and the spectral distribution of the light. Because a ballast is primarily a current limiting device, changes in lamp arc voltage can affect lamp power draw as well as ballast losses. The peak power draw occurs at about 90ºF, which is below typical operating temperatures. The light output of the lamp is also affected by the mercury vapor pressure with a peak at about 100ºF. Because most fixtures maintain bulbwall temperatures above 100ºF, the actual “in-luminaire” lumen output and power draw tend to be less than the nominal rated values (by 5%-15% in many applications). Energy saving retrofits tend to reduce operating temperatures and therefore bring power draw and light output closer to rated values. These effects can lead to overestimating retrofit energy savings by 10%-25% while also misestimating changes in lighting level (Davis 1992).

If temperatures changed systematically over the life of a fixture / lamp / ballast, then energy savings from an efficiency measure may also change over time. While no empirical data were found, the temperature is not believed to change significantly over the life of the system. For a given fixture / lamp / ballast combination in a given environment, changes in temperature would occur with changes in heat generation. Heat generation would increase if ballast losses increased or the amount of light exiting the fixture decreased. Ballast issues are covered separately. The light output of a fixture will decline over time due to lamp lumen depreciation and luminaire dirt and surface depreciation. These losses may start at around 25% and gradually reach 50%, implying that about a third of the energy that had exited as light must now exit as heat, increasing operating temperatures over time. However, these changes are small in the overall heat balance of the fixture. The combination of a typical 40 watt fluorescent lamp with an energy efficient magnetic ballast generates about 34 watts of heat and 9 watts of light, of which about 7 watts of light exit the fixture. A doubling of light losses would only increase the heat generation rate from 36 watts to about 38 watts, or by about 6%. This increase would raise operating temperatures by no more than about 3ºF (based on the assumption that it would affect fixture temperature elevation above ambient proportionally). This analysis indicates that fixture temperatures should be approximately constant over time for a given set of equipment characteristics and operating conditions.

2.5 Electronic Ballasts

The baseline measure is an energy efficient magnetic ballast operating standard fluorescent T12 lamps. The efficient measure is an electronic ballast operating the same lamps. The primary functions of a fluorescent lamp ballast are to provide the voltage needed to start the lamp and then to limit the current of the lamp and provide voltage regulation. Other ballast features include cathode heating to stabilize the evaporation of emission material (for rapid start ballasts), thermal protection and, for electronic ballasts, high frequency operation and dimming capability in some applications.

The standard magnetic ballast is essentially a current limiting core and coil transformer which is made of laminated transformer-grade steel wound with copper or aluminum magnet wire. A capacitor is commonly used for power factor correction and may play a role in lamp starting. High efficiency magnetic ballasts use higher grade materials to reduce losses in half (from about 20% of input to 10%). Electronic ballasts accomplish the same functions as a magnetic ballast but use solid state circuitry which allows for high frequency operation (increasing efficacy). The high frequency magnetics have lower losses and the solid state design allows for better voltage and current regulation. Overall ballast losses are reduced to about 5 percent while lamp efficacy is improved by about 10% from high frequency operation.

There are a number of design issues and options in electronic ballast construction which make them much more complex than magnetic ballasts (e.g., high frequency operation, EMI, protection from voltage transients, harmonic distortion, power factor, current crest factor, glow current, electrode preheat time). Some of these issues, combined with component reliability problems, created difficulties with earlier designs. However, improved designs and the availability of higher quality high frequency components has led to excellent reliability and electrical characteristics for most newer electronic ballasts. Electronic ballasts are available with a rated life of 20 years, power factors of .99, THD less than 10%, and a ccf of less than 1.5. These figures compare favorably with energy efficient magnetic ballasts (see Alling 1989, Christiansen 1990, Hammer 1991, and Ji 1994 for discussions of electrical characteristics and issues).

The typical savings from replacing an energy efficient magnetic ballasts with a comparable electronic ballast in a two lamp fixture with four foot T12 lamps is on the order of 14 nominal watts or about 11 watts after accounting for thermal effects. Part of these savings are derived from electronic ballasts taking advantage of their improved efficacy to drive the lamps at lower than their nominal wattage. Electronic ballasts designed to operate three or four lamps are often used to reduce the overall number of ballasts (and cost) in many retrofits.

2.5.1 Energy Consumption

The energy consumption of a ballast/lamp system is a function ballast losses, lamp characteristics, operating environment, and the interaction of the lamp and ballast (how the ballast regulates lamp current and voltage). All manufacturers and researchers contacted stated that they believe that the power draw will remain constant over the life of the system and that there is no noticeable change in ballast losses or performance over time for either the electronic or magnetic ballasts. Many contacts noted that the prime function of a ballast is to ensure that the lamp operates at the proper current and voltage, and therefore that the system draws the desired wattage. While the exact wattage will vary somewhat between applications, it should remain constant over time. The stability of the low pressure mercury system employed in fluorescent lamps was often cited as a reason for stable long-term electrical performance. No empirical data were found which measured ballast losses or lamp / ballast power draw over time for any types of fluorescent ballasts or lamps. However, pre-retrofit metered data collected by several utilities have indicated that actual in-field power draw of fluorescent lighting systems are usually within 10% of expected values (with slightly lower than rated wattages being accounted for by thermal effects and underestimates of the prevalence of existing energy efficient magnetic ballasts).

When asked to compare electronic to magnetic ballasts, most sources expected electronic ballasts to be more stable over time than magnetic ballasts due to the higher level of control afforded by solid state designs and to the lower operating temperatures. However, these same sources expected magnetic ballasts to also be stable and not degrade in performance. Electronic ballasts have many more components than magnetic ballasts which may imply a greater likelihood of failure and perhaps degradation. Excessive premature failures were a problem several years ago, but recent studies have shown good reliability (Abesamis et al. 1990 and Huizenga et al. 1992). Manufacturers were not willing to release detailed information on electronic ballast designs since they are considered proprietary. Potential ballast and system degradation mechanisms which were identified include:

- Some contacts noted that the power factor correction capacitor used in many magnetic ballasts may degrade (due to heat) which would affect power draw by perhaps 2%-4% in some systems. The overall affect of this change on energy savings over time would be negligible because it only occurs in some systems and tends to occur late in the rated life.
- One contact stated that losses could increase for magnetic ballasts due to damage of the electrical insulation (most likely caused by excessive heat), but it is believed to be rare. Instead, excessive heat and other potential adverse operating conditions are more likely to lead to ballast failure rather than continued operation at a degraded level. It is commonly asserted that a 10ºC increase in temperature will reduce ballast life by 50 percent.
- Lamp-ballast interactions were explored for possible changes in energy usage over time. Published research has shown that the light output and power consumption of lamps driven by electronic ballasts tend to be less affected by temperature changes than magnetic ballasts because of their superior wattage and current regulation (Siminoritch et al. 1984). Therefore, if bulbwall temperatures increased over time in an enclosed fixture, energy savings would be reduced because the magnetic ballast fixture would decrease in wattage at a greater rate than the electronic ballast fixture (although relative light output and efficacy differences would increase). However, operating temperatures are not expected to increase significantly over time (see section 2.4.2).

Overall, the investigation found no evidence to suggest that energy savings from electronic ballasts may degrade over time. Both the efficient and baseline technologies are believed to be quite stable.

2.5.2 Light Output

The light output of a lamp / ballast system primarily depends on the lamp design and operating conditions (e.g., temperature) and the ballast's characteristics (including current and voltage regulation). The impact of a given ballast on lamp light output is rated by its "ballast factor" (typically about .95 for energy efficient magnetic ballasts and available in a wide range of values for electronic ballasts). However, the ballast factor rating does not account for differences in bulbwall temperatures which may be due, in part, to the lower power draw of electronic ballasts. Therefore, ballast factor ratings may understate the relative light output of systems with electronic ballasts which operate at lower temperatures.

In terms of changes in light output over time, the only feature of the lamp / ballast system expected to change is the lumen output of the lamp as it depreciates. Lamp lumen maintenance is affected by starting scenario and the current crest factor (ccf) of the ballast (ratio of peak to rms amperage, typically 1.5 - 1.7). Electronic ballasts are available with a variety of starting scenarios and current crest factors but most recent designs have excellent characteristics with low ccfs of about 1.5 providing good lumen maintenance and lamp life.

> **PEG concludes that the energy savings from electronic ballasts are unlikely to degrade over time. The lumen maintenance of different lamp/ballast combinations varies, but no systematic differences were found.**

2.6 Electronic Ballast and T8 Lamp

The baseline measure is a typical fluorescent fixture with T12 lamps and an energy efficient magnetic ballast. The efficient measure is T8 lamps with an electronic ballast. General fluorescent lighting and ballast issues are discussed in sections 2.4 and 2.5. The key issue for this measure is T8 lamp performance and any interactions between the lamp and ballast.

T8 lamps provide higher efficacies than T12 lamps because of their decreased diameter and, in many designs, because of improved phosphors. Reduced diameter lamps are more efficient primarily because they allow more of the photons produced to strike the phosphors. T8 lamps are well suited for use with improved phosphors because of their reduced surface area (saving on material costs). T8 lamps have the same 20,000 hour rated life as standard 4 foot T12 lamps. Eight foot T8 lamps tend to have a 25% longer rated life than their T12 counterparts (15,000 hours vs. 12,000).

2.6.1 Light Output

The typical nominal 32 watt T8 lamp provides about 5% fewer initial rated lumens than a comparable 40 watt T12 lamp. However, the smaller diameter of the T8 lamp improves the efficiency of the luminaire, compensating for half or more of this reduction. T8 lamps have better lumen maintenance characteristics than T12 lamps (7%-10% depreciation at 40% of life compared to 12%-13%), providing only 1%-2% fewer rated mean lumens.

2.6.2 Energy Consumption

When operated on high frequency electronic ballasts, efficacies of T8 lamps can approach 100 lpw, 25%-33% better than typical T12 lamps on efficient magnetic ballasts. The efficacy improvement is slightly greater for 8 foot lamps than 4 foot. Electronic ballasts take advantage of this combined efficacy improvement to drive the lamps at less than the rated 32 watts yet still providing mean light levels equivalent to T12 systems. For example, Osram / Sylvania states that a 4 lamp recessed lensed fixture with 4 F032 T8 Octron lamps will draw 106 watts to produce the same light output as standard T12 lamps with an energy efficient magnetic ballast that draws 162 watts under the same conditions. The T8 system draws only 26.5 watts per lamp compared to 40.5 watts for the T12. No evidence was found to indicate that the power draw of T8 lamps with electronic ballasts is any less stable over time than T12 systems.

The improved T8 system efficacy is primarily based on factors that do not degrade over time: smaller tube diameter and high frequency operation. The efficacy gained from improved phosphors suffers less performance degradation than the standard system, as shown by improved lumen maintenance characteristics.

> **PEG concludes that energy savings from T8 lamps with electronic ballasts will not degrade over time and that light output degrades at a slower rate than the standard T12 systems which are replaced.**

2.7 Optical Reflectors

The baseline was defined as a white enamel fixture with four lamps and a standard lens. The fixture may contain either 40 watt T12 or 32 watt T8 lamps with either an efficient magnetic ballast or an electronic ballast. The measure was defined as installing a front reflective silver film reflector, cleaning the lens, and delamping by removing two tubes and one ballast. The project advisory committee recognized that energy savings are unlikely to change substantially over time and instead chose to have PEG focus more on changes in light output over time (i.e., lumen maintenance).

2.7.1 Energy Savings Degradation

Because the measure does not consume energy, the energy savings can only change over time if:

- the removed lamps and ballast would have experienced changes in energy usage, or
- the energy usage profile over time of the remaining lamps and ballast are affected by the reflector or delamping.

Neither of these effects are believed to be significant. Sections 2.4 and 2.5 of this report concluded that the power draw of a fluorescent lighting system is essentially constant over time. Therefore the savings are likely to persist. The delamping does tend to reduce the operating temperature of the remaining lamps and ballast (by 16-19 ºF in an enclosed fixture according to Lindsey 1991). This reduction in temperature can be expected to increase light output of the remaining lamps (by 6%-11.5% ibid.) and will lead to a slightly smaller increase in power draw. The particular amount and impact of the temperature reduction depends upon luminaire design and other factors. However, these effects are not believed to vary over time (see section 2.4.2 on temperature effects). No information was found to indicate whether reduced temperatures will affect lumen maintenance, but it should improve ballast life, particularly for systems with magnetic ballasts.

2.7.2 Light Levels

Changes in lighting levels over time are a function of many factors including lamp lumen depreciation, relamping strategy, degradation of luminaire surfaces (including lens and enclosure), dirt accumulation on luminaires and room surfaces, and maintenance practices. These factors can vary dramatically from application to application. The key issues for assessing the relative performance degradation of the reflector retrofit are:

- a comparison of the degradation of the reflector material to standard luminaire depreciation;
- an assessment of whether the delamping affects any of the degradation factors, and;
- an assessment of whether the other services often performed during a reflector retrofit (e.g., fixture cleaning and new lamps) are likely to depreciate differently than the pre-retrofit situation.

The performance of a reflector material, like any luminaire material, may decline over time due to dirt depreciation and surface depreciation. Reflector surface depreciation may occur due to humidity, ultra-violet radiation, temperature cycling, chemical action, and abrasion from improper cleaning. No data were found which quantified these effects in the field. However, an engineer from one manufacturer published a paper on some aging characteristics of reflectors (Brekken 1987). Front reflective silver film was tested using two different ASTM accelerated aging tests (both involved alternating extreme ultra-violet and moisture conditions under elevated and varying temperatures). The tests simulated many years of exposure to these potential degradation factors. Neither test found significant performance degradation (less than 2%). However, the testing measured the impacts of only some of the degradation factors identified above. The lack of information on depreciation from abrasion or other damage from improper cleaning is cause for concern.

Surface depreciation of the baseline condition -- an enamel painted luminaire -- is mentioned in the IES handbook (IES 1993) as potentially significant and permanent, but no values are provided for quantifying this effect. It is likely that the depreciation would tend to stabilize over time (much like the flattening shown in dirt depreciation curves). Therefore, the continuing surface depreciation of the baseline luminaire is likely to have been small after the retrofit if the reflectors are applied to older fixtures. Overall, surface depreciation may be expected to be greater for the reflector than the baseline condition because, at least for film-based products, the reflective material would seem to be more fragile and more likely to suffer continuing degradation.

Dirt depreciation is another factor which reduces light levels over time. Another manufacturer-sponsored study (Clark 1989) measured the reflectivity in the field of four year old reflectors in a variety of environments ranging from clean (non-smoking office) to dirty (enclosed parking garage). No maintenance had been performed on the reflectors and the measured reflectivity declined by less than 3%. Thorough cleaning restored reflectivity to 99% of initial values. These limited, unpublished results are generally encouraging. IES values for expected luminaire dirt depreciation generally range from about 10%-30% for reasonably clean environments over a four year period. However, these values are not directly comparable to the reported study values because they include dirt depreciation of the entire fixture, not just the top of the luminaire. Overall, there is no evidence which indicates that a fixture with a reflector will experience any faster dirt depreciation than a standard painted fixture.

Reflector retrofits often achieve much of their effectiveness at maintaining a large percentage of pre-retrofit light levels due to lens cleaning and relamping. However, the benefits from these services are likely to diminish over time. Lamp lumen depreciation curves show that the light output degrades faster at the beginning of the lamp life than at the end, so short term relative degradation is likely. After a few years, relamping schedules should be back to normal and no net benefit from the initial relamping will remain. IES data on luminaire dirt depreciation factors show that dirt depreciation is also fastest when the fixture is cleanest. Therefore relative degradation is likely to occur during the first few years after the retrofit. Again, once maintenance schedules are back to normal, no net benefit from the lens cleaning will remain if dirt depreciation rates are the same.

> **PEG concludes that energy savings from reflector retrofits will not degrade over time. However, light output may experience relative degradation due to reflector surface depreciation and, perhaps more importantly, the short-lived**

benefits of lens cleaning and relamping performed during the retrofit. The light output issue should be explored in future retention studies.

2.8 High Intensity Discharge Fixtures

The baseline measure is defined as a 400-1000 watt mercury vapor fixture used indoors. The efficient measure is a 250 or 400 watt metal halide fixture in the same application. Mercury vapor and metal halide lamps are high intensity discharge (HID) lamps with fairly similar construction and operation features (see G.E. 1975). HID lamps work similarly to fluorescent lamps in that a voltage arc is established which excites mercury vapor causing it to emit radiation. However, HID lamps are considerably smaller and operate at much higher energy intensities, vapor pressures, and temperatures. The higher pressures shift the wavelength of the emitted radiation into the visible region. Because of their high temperature operation, HID lamps have relatively long warm-up times and must cool down for the arc to be re-struck. HID lamps have two jackets to provide thermal isolation and protection.

In a mercury vapor lamp, the high temperatures vaporize all of the mercury and the emitted radiation is a cool blue-green white light. Some ultraviolet radiation is also produced which is converted to visible light by a phosphor coating on the outer jacket.

Metal halide lamps are very similar to mercury vapor except they contain metals added to the discharge gas. The metals (typically some combination of sodium, scandium, thallium and indium) are in a halide form which vaporize during lamp operation. The addition of these metals improves efficacy and shifts the radiation spectrum to provide better color rendering (and limits the need for phosphors in most applications). The added metals do not all vaporize in the arc stream and therefore minimum bulbwall temperature has an effect on light output and color rendering (unlike in fluorescent lamps, this temperature is relatively unaffected by ambient temperature because of the much higher operating temperatures). Metal halide lamps have a higher operating temperature than mercury vapor lamps and so require longer start-up and restrike times. They are sensitive to operating position as the arc has a tendency to bow when operated horizontally (special lamp designs are employed for horizontal operation).

Most mercury vapor and metal halide lamps are operated on magnetic ballasts with similar functions as fluorescent system ballasts: to provide the starting voltage and then to limit current and regulate voltage during lamp operation. HID ballast designs tend to vary more than fluorescent system ballasts and have no well-defined standards (ANSI standards only ensure compatibility and there is no HID equivalent of Certified Ballast Manufacturers). Wide variations in designs and components and substantial interactions between lamps and ballasts make generalizations about overall performance difficult. However, some common characteristics can be noted. The most common mercury vapor lamp ballast is a constant wattage autotransformer (CWA) which contains a high reactance autotransformer with a capacitor in series with the lamp. Metal halide ballasts have a similar design with modification to provide a proper starting scenario (usually a higher voltage is needed) and operating voltage. Typical ballast losses are about 10 -15% for 400-1000 watt mercury vapor systems and 15%-20% for 250-400 watt metal halide systems.

2.8.1 Energy Consumption

The energy consumption of an HID fixture depends on the lamp power draw and ballast losses. Lamp power draw is a function of current from the ballast and operating arc voltage. Ballast losses are primarily a function of ballast design and components and lamp arc voltage. Fixture design interacts with this system through thermal effects. Lamp manufacturers tended to avoid questions about long term energy usage and some contacts stated that there are no changes while others claimed that it depends on the ballast and therefore ballast manufacturers should be the source for such information. Ballast manufacturers stated that power draw over time depends on lamp characteristics and that ballast losses shouldn't increase over time.

No data were found concerning ballast manufacturer claims that ballast losses are constant. However, the analysis of fluorescent ballasts indicated that losses should be constant over time. Still, HID ballast design differs somewhat from fluorescent, particularly with respect to the key ballasting role of the capacitor in many HID designs. The modular nature of many HID ballasts creates additional possibilities for performance changes over time (e.g., capacitors may be improperly replaced). While substantial increases in losses seem unlikely without inducing failure from overheating, more research may be needed to confirm the manufacturers claims. In terms of relative degradation, no design differences were identified which indicate that the two systems would differ in any long term performance changes. Therefore, it is considered unlikely that any systematic relative degradation would occur due to increases in ballast losses.

Lamp / ballast interaction has been identified as a key issue in actual system performance. An IES publication on HID operating factors notes the difficulty in determining system performance due to these interactions and the lack of standards (IES 1989). Contrary to their name, CWA ballasts do not necessarily maintain a constant wattage but are instead primarily a current limiting device. Variations in lamp arc voltage affect power draw, although not in a linear fashion. For most standard and higher wattage systems (>= 175W), power draw will increase with arc voltage at a somewhat less than linear rate. For lower wattage systems (<175 watts) with high reactance non-regulating ballasts, power draw may not consistently rise with arc voltage.

According to all sources contacted, mercury vapor lamps are quite stable and arc voltage and power draw do not change over time. This stability arises because all of the mercury is vaporized during operation, minimizing potential changes in pressure due to temperature rises over time. However, metal halide lamp arc voltage can increase over time leading to increased power draw. Although not well-documented, the arc voltage can rise because of sodium migration, electrode erosion, and vapor pressure increases caused by temperature increases due to tube darkening (and other causes of lumen depreciation). The overall increase in arc voltage may be about 15% ±5% over the life of the lamp. The system wattage will increase by less than this amount because the current from the ballast will decrease (depending on ballast type) and the power factor of the lamp will also decrease. No published data on the net effect of these changes was found. However, persistent contact with manufacturers uncovered some estimates based on unpublished studies.

Two lamp manufacturers provided estimates of the net changes in wattage draw. A GE representative stated that metal halide power draw may increase by 3% to 5% over lamp life. An Osram Sylvania engineer stated that they had recently measured this effect and found wattage increases of 0% to 6% with a typical increase consistent with GE's 3%-5% range (results primarily varied with ballast characteristics). The wattage increase is approximately linear over the life of the lamp.

The two estimates seem reasonable because they are consistent yet were developed independently and because if power draw increased by much more then the effect would have likely received considerably greater attention. For example, low pressure sodium lamps experience noticeable wattage increases over time (10% to 35%) which has been well documented with many manufacturers providing specific information on tested values over the life of the lamp. High pressure sodium lamps experience substantial increases in arc voltage over time (1%-2% per 1000 hours of operation) leading to some increases in wattage draw (although mentioned infrequently in the literature, 10%-20% wattage increases may be possible). The HPS arc voltage rise is well known because it eventually causes the lamp to fail as the required arc voltage exceeds what the ballast will provide. Therefore, if metal halide lamps experienced much more substantial arc voltage rises or power draw increases over time, additional data would likely have been found.

The impact of the metal halide wattage increase on annual energy savings over time will depend on particular lamp and ballast characteristics, actual initial wattage draw, annual operating hours, and relamping strategy. Under all scenarios the effect will be modest. PEG calculated degradation factors using several sets of assumptions. Table 3 provides annual degradation factors for the most common retrofit -- a 250 watt metal halide fixture replacing a 400 watt mercury vapor fixture. This retrofit is expected to save 164 watts when ballast losses are included (459 watts minus 295 watts). The metal halide wattage is assumed to increase linearly by 0.4% per 1000 hours over the 10,000 hour life of the lamp. Separate factors are provided for three levels of annual operating hours and two types/timings of first year impact estimates.

Table 3. Degradation Factors for Metal Halide Retrofits

1st yr. impact	Engineering Estimate			Billing Analysis		
Hrs/yr.	1500	3000	4500	1500	3000	4500
Year 2	.984	.968	.951	.989	.978	.968
Year 3	.973	.946	.932	.978	.957	.948
Year 4	.962	.932		.968	.942	
Year 5	.951			.957		
Year 6	.941			.946		
Year 7	.932			.937		

Note 1: For applications where lamp life differs from the assumed 10,000 hours in the table (e.g., due to group re-lamping or the use of longer life lamps), then the results need to be truncated or extended.

Note 2: If retrofit savings are credited over the life of the fixture and not just the lamp, then the degradation factors for future lamps in the life of the fixture should start again at the first row of the table.

Note 3: Degradation factors are calculated by calculating the average cumulative operating hours of a lamp in a given year and the average age of a lamp in the first year impact estimate. These ages are used in an equation which relates wattage to operating age in order to calculate savings for any given year. The degradation factor is then calculated as the current year savings divided by the first year savings. The equations below show the calculations.

LampAge [yearT] = (T - 0.5) * Operating hours/yr (if 1st year impact is engineering est., then Lamp Age [1]=0)

Savings [yearT] = RatedWatt[MV]-RatedWatt[MH]*(1 +0.04*LampAge[yearT]/10000)

Degradation Factor [yearT] = Savings[yearT] / Savings[year1]

The table shows that the degradation in savings will be small under all sets of conditions. For the example retrofit with initial savings of 164 watt, the savings decline to 152 watts over the full rated life of the lamp. Assuming a linear change over time, the average savings over the life of the lamp are 158 watts, or only 4% lower than the initial savings. The impact on average savings would be even lower if common group relamping strategies were included in the analysis.

Given the small effects and the complexity of the multiple scenario approach, it may be preferable to adopt just one set of typical assumptions and simplify the tables into one column of degradation factors.

> **PEG concludes that the energy savings from replacing mercury vapor fixtures with metal halide fixtures are likely to degrade slightly over time. This degradation can be estimated by the table provided (or variations upon it), although a simplified approach is recommended.**

2.8.2 Light Output

The improved efficacy of metal halide lamps allows a 250 watt metal halide lamp to have the same typical initial rated lumens (about 20,000) as a 400 watt mercury vapor lamp. Actual light output in the field is dependent on the lamp/ballast/fixture system and generalizations are difficult. Lumen maintenance comparisons are particularly problematic because of the key role played by the ballast and the different shapes of the depreciation functions. The current crest factor of the ballast plays a large role in lumen maintenance, particularly for mercury vapor lamps. A high current crest factor can almost double the rate of lumen depreciation. In addition, mercury vapor lamp lumen depreciation continues at an almost constant rate throughout the life of the lamp, causing most end-users to relamp far before the lamp actually fails to operate. Metal halide lamps have a decreasing rate of lumen depreciation over time, providing far superior lumen maintenance in the latter portion of the lamp life. Differences in rated lamp life (mercury vapor typically are rated for 24,000+ hours, metal halide at 10,000-20,000 hours) and in methods for assessing “mean” lumens and in published “design factors” compound the difficulty in making direct lumen maintenance comparisons. Overall, manufacturers and lighting experts describe the lumen maintenance of metal halide lamps as superior to that of mercury vapor lamps. However, the rated mean lumens and initial lumens are approximately the same for the most common retrofit situation.

> **PEG concludes that the light output of a metal halide system does not consistently degrade relative to the mercury vapor system it replaces and may be considered superior. However, relamping and maintenance practices, lamp/ballast interactions and other application specific factors can play a dominant role in determining the relative light levels of the two systems over time.**

2.9 Occupancy Sensors

The baseline measure is a standard on / off switch. The efficient measure is an occupancy sensor, either ultrasonic or infra-red. Occupancy sensors save energy by turning off lights when no occupancy is detected and turning lights back on when occupancy is detected. Savings are achieved to the extent that lights would have been on when there was no occupancy and that the detector will properly detect this and turn them off. Savings will be reduced if:

- the standard control of the system would have led to reduced operating hours;
- the sensors fail and are replaced with the standard control system;
- the sensors are over-ridden or tampered with in a way which reduces or eliminates their ability to turn off the lights;
- the sensors falsely detect occupancy when there is none.

Relative degradation will occur to the extent that these factors change over time. Changes in standard control strategies and sensor failure are outside the scope of this study (they are components of persistence but fall under the categories of behavioral changes and measure life / retention). Sensor over-riding or tampering by occupants is a retention issue outside the scope of this study except to the extent that it is caused by technical degradation of the measure. The key issue is whether the sensors will perform consistently over time.

The performance of a sensor will depend on its sensitivity to occupancy. Low levels of sensitivity imply that the sensor will turn off the lights while the space is still occupied and large movements may be needed to turn the lights back on. For infra-red sensors, this type of failure may also occur if the occupants are "hidden" from the sensor due to changes in furniture layout or even occupant orientation. In either case, the unwelcome shutting off of the lights presents an annoyance to occupants and may lead to defeating the system and returning to standard controls. If sensitivity is too high, the lights may turn on even when the space is unoccupied. False detection of occupancy may occur due to changes in temperature or hall traffic (passers-by outside of the controlled space) for infra-red units and from air flow patterns due to wind or HVAC operation for ultrasonic units. Sensors tend to have adjustable sensitivity levels and time delays.

The issues of sensor sensitivity have been explored by researchers at the RPI Lighting Research Center (Maniccia 1993 and Maniccia and Luan 1994). However, their work has not examined changes in sensitivity over time.

Manufacturers stated that their designs are proprietary and that they have not performed tests which examine long-term sensor performance. They do state that the sensors are built with reliable and proven components that will not degrade over time. Some defects occur but these are normally discovered and rectified immediately upon installation. The basic principles and components which comprise ultrasonic and infra-red sensors are not known to degrade over time without a failure. However, problems with sensor sensitivity are apparently considered significant enough to cause one manufacturer to create a sensor which adjusts its own sensitivity over time using a microprocessor (DSTR 1995). The justification for this device is that sensor sensitivity may be improperly set or need adjustment over time due to changes in space layout or HVAC air flow patterns.

The only direct technical degradation mechanism identified was dust or dirt accumulation on the detection ports, leading to decreased sensitivity. No data on this effect was found. However, as noted above, reduced sensitivity would not reduce energy savings because the lights would turn off more often. But if this reduced sensitivity caused occupants to over-ride the system, energy savings would be compromised. Savings could also be reduced if occupants adjusted the sensitivity too high in response to dust build up and false detection of occupancy occurred more often (due to the factors mentioned above). Occupants may also adjust the time delay to a longer setting, which would also reduce savings. These potential problems of tampering or over-riding are issues which can be best addressed in retention studies of this measure, which will need to note the sensitivity and time delay settings of installations visited and assess whether they are changing over time. Therefore, PEG concludes that no further research on technical degradation mechanisms is needed.

> **PEG concludes that energy savings from occupancy sensors may degrade over time due to occupant interaction to defeat or tamper with the system. These effects and their potentially changing likelihood over time need to be examined in measure retention studies.**

2.10 High Efficiency Motors

The baseline measures are either a new 10-20 hp motor or a rewound motor of 25-200 hp. The efficient measure is a new high efficiency motor of the same size. All motors are assumed to be squirrel cage poly-phase induction motors. Motor energy usage depends on hours of use, load, and motor efficiency at actual load. Motor efficiency is characterized by four main categories of losses: Core (or iron) losses, stator and rotor I^2R losses, friction and windage losses, and stray load losses. High efficiency motors reduce all of these loss mechanisms.

2.10.1 Core Losses

Core losses are the sum of the energy needed to magnetize the core material (hysteresis losses) and losses due to small eddy currents which flow in the core. These losses are generally constant regardless of motor load and account for 15% to 25% of losses under full load. High efficiency motors typically reduce these losses by half or more using several design changes. Hysteresis losses are reduced by using high grade silicon steels in the core. Eddy current losses are reduced by using thinner gauge material and improved interlaminer insulation. Core losses may also be reduced by lengthening the core to reduce magnetic density. All of the changes to achieve higher efficiency are fundamental design and material improvements which should not degrade over time.

2.10.2 Stator and Rotor I^2R Losses

Stator and rotor I^2R losses occur from electrical resistance in the windings of the stator and in the rotor and end rings. They vary with the square of the current and usually represent half or more of all losses at full load. High efficiency motors typically reduce the losses in the stator by using improved slot designs and by increasing copper content. The rotor losses are reduced by increasing the cross-sectional areas of the rotor bars and end rings and changing the shape of the rotor slot. These changes involve dimensions and materials and should not degrade over time.

2.10.3 Friction and Windage Losses

Friction and windage losses result from bearing friction and friction from the air flow through and within the motor. These losses usually represent less than 10% of all losses at full load and are considered constant regardless of load. These losses are reduced in most high efficiency designs by modifications to the ventilation system (e.g., reduced fan size). The change in losses from high efficiency designs is moderate and any difference is unlikely to degrade. Reduced ventilation can be used in high efficiency motors without adverse effects because of the lower temperature rise inherent in high efficiency designs due to their lower losses.

2.10.4 Stray Load Losses

Stray load losses are due to a variety of other small loss mechanisms (the largest of which is harmonic flux induced by the load current). These losses usually total 1%-2% of motor output and may represent about 10%-15% of total losses at full load. They tend to vary with the square of the current. They are reduced somewhat in high efficiency motors through a variety of improved design, manufacturing, and quality control mechanisms (including maintaining a concentric air gap, using coil spans in the winding, and improved casting of the squirrel cage). These changes may reduce the losses by about a third. None of the changes identified are likely to lead to relative degradation.

2.10.5 Relative Degradation Analysis

The above analysis of motor loss mechanisms indicates that relative technical degradation of the efficiency improvements is unlikely because they are primarily due to fundamental changes in materials and dimensions (see Singh 1994 for a more detailed analysis of the effects of each of these design changes). Many manufacturers and researchers state that high efficiency motors are less likely to degrade than standard efficiency units because they are made with improved materials and processes and their lower losses lead to lower operating temperatures and therefore longer life for lubrication, bearings, and insulation. Some researchers point out that high efficiency designs may not run cooler because other design and maintenance changes, such as smaller fans and less frequent lubrication, are made to take advantage of this fact (Nailen 1994). However, manufacturers still claim that they run cooler after accounting for these effects (Evans 1984, Moser 1984). Manufacturers also state that the high efficiency designs are better able to withstand overloads, frequent starting, voltage and frequency variations, high ambient temperatures, and high elevations (McGovern 1984). One manufacturer claims that the high efficiency motors will have double the life of standard efficiency units according to accelerated life testing (ibid.). Many sources indicated that efficient motors provide numerous benefits in terms of reliability, service life, part-load efficiency, and electrical characteristics (for example, see McCoy et al. 1993 and Nadel et al. 1992). No researcher or manufacturer contacted believed that high efficiency motor savings would degrade over time. In fact, nearly all contacts believed that standard and high efficiency motors fully maintain their efficiency over time if they are not rewound.

2.10.6 Common Degradation Mechanisms

Friction losses and insulation deterioration were identified as two potential degradation mechanisms. While friction losses could increase as lubrication breaks down or bearings degrade, if such losses were significant (e.g., >0.5% of motor load) they would quickly lead to motor failure as they are self-aggravating -- the increased losses result in self-heating which leads to more losses until failure occurs rapidly. Similar arguments can be made for other potential degradation mechanisms (e.g., insulation deterioration) as heat is the main cause of material degradation and failure and increased losses lead to higher temperatures.

The only significant motor efficiency degradation mechanism identified was from improper rewinding which can damage the core when high temperatures are used to strip out the old windings (Montgomery 1989). This loss in efficiency happens during the rewind and does not accumulate over time, although the likelihood of motor failure in such cases may substantially increase. No evidence was found indicating that high efficiency motors would be either more or less likely to suffer from efficiency degradation due to rewinding. If proper rewind standards are followed (EASA 1992), no efficiency loss should occur from rewinding either type of motor.

PEG sought empirical data to substantiate claims that motor efficiency does not degrade over time. The only suitable data found were in a study by GE of measured in-field motor losses (McGovern 1984 and Evans 1984). The results from 70 motors were presented. Of the 43 motors which had never been rewound, losses averaged 98% of nameplate information, indicating that there was no degradation over time. The 27 motors which had been previously rewound showed a 16% average increase in losses over the nameplate. This data is in the same range as other GE tests of core losses on previously rewound motors (Montgomery 1989). Those tests showed an average 32% higher than expected core loss in a large sample of rewound motors, implying a 5%-8% increase in overall losses on average. No other data directly comparing nameplate to in-field motor efficiency were found. However, the engineering analysis, the available data, and the opinions of researchers and manufacturers point to no significant degradation in motor efficiency over time and no relative technical degradation for the high efficiency motors.

2.10.7 Other Motor Savings Issues

If motor efficiency remains constant over time, then savings could still degrade if motor loads or operating hours were to change systematically. There is no evidence to suggest that either of these would occur except for perhaps systematic load increases in new facilities as the equipment driven by the motor degrades (e.g., fans get dirty). However, the savings from a high efficiency motor would increase if loads increased and would decrease less than proportionally if loads decreased because high efficiency motors have a flatter efficiency vs. load profile, especially at loads below 50% (WSEO 1993). Therefore, these factors are unlikely to lead to relative degradation.

2.10.8 Conclusions

The analyses of relative and absolute performance degradation mechanisms and other operating factors which may influence energy savings all point to no relative degradation in savings over time from efficient motors. The superior materials and design of efficient motors make it more likely that any relative changes in motor performance over time will lead to greater energy savings.

> **PEG concludes that energy savings from high efficiency motors will not decline over time due to technical degradation.**

2.11 Adjustable Speed Drive for HVAC Fan

The baseline measure is a 100 hp motor operating a supply air fan controlled by variable inlet vanes or discharge dampers. The efficient measure is a pulse-width modulating (PWM) adjustable speed drive (ASD) controlling the same motor.

No information was found concerning degradation in the baseline technologies. They are fairly simple mechanical devices which may fail (lock in position or fail to adjust properly) although no evidence was found indicating that these failures were common and went unfixed. Overall degradation in system performance is believed to be small.

ASD’s save energy by varying the speed of a motor to meet load instead of using throttling devices which restrict flow (in fan or pump operation). Savings are particularly high when an ASD is used to adjust the speed of a fan because the energy required to drive a fan is related to the cube of its speed. Therefore, operating a fan at half speed ideally requires only one eighth as much energy as operating it at full speed. ASD’s are usually controlled by sensors monitoring the process or a control panel (if frequent adjustments aren’t required).

Electronic ASD’s are solid state devices with no moving parts. Pulse width modulating ASDs work by using solid-state components to convert the AC input power into filtered DC power and then chopping this power into variable width pulses that synthesize the desired variable frequency and voltage AC waveform. The speed of the motor changes based on the frequency generated. The shape of the generated output is not as smooth as the waveform found on most power distribution systems, but most PWMs have low harmonics and high power factor at reasonable loads. ASD’s are not 100% efficient and have switching and transformer losses. These losses require cooling (usually passive) and thermal protection. Overheating caused by inadequate passive cooling has been a significant source of system failures and forced ventilation is not an uncommon retrofit.

2.11.1 Component Degradation

Manufacturers and researchers were asked about potential ASD degradation mechanisms. One manufacturer noted that the input line rectifier and the inverter should not degrade in performance over time, however the electrolyte in the electrolytic capacitor may dry out over time and increase system energy usage, but probably by less than 0.1% (this should amount to less than a 1% loss in savings). Another source noted that ASDs themselves can be damaged by harmonics which may affect efficiency, but no documentation of such efficiency losses was found. Most sources believe that significant ASD efficiency degradation is unlikely due to its solid state design. Instead, problems with components should cause total failure, not degraded performance. If any loss mechanism increased significantly, the unit would overheat and fail.

2.11.2 Sensors and Control Settings

ASD savings depend upon proper sensor performance and control settings. No information was found which documents sensor performance degradation, although the design of some types of sensors could lead to drift over time. Improper adjustment of control settings by building operators is another potential cause for reduced savings over time. One recent study in Texas found that increases in the pressure settings for ASDs used in VAV systems reduced energy savings significantly at some sites (Haberl et al. 1995). Overall, there is insufficient information available to assess the frequency or severity of sensor and control setting problems, but the potential for degraded energy savings exists. In addition, sensor failure or ASD failure could lead to system bypass, eliminating energy savings. These issues would be best addressed in retention studies for this measure. Retention studies will need to note control settings and check sensor calibrations over time at the sites visited.

2.11.3 Interactive Effects

Interactions between varying loads, ASDs, motors, and the systems which they drive were also identified as a potentially significant source of performance uncertainty over time. Again, little information was found on this topic.

In terms of electrical interactions, several manufacturers are working to try to optimize the electrical characteristics of the motor-ASD system (including detailed “motor mapping” to optimize ASD control for a particular motor). ASD’s tend to increase motor losses and therefore motor temperatures because of harmonics. If the motor operates at a higher temperature it may fail sooner but it is unlikely to experience declining efficiency over time (see section 2.10 on motors). The impact of operating motors which were designed for a fixed speed and voltage on an ASD are not fully understood. However, motors do not lend themselves to many degradation mechanisms without failure.

ASDs may also provide several benefits to the equipment and systems which they drive (see Welch et al. 1992). ASDs have soft starting capabilities and may also dramatically reduce on-off cycling, thereby reducing stress and wear on motors and drivetrain components. This reduced stress may lead to greater reliability and equipment life and could also provide for better long term overall system efficiency. ASDs can also maintain more precise control over HVAC system operating conditions (e.g., narrower temperature deadbands) which can translate to more efficient system operation. No information on the long-term impact of either of these benefits was found.

> **PEG concludes that energy savings from ASDs are unlikely to degrade over time due to changes in measure performance. However, sensor and control setting changes, including system bypass, may significantly affect the persistence of ASD savings and should be investigated through measure retention studies.**

2.12 Infrared Gas Fryer

The baseline measure is a commercial gas-fired deep fat fryers equipped with standard atmospheric burners The efficient measure is a deep fat fryer equipped with an infrared burner. Fryer efficiency has received little attention in part due to the lack of uniform efficiency testing procedures for the equipment. This issue is currently being addressed by PG&E through the development of the Uniform Testing Procedure (Conner et al. 1991). Very little information is available on fryer performance, with PG&E, SCE, and AGA being the primary sources. No published information on performance degradation was found.

Infrared deep fat fryer efficiency is typically cited at 75 - 80% compared to atmospheric burner deep fat fryers that have efficiencies of 40 - 45% (Lobenstein et al. 1994). AGA lab tests indicate that infrared deep fat fryers consume 35% less total energy than atmospheric burner type fryers (Diggins et al. 1987). This improved efficiency allows the equipment to operate with the same cooking capacity but a substantially lower energy input rate (the Frymaster GF-40 atmospheric fryer has an input of 122,000 Btu / hr, the Frymaster MJH-50 & 52 infra-red fryers have rated inputs of 80,000 Btu / hr, while all have the same shortening capacity of 50 lbs.).

The energy savings from infra-red fryers occur due to three primary design differences: burner design, vat / heat exchanger design, and ignition system.

2.12.1 Burner Design

Infra-red fryers use a power burner instead of an atmospheric burner. This burner design improves efficiency by reducing excess air. PG&E’s UTP tests found that the infrared fryer had a water boil efficiency of 65% while the atmospheric burner equipped fryer had a water boil efficiency of 57%, providing a savings of about 12% (Nickel 1991a 1991b). This savings value is considerably lower than the total expected savings and represents an estimate of savings when the burner is on, which may not be a large proportion of the time. Clearly, design differences other than the burner account for the majority of the savings.

In terms of performance degradation, each burner technology may suffer a small amount of reduced efficiency. Atmospheric burners used in “dirty” environments are subject to fouling which results in incomplete combustion. With incomplete combustion, the total heat content of the gas is not delivered and sooting of the heat exchanger tubes may result. Some atmospheric burners also have baffles in the burner tube, which can increase the likelihood of fouling. Infra-red burners have combustion air intakes and blowers which may become clogged or fouled. Frymaster infra-red units use a centrifugal end switch to allow burner ignition and not a pressure proving switch. This device will not detect insufficient air flow and therefore obstruction of the air supply (e.g., due to dust, dirt, or grease buildup on the air inlet or blower wheel) could occur and eventually reduce efficiency. Frymaster plans to change to a pressure proving switch and currently equips units shipped overseas with these switches but they are not in production yet for U.S. models.

When asked about overall performance degradation of fryers, a contact at Frymaster stated that the infrared fryer would not experience any different rate of degradation than the atmospheric unit. Both designs may experience some degradation due to clogging of ports and fouling of heat exchange surfaces. They stated that they have never investigated the degradation of equipment over time and do not know of anyone that has. They also stated that their infrared burner is a ceramic type burner and would not be as prone to clogging.

Based on experiences with gas space heating systems, efficiency degradation of the combustion process is unlikely to be large in comparison to overall energy savings from the infra-red unit (the vast majority of heating systems operate at steady state efficiencies close to their ratings). While this experience may not be completely applicable to fryer technology and the environment and demands of commercial cooking establishments, it provides some support for suggesting that large degradation rates due to incomplete combustion are unlikely.

2.12.2 Heat Exchanger / Vat Design

The infra-red unit's burner sits outside the vat and the vat design provides a large heat exchange area. The standard unit's burners are located in tubes immersed in the vat (although some atmospheric units do not use this design). The standard immersion tube design experiences much higher stand-by losses because of the effective increase in vat area (and this extra area has a free flow of air). This design difference contributes significantly to the infra-red unit's 40% lower energy usage rate in stand-by mode compared to the standard unit (as tested by PG&E).

Heat transfer surfaces may degrade from fouling due to flame impingement or incomplete combustion leading to the production of carbon. No information was found which would indicate that there is any relative degradation from this design difference. The infra-red vat design would appear to provide for easier identification of fouling and cleaning of the heat exchange surfaces than the standard immersion tube design.

Another performance advantage of the infra-red design is that it allows the frying vat to be split into two separate vats. The split vat design can provide additional savings during non-peak times because it can be operated with only half as much oil. These savings should not degrade. The splitting of the vat does add to the number of thermostatic controls and pumps but these changes may only affect reliability and should not be subject to relative degradation.

2.12.3 Ignition System

The infra-red unit uses an intermittent ignition device instead of a standing pilot light. The savings from this difference can be significant. The iid could suffer from more reliability problems than the standing pilot, but the savings will not degrade (see Farnsworth et al. 1984).

2.12.4 Relative Contributions to Overall Savings and Conclusions

The total savings from infra-red fryers are typically estimated at 30%-40%. The actual savings and relative contribution from each of the design difference will depend on the how the fryer is used. In most applications, the fryer operates the vast majority of time in either stand-by mode or off. In fast food restaurants with long operating hours, stand-by mode comprises most of the operating time. In many ways, a fryer is similar to a domestic water heater with an open, uninsulated top -- most of the energy is used to maintain set-point temperature in stand-by mode and overall efficiency is much less than combustion efficiency (ASHRAE Fundamentals Chapter 26 estimates 28% and 37% overall system efficiency for standard and infra-red fryers).

PEG analyzed a variety of scenarios concerning fryer usage patterns and estimated the potential impacts of combustion efficiency losses associated with the only relative degradation mechanism identified -- obstructed combustion air flow. This analysis indicated that only a third of the total savings are likely to come from steady state efficiency differences and that combustion air obstructions are unlikely to affect that component of savings by more than a third. Therefore, the total relative degradation in savings which could occur due to this mechanism is probably less than 10% (i.e., about 3%-4% out of the 30%-40% savings). This small loss in savings would only occur in those units which experience problems with combustion air, implying that the average effect is much smaller than this value. In addition, this potential degradation may be offset by relative degradation of the standard unit due to the greater likelihood of fouling problems with the immersion tube design. The overall conclusion of this analysis is that, while a small amount of relative degradation may occur, it is most likely that there will be no relative degradation. In addition, due to the small magnitude of the potential degradation, it is unlikely that it could be reliably measured at a reasonable cost.

> **PEG concludes that the savings from gas infra-red fryers are unlikely to degrade over time. Small potential performance degradation from reductions in combustion air flow are possible but are believed to be unlikely to significantly affect average savings and are equally likely to be offset by other potential degradation mechanisms which favor the infra-red design.**

2.13 Residential Ceiling Insulation

The baseline measure is defined as either R-11 insulation in an existing attic or code-required insulation in a newly built home's attic. The efficient measure is the addition of insulation to bring the existing home's R-value to 30 or the new home's R-value to 38. The most common insulation material is fiberglass, either batts or blown.

Attic insulation saves energy by reducing the heat loss rate through the ceiling. The conductive heat transfer is inversely related to the effective R-value. The R-value of fiberglass is primarily determined by its thickness and density. Energy savings from the increased level of insulation depend on proper coverage and performance of the material at rated R-value and may also be reduced by parallel heat transfer mechanisms into the attic (air or duct leakage and other "thermal bypasses"). Performance degradation may occur over time if the insulation is removed, compressed, disturbed, or damaged. A number of circumstances were identified which could lead to these results including: human intervention. settling, wind shifting, moisture damage, and animal disturbance.

Human intervention may be the largest potential degradation mechanism for attic insulation. Many situations can arise which reduce insulation effectiveness:

- Occupants may decide to add storage space to the attic on top of the insulation, compressing it to the height of the framing. This event may be more likely in new construction than in retrofit situations where occupants have already created their storage areas.
- Some homeowners may choose to turn the attic into additional living space or perform other major renovations that could eliminate the insulation (although some other form of insulation would presumably be used on the finished space, the "savings" from the higher insulation levels would likely be lost). This occurrence is considered a measure retention, not technical degradation, issue.
- Contractors or occupants may perform work in the attic which leads to the disturbance, removal, or compression of some insulation. Some of the more common examples include alarm system and cable TV installers and HVAC technicians (if heating equipment or ductwork is located in the attic). Although large scale disturbances are unlikely, removal of some sections of fiberglass batt and significant compression of blown fiberglass are not atypical results from these activities.

Settling of blown insulation is a well-known phenomenon. Cellulose is particularly prone to settling after installation. Research indicates that R-values may decrease by about 10% due to this effect and most of the settling occurs within in the first year after installation (see Svennerstedt 1992 and Wilkes et al. 1992). In contrast to cellulose, fiberglass insulation does not settle appreciably and is generally not tested for settling. Rockwool is somewhat similar to fiberglass and test data has shown settling of less than 1% (ibid.). Settling is not considered a likely degradation mechanism for fiberglass insulation.

Blown fiberglass insulation may be subject to shifting from wind patterns at edges of the attic. This effect has been noted in windy climates with substantially open soffit venting. Insulation can become moisture damaged from roof leaks or, in extreme circumstances, from moisture transfer from the house below. In addition, fiberglass batt insulation apparently provides an appealing nest-building material for squirrels and significant plundering of insulation for this purpose has been reported (although it is uncommon).

The potential impacts of the above effects can be reasonably estimated using standard heat transfer theory. Conversations with insulation contractors and weatherization providers were used to provide rough estimates of the frequency and severity of these occurrences with a particular focus on California's climate and housing stock. The key degradation issues identified were compression due to added storage and disturbances caused by miscellaneous contractors working in the attic. A "worst case" scenario was developed in which every house adds storage space equal to 3% of attic area which compresses the existing insulation to 5.5 inches. In addition, every house has 2% of its insulation removed due to contractor or homeowner actions. The impact of these events will change the conductive heat transfer rate through a typically 1600 square foot attic with R-19 insulation from 78 to 97 Btu / hrºF while the same attic with R-30 insulation will change from 51 to 71 Btu / hrºF. The relative increases in heat loss rates are 25% and 40% respectively, but the absolute increases are virtually identical -- 19 Btu / hrºF for the R-19 attic and 20 Btu / hrºF for the R-30 attic. Therefore, there is little net impact on energy savings (a change from 27 to 26 Btu / hrºF). This result makes sense when one considers the case of insulation removal. When insulation is removed, the savings are only lost in the area removed; the remaining undisturbed area continues to provide the same savings. Given the relatively small areas involved and the small proportion of houses likely to actually be affected, the net degradation in overall savings should be unmeasurably small. Therefore, while disturbances to attic insulation caused by human interaction can have a large impact on heat loss, no significant relative degradation should occur from higher insulation levels.

The level of degradation in attic insulation savings may also be roughly assessed based on savings persistence studies of weatherization programs. Attic insulation retrofits have often been the key component responsible for most of the savings of weatherization programs. Studies of weatherization programs based on billing data have generally indicated good persistence of savings. The results of a DOE-sponsored persistence study of the Wisconsin weatherization program over a seven year period found that net savings were stable or increasing over time (Narum et al. 1992). The primary measures in the program were attic insulation and heating system retrofits. The results for houses which received only building shell measures (insulation and air sealing, but no heating system work) also showed that savings persisted. While the stability of these savings over time may be due to many factors (including comparison group usage increases), they tend to refute the idea that insulation savings are significantly degrading over time.

In summary, no mechanisms for relative degradation were identified and available studies support the belief that attic insulation savings persist over time.

PEG concludes that the energy savings from added attic insulation are not likely to suffer from relative technical degradation over time.

3.1 A Research Plan for Assessing the Relative Technical Degradation of Commercial Package Air Conditioners

3.1.1 Introduction

This research plan was developed as part of the CADMAC Statewide Measure Performance Study to assess the impacts on energy savings of technical degradation which may be experienced by high efficiency commercial package air conditioners relative to standard efficiency units. A more detailed assessment of potential technical degradation mechanisms for this technology is provided in section 2.1 of this report. This plan was developed based on that analysis which concluded that relative degradation may occur due to heat exchanger design differences.

3.1.2 Technology Description and Review of Degradation Issues

Because of the many variations in the designs of standard and high efficiency units, the degradation analysis focused on the most common models which have a significant proportion of the market. PEG contacted distributors and manufacturers to identify the most popular rebated and standard efficiency units and acquired product specifications.

A review of the product specifications found that the main design change employed by manufacturers to increase efficiency involved increasing heat exchanger size, primarily by increasing the number of heat exchanger rows (for both evaporators and condensers). One manufacturer also switched from reciprocating to scroll compressors. The engineering analysis of these design changes, presented in section 2.1, concluded that fouling rates may increase from adding heat exchanger rows. The analysis also concluded that an increased fouling rate in high efficiency units may still not cause relative degradation because systems with over-sized heat exchangers would be less sensitive to changes in heat exchanger capacity than systems with standard sized heat exchangers. The lack of information on absolute and relative heat exchanger fouling rates and their impacts on system efficiency led PEG to conclude that more research was needed to assess relative technical degradation for this measure.

3.1.3 Research Questions

The main research objective is to assess the relative technical degradation of the high efficiency commercial package air conditioners compared to baseline units. If relative degradation is found, then the expected rate of degradation needs to be quantified in terms of multipliers which can be applied to the first year savings figures for each year of measure life. The literature search and engineering analysis presented in section 2.1 led to the development of the following specific research questions:

1. For each heat exchanger (evaporator and condenser), does adding rows to the heat exchanger increase its rate of fouling (defined here as change in heat transfer capacity per year)?
2. If yes, does this increased rate of fouling reduce system efficiency at a greater rate in systems with more rows than the efficiency loss in baseline systems which have a lower fouling rate?

3. If yes to 1 & 2, what are the average fouling rates for systems installed under the 1994 DSM programs in California and what would the fouling rates be for standard systems exposed to the same conditions?
4. If yes to 1 & 2, what are the efficiency impacts of the fouling rates estimated in question 3 on the efficient and baseline systems for each year of their useful life and how does this affect the difference in energy usage rates by year?
5. If yes to 1 & 2, are there any other design differences between the baseline and efficient units which would mitigate this relative degradation.

The uncertainty in the existence of increased fouling and its impacts on system efficiency create two levels of research questions. Only if the first two questions are answered affirmatively do the last three questions need to be addressed. This feature of the research questions provides the opportunity to design a two stage research plan where the performance of the second stage is contingent upon the results of the first stage.

3.1.4 Technical Discussion

The key research issue concerns heat exchanger fouling and its impact on system efficiency. In developing a research plan to answer these questions, one needs to consider the factors affecting fouling rates and their impacts.

3.1.4.1 Factors Influencing Fouling Rates

In addition to heat exchanger design issues such as materials, geometry, fin spacing and number of rows, there are many factors which affect fouling rates and their impacts. For evaporators, the rate of fouling depends on many aspects of the indoor environment and air conditioning system including:

- the levels, types, sizes and “stickiness” of particulates (e.g., dust, smoke), chemical vapors, aerosols, biological agents (bacteria, mold spores) and other pollutants ;
- relative humidity and temperature (which affect coil wetness and potential biological growth);
- filter type, location and maintenance;
- duct location and leakage;
- air handler flow rate;
- annual operating hours;
- maintenance practices and effectiveness concerning cleaning heat exchangers; and
- specific combinations of all of the above.

While some information exists about the typical conditions for some of these factors, others are poorly understood and virtually nothing is known about the range of combinations and how it may vary due to factors such as geography, business type (e.g., offices vs. restaurants), and facility smoking policy. Different combinations of factors may lead to differing types of fouling and impacts on performance. Fouling may occur throughout the coil providing an insulating layer over the fins (whose insulating effect will depend on fouling material composition and density), or it may primarily build up on the coil face, reducing the effective coil size. The primary impacts of evaporator fouling are reduced air flow through the coil and a reduced heat transfer coefficient. These changes will reduce system capacity while also reducing indoor fan power draw and compressor power draw. The overall efficiency is reduced because capacity is reduced at a greater rate than power draw, but peak demand will tend to decrease for units running continuously during peak.

Condensers are subject to many of the same factors as evaporators but the operating environment tends to be somewhat better understood because it depends upon outdoor, not indoor, conditions. However, there are still many unknowns and variations in terms of pollution levels, exposure to salt (a common cause of fouling in coastal areas) and other climatic influences. A fouled condenser coil will increase compressor power draw and slightly reduce outdoor fan power draw. The overall effect is to reduce system capacity and efficiency while increasing power draw.

3.1.4.2 Fouling, Efficiency, and Energy Usage

The primary method used by manufacturers to improve system efficiency involves increasing heat exchanger effectiveness through adding rows which increases the heat exchange area. Such increases in heat exchange area have diminishing returns in terms of improved efficiency as described in section 2.1. This relationship has important implications for investigating fouling impacts because fouling may be viewed as a decrease in effective heat exchange area. Energy savings will increase over time if the standard and oversized heat exchangers both foul at the same rate because the efficiency curve is flatter with a larger evaporator. Therefore, relative degradation will only occur if the relative rate of fouling for the efficient unit’s heat exchanger is significantly greater than the standard unit’s rate. This relationship needs to be considered and further developed through the research efforts.

The analysis presented in section 2.1 indicate that heat exchanger fouling should rarely affect system efficiency by more than about 20%. This level of impact is significant relative to the savings expected from high efficiency units, but is small enough when occurring over a number of years to go unnoticed by most customers in their energy bills. In addition, because most units are significantly oversized, fouling is unlikely to reduce capacity to the point where loads can not be met. Therefore, customers can not be expected to have any knowledge about fouling problems. Field research has also indicated that heat exchangers are rarely cleaned and cleaning efforts are often ineffective.

3.1.5 Data Collection and Measurement Approaches

Given the research questions and the brief technical discussion above, three potential data collection and measurement approaches were considered in developing a research plan: laboratory tests, field tests, and energy usage analysis.

3.1.5.1 Laboratory Tests

Laboratory tests can accurately measure the performance and efficiency of air conditioning systems in detail. They also provide the ability to carefully specify and control test conditions and accelerate certain aspects of real-life aging phenomena. The results of lab tests may be used to develop and validate models of how performance is affected by given operating conditions. The disadvantages of lab testing include: the difficulty in specifying test conditions which properly replicate the range and typical values of actual field conditions, the uncertainty in extrapolating test results to a large and varied field population about which little is often known, and the relatively high cost for the facilities and expertise needed to design and perform the tests.

3.1.5.2 Field Tests

Field tests can assess, and potentially measure, actual field operating conditions and performance. The advantages of field tests include their ability to represent actual field operating conditions and performance and their relatively modest cost. The disadvantages include little or no control over test conditions, a limited range of ages for the measures of interest, and the logistical and technical difficulties in measuring the desired performance parameters.

For commercial package air conditioners, no reliable, proven field testing procedures exist to measure heat exchanger fouling or overall system efficiency. While efficiency can be measured reasonably well for the testing conditions, these results are difficult to relate to typical or seasonal efficiency. In addition, the actual field efficiency of an air conditioner depends upon many factors, such as refrigerant charge and air flow rates, which would add considerable variability into any measured results. Fouling is even more difficult to measure than efficiency but it can be assessed qualitatively through visual inspection and quantitatively through coil pressure drop and air flow measurements (although these measurements are time-consuming and logistically difficult). A comparison of field pressure and flow measurements with manufacturers' or laboratory data may be used to assess relative fouling through its impact on blocking the coil. For the condenser, a pressure measurement alone would probably suffice for making this calculation. The impact of the level of fouling on system efficiency would need to be based on models of system performance, which would need to be calibrated and/or developed through laboratory testing.

Another field testing approach would involve testing the system and then cleaning the coils and re-testing. One advantage of this method is that the change in measured parameters from cleaning coils can provide a much more direct measure of fouling then just a single measurement which is affected by many factors. However, this approach may understate fouling if coils can not be fully cleaned to original condition. Unfortunately, the design of most package unit coils makes a thorough cleaning very difficult and coils with more rows are harder to clean. Therefore, comparisons between coil types would likely be biased toward understating relative degradation.

3.1.5.3 Energy Usage Analysis

One could attempt to measure overall system performance degradation through a long term analysis of billing and/or sub-metered data. By comparing the changes in cooling loads over time for buildings with standard and high efficiency equipment, changes in savings may be estimated. The advantages of billing analysis include large sample size availability and relatively low costs. Its disadvantages include its inclusion of all other factors affecting energy usage (not just technical degradation of the equipment of interest) and an associated high level of variability. Submetered data is considerably more expensive, but provides usage data for the equipment of interest and also provides load shape information. Unfortunately, many factors affect cooling usage beyond air conditioner efficiency. Changes in occupancy patterns, thermostat settings, internal heat gains (e.g., from lighting, equipment, occupants, and solar) and the building shell can all have large impacts on cooling usage. Therefore, considerable variability can still be expected. The problems caused by this variability are further compounded by the small impacts which would need to be discerned over time. For example, if the efficient equipment is expected to provide 20% savings and if technical degradation causes this savings to drop in half over ten years, then the usage analysis will need to detect and accurately measure a process which changes the difference in usage by only 1% per year over the noise of year-to-year variability, changes in occupancy, and any other temporal trends in cooling usage. The analysis would need to provide an extremely high level of precision in examining a long time series of data while somehow identifying and maintaining an appropriate comparison group. It is unlikely that this effort would be successful.

A potentially more promising analysis approach would be to clean the coils in a number of systems and measure the energy savings through pre / post metering or billing analysis. This approach would improve precision because the effect size is larger, but the need to compare the relative savings for the two groups would still lead to precision difficulties. In addition, this approach is based on the assumption that the coils could be fully cleaned, which is unlikely as described previously.

3.1.6 Proposed Approach

Based on an assessment of the research questions, the technical discussion, and the relative costs and value of different potential approaches, PEG developed a two stage research plan involving laboratory and field testing to cost-effectively meet the research objectives. Laboratory testing of baseline and efficient systems will be used to assess whether relative degradation may exist due to added rows of heat exchangers, answering the first two research questions. If the results of this testing indicate that no relative degradation will occur, then the research is complete. If a small amount of relative degradation is deemed likely, then default degradation factors may be developed which are agreeable to all parties. If the tests indicate that large degradation is possible, then field testing will be needed to quantify the average impact of this effect.

3.1.6.1 Stage 1 - Laboratory Testing

The first two research questions relate to the relative rates of heat exchanger fouling and the impact of fouling on system efficiency. These questions are best assessed through controlled laboratory testing. A field testing approach would likely prove inconclusive due to measurement difficulties. Even if reliable measurements of fouling and efficiency could be made, the large expected variation in field conditions would require either large samples or long term tracking of smaller representative samples, both of which would be extremely expensive. In contrast, laboratory testing can provide accurate and detailed comparisons of two systems over a wide range of potential field conditions simulated through accelerated testing procedures. This level of control and accuracy can produce definitive answers to the first two research questions in a relatively short period of time. If no relative degradation is found, then no further research is needed. If potential degradation is indicated, then additional work will be needed to quantify the impact. This process may involve developing a model which relates efficiency impacts to quantities which could be reliably measured in the field.

The recommended approach involves acquiring the most popular standard and efficient systems in the California market (Carrier models 48TJE006 and 48HJE006) and purchasing four or more additional heat exchangers (evaporators and condensers) for each unit. The units would be tested in a controlled split-psychrometric chamber with highly accurate measurement of system and operating parameters to establish baseline efficiency. An experimental design would be developed to expose the heat exchangers to selected reproducible accelerated fouling environments. Because standard fouling test procedures do not exist, they will need to be developed as part of this project. The nature of the environments to simulate accelerated aging would be determined based on a literature review and analysis of indoor and outdoor air quality research, preferably for commercial buildings in California, combined with a review of program records (to identify the distribution of system locations and applications). In addition to standard pollutants such as dust, smoke, grease, and particulates, consideration will also need to be given to dry vs. wet coil operation as well as salt levels in coastal areas.

The performance of each system will be tracked as the cumulative exposure increases and fouling occurs. Coil pressure drops and system flow rates need to be monitored in addition to standard performance and efficiency parameters. Periodically in this process, an ARI standard efficiency test will be performed and the heat exchangers will be examined to assess the level of fouling through magnified visual examination and weight. The accelerated testing will continue until air flow drops by at least a specified amount (perhaps 50%) or efficiency declines by a specified amount (e.g., 25%). At the conclusion of testing for a given heat exchanger and environment, the heat exchanger will be cleaned using a “standard” but thorough approach and performance re-tested. The heat exchanger will then be replaced with a new heat exchanger and a different accelerated fouling environment. A total of at least four testing environments for each heat exchanger on each unit will likely be needed in addition to some tests to assess interactive effects by fouling both heat exchangers simultaneously.

The primary data analysis task will be to assess whether changes in system efficiency measured during any of the tests would cause energy savings from the efficient unit to decline relative to the standard unit. If this analysis finds that no combination of factors will produce relative degradation, then the research is concluded. However, if significant potential degradation is indicated, then field testing may need to be performed in order to assess actual operating environments and fouling. If the estimated potential degradation is small, the parties may decide that field testing is not a worthwhile use of resources and instead could estimate degradation factors based on available information.

3.1.6.2 Stage 2 - Field testing

The best way to capture the overall impact of the many field factors which affect heat exchanger fouling is to develop field test procedures which can assess fouling and then apply these procedures in a representative sample of baseline and efficient units with a range of ages. Because direct field measurement of overall system efficiency is impractical, the field assessment will need to measure system parameters which can be used as inputs to a model of fouling and system efficiency. This model will need to be developed from the laboratory testing and therefore the specific design of the field tests will need to be adjusted based on those results. The lab testing will also provide information on which environments are most likely to cause degradation and how fouling rates may vary over time. These findings will play an important role in developing a sampling strategy in terms of both stratification and sample size.

The field testing would likely involve measuring coil pressure drop and air flow to assess relative fouling (this approach has been used in the few ASHRAE papers which have looked at this issue). Visual inspection may be used to assess the pattern (e.g. face loading, vs. throughout coil) and composition of this fouling. Data from efficiency-related tests (e.g., heat exchanger temperature differences and power draw) may also play a role in relating the fouling to efficiency changes. The site visits will also be used to collect information on maintenance practices, particularly concerning heat exchanger cleaning.

A sampling and recruitment plan for the field testing will be developed based on the lab test results and an analysis of program records which characterize the participant population (e.g., in terms of location and business type). A stratification plan will be based on this information and consider geography (e.g., coastal vs. inland, hot and dry vs. mild and moist), facility use / business type (e.g., offices, retail, and other “clean” spaces vs. restaurants, factories, and other “dirty” spaces), and system age (systems of two or three vintages spanning as long a period as possible given product life on the market).

Final sample design issues, such as number of strata and number of sites in each cell, will need to be decided based on the expected effect size (i.e., the amount of relative degradation expected), the cost of the data collection activities, and other results of the lab testing stage of the work. Because these results will not be known until the lab testing is complete, it may be best to divide the research into two separate projects. The scope of work for the first stage laboratory testing would include developing the sample design and test procedures for the second stage field testing if relative degradation is indicated. If no relative degradation is found in the lab testing, then the second stage would not be needed.

3.1.6.3 Data Analysis

The primary approach for estimating relative degradation rates will be to use the field testing to establish typical fouling types and rates and then use this information with the lab test results to generate estimates of efficiency vs. time for the baseline and efficient systems. The relative degradation can then be calculated based on these two efficiency vs. time curves. The final results will need to be expressed in terms of multipliers to be applied to first year savings figures for each year of the measure life.

The degradation calculations will most likely need to be performed separately for key sub-groups/strata and then combined through weighting based on population estimates of group membership. If significant inter-group variations are found, separate sets of multipliers may need to be developed for different applications and / or regions which are readily identifiable.

3.1.7 Task List and Estimated Budget

The table on the next page lists the key research tasks and provides low and high budget estimates for each. PEG recommends separating the research into two sequential projects and sub-totals are provided for each. There is a good chance that laboratory testing will find that technical degradation will not occur or will be very small. If so, then total project costs should range from $65,000 to $101,000.

If field testing is needed, then total project costs could range from $142,000 to $339,000. Budgets at the high end of this range may not be realistic (if expensive testing is needed then smaller sample sizes will be used). The field testing costs should be considered speculative and are based on the assumption that well-trained technicians will need to expend considerable time performing complex tests on the equipment and that sites will be located throughout the state requiring significant recruitment and travel costs. Lab test results may be able to identify a simpler field procedure and sampling plan. The possibility for other cost reductions may also be discovered during the first stage. In any event, trade-offs between cost and accuracy may need to be made in order to provide sound estimates at a reasonable cost.

Commercial Package Air Conditioner

Technical Degradation Research Project - Task List and Budget

Task	Budget Low	Budget High
Stage 1 - Laboratory Testing		
Equipment Purchase	7,000	9,000
R&D on Accelerated Fouling Test Procedure	8,000	12,000
Lab Rental & Staffing	20,000	35,000
Data Analysis	20,000	30,000
Reporting	10,000	15,000
Sub-Total Stage 1	**$65,000**	**$101,000**
Contingent on findings: Design field testing & sampling	8,000	12,000
Total Stage 1, if relative degradation found	**$73,000**	**$113,000**
Stage 2 - Field Testing		
Per Site Costs:		
Recruitment, Scheduling, and Customer Incentive	250	400
On-Site Testing	400	1200
Travel, Materials, Misc. Expenses	200	600
Total Per Site Costs	$ 850	$2,200
Number of Sites	40	80
Sub-Total Field Work	$34,000	$176,000
Data Analysis	25,000	30,000
Reporting	10,000	20,000
Total Stage 2 Costs	**$69,000**	**$226,000**
Total Project Cost if both phases needed	**$142,000**	**$339,000**

3.2 A Research Plan for Assessing the Relative Technical Degradation of Oversized Evaporative Cooled Condensers

3.2.1 Introduction

This research plan was developed as part of the CADMAC Statewide Measure Performance Study to assess the impacts on energy savings of technical degradation which may be experienced by oversized evaporatively cooled condensers for refrigeration systems relative to air cooled condensers. A more detailed assessment of potential technical degradation mechanisms for this technology is provided in section 2.2 of this report. This plan was developed based on that analysis which concluded that relative degradation may occur due to scaling of the condensers.

3.2.2 Technology Description and Review of Degradation Issues

The baseline technology is a supermarket refrigeration system with an air cooled condenser. The efficient measure is the same system with an oversized evaporative cooled condenser. Evaporative cooled condensers (ECC) use a water spray to take advantage of the difference between wet bulb and dry bulb temperatures and reduce condenser temperatures thereby improving system efficiency. The ECC can provide the same heat transfer capacity in a much smaller area. Oversized units provide a large heat transfer area and are designed to operate with a very low “approach” temperature (difference between condenser temperature and wet bulb temperature), providing improved efficiency over standard ECC designs.

The energy savings of an ECC depend on the improved heat transfer rate and reduced operating temperatures of the condenser compared to an air cooled unit. The key degradation issue is whether this improved heat transfer is maintained over time. Both types of condensers are subject to degradation caused by fouling. For air cooled condensers this fouling may arise from particulates and vapors in the outdoor air (or exhausted from the building near the condenser) and from corrosion caused by salt in the air in coastal regions. For ECC’s, the primary fouling mechanisms are biological growth and scaling from contaminants and minerals in the water (which include air pollutants brought into the water spray).

The lack of information on absolute and relative condenser fouling rates and their impacts on system efficiency led PEG to conclude that more research was needed to assess relative technical degradation for this measure.

3.2.3 Research Questions

The main research objective is to assess the relative technical degradation of the ECC compared to an air cooled unit. If relative degradation is found, then the expected rate of degradation needs to be quantified in terms of multipliers which can be applied to the first year savings figures for each year of measure life. The results of the literature search and engineering analysis presented in section 2.2 led to the development of the following specific research questions:

1. What are the average fouling rates for ECCs installed under the 1994 DSM programs in California and what would be the fouling rates for air cooled systems exposed to the same conditions? (where fouling rate is expressed as changes in heat transfer capacity per year)?
2. What factors affect the rate of fouling and how do these factors vary in the population?
3. How do changes in condenser heat transfer capacity affect the efficiency of the refrigeration systems typically used for each type of condenser? What factors affect this relationship?
4. Based on the answers to questions 1-3, what is the expected relative change in annual energy usage for the two types of systems for each year of their useful life?
5. If relative degradation is found, are there any other design differences between ECCs and air cooled condensers which would mitigate this relative degradation.

3.2.4 Technical Discussion

The key research issue concerns condenser fouling and its impact on system efficiency. In developing a research plan to answer these questions, one needs to consider the factors affecting fouling rates and their impacts as described in section 2.2. The key issues identified for air cooled condensers involved poor maintenance (infrequent cleaning), salt corrosion in coastal areas, and high fouling loads on first and second stage condensers of multi-stage systems. Efficiency losses of 20% or more may occur, but no empirical data are available for estimating average field conditions. The key issues identified for ECCs involved scaling and biological fouling caused by potential problems with water treatment, bleed rates, spray patterns, operating temperatures, air pollution levels, and the effectiveness of regular maintenance activities. ECC scaling is not a linear process involving a slow build-up but tends to proceed rapidly when conditions are right.

As noted in section 2.2, there are widely varying opinions and virtually no empirical data concerning the frequency and extent of scaling problems. In order to estimate relative technical degradation for ECCs, information on fouling rates and their impacts on both the air and evaporative cooled condensers are needed. Available evidence indicates that both types condensers can suffer substantial degradation. The actual frequency and severity of degradation in the field is unknown and additional data will need to be collected in order to make informed estimates.

3.2.4.1 Fouling, Efficiency, and Energy Usage

Oversized ECCs save energy by improving the heat rejection capacity of the condenser, thereby allowing the system to operate at lower condensing temperatures and pressures. As condenser heat rejection rates increase, changes in the rate have diminishing effects on efficiency (similar to the analysis presented about air conditioners in section 2.1. This non-linear relationship means that the efficiency of a system with a high heat rejection capacity, such as an oversized ECC, is less sensitive to losses in that capacity than a system with a standard heat rejection capacity. The relationship between condenser heat rejection capacity and system efficiency is a key element in assessing relative technical degradation.

There are also a considerable number of factors and variations in supermarket refrigeration systems, such as control settings and strategies and compressor heat recovery systems, which further complicate an analysis of the potential performance impacts of condenser fouling. These issues need to be considered in sample design and analysis.

3.2.5 Proposed Approach

Given the research questions and the brief technical discussion above, PEG and VaCom Technologies considered a number of potential data collection and measurement approaches. Laboratory testing was deemed unfeasible given the nature of the technology, lack of appropriate facilities, and the difficulties anticipated in creating an accelerated testing approach. Billing analysis was also considered unlikely to be successful for reasons similar to the analysis in the air conditioner research plan. Instead, a combination of brief site visits to a relatively large number of customers combined with more intensive field testing and engineering modeling in targeted smaller samples was selected as the most cost-effective approach to meeting this project's objectives.

3.2.5.1 Site Visits

Brief site visits will be used to collect basic information, through observation and interviews, about customers, facilities, and the refrigeration systems, controls, and maintenance practices. These visits will also be used to perform a visual assessment and rating of condenser fouling / scaling (e.g., photos will be taken and ratings will be assigned on a 1-10 scale with reference rating photographs as a guide). The purpose of these visits is to characterize the population of interest and the distribution of fouling problem severity while providing a sampling frame for more intensive data collection efforts. Initial samples of approximately 30 site visits each for air cooled and evaporative cooled condensers will be needed to provide an indication of common field conditions in areas and applications where problems are likely (e.g., older systems in coastal vs. inland areas with hot and dry vs. mild and moist climates. Customers will be recruited for these visits through contacts with major supermarket chains and from program records.

The results of the site visit will be tabulated and the need for additional site visits will be assessed. If large relative degradation appears likely, then additional site visits will probably be needed to ensure that the sample data represents the population of interest well.

The site visit data will also be used to develop a sampling strategy for more intensive field testing. The sampling strategy will involve identifying a reasonable number of key performance-related factors for use as stratification variables. These factors are likely to include estimated fouling (from the site visits), location / climate, system age, control settings and strategy, and heat recovery approach. Samples will be selected to represent a range of typical conditions with some oversampling of sites which can help address key issues and / or uncertainties (e.g., sites with high fouling ratings).

3.2.5.2 Field Tests

Field tests will be used to measure certain key operating characteristics and parameters of system performance for approximately 20 sites. While overall heat of rejection and system efficiency are very difficult to measure in the field (due to the high cost of measuring refrigerant mass flow rates and a lack of control over ambient conditions and loads) data can be collected to characterize certain key aspects of system performance and provide a means to compare these results to design. Relative degradation may be assessed by combining this information with simulation models of system performance. The accuracy of these assessments will depend on careful data collection and analysis and may be significantly improved by collecting data under differing weather conditions for the same site.

The specific testing strategy will likely involve using a data logger to monitor key pressures, temperatures, ambient humidity, and system status information. Approximately two hours of data logging could provide a good indication of system performance, particularly if the system can be controlled to achieve certain desired conditions (e.g., design approach). In some cases, existing EMS systems may be able to provide some or all of the needed data. To better assess annual performance, these tests will need to be repeated so that summer and winter data are collected.

A potential addition to the field testing approach would involve cleaning the condensers at some sites and re-testing. If cleaning can be successfully performed, then this approach may provide another indication of degradation. However, to the extent that some fouling remains, the results would be biased low. Still, it may prove worthwhile to try this at several sites.

3.2.5.3 Data Analysis

The relative technical degradation rates by year will be estimated based on engineering modeling of the field test data combined with population characteristics data from the site visits. The engineering modeling will involve comparing measured system performance characteristics to design values and adjusting the two to provide a common analytical basis. Design information (collected from the refrigeration legend at each site) will be recalculated using a common approach for all systems. The modeling will also need to account for control strategies in addition to physically modeling capacity. The end result of the modeling process will be an assessment of the change in system efficiency for each system. Overall degradation rates can then be calculated based on the sampling strategy and the characteristics of the larger site visit samples. The shape of the degradation curves over time can be estimated by analyzing the fouling ratings by vintage from the site visit samples and then using the modeling results to develop absolute and relative degradation factors by year.

If significant variations in relative degradation are found across sub-groups (e.g., coastal vs. inland), then separate sets of degradation factors may need to be developed for different applications and/or regions which are readily identifiable.

3.2.6 Task List and Estimated Budget

The table below lists the key research tasks and provides low and high budget estimates for each. There is considerable uncertainty in the travel-related costs associated with site visits and field testing because the final sampling plan is not known at this time.

Oversized Evaporative Cooled Condenser

Technical Degradation Research Project - Task List and Budget

Task	Budget	
	Low	High
Sampling Plan & Data Collection Instruments	6,000	10,000
Site Visits (60-90 sites, $200-$300 / site)	12,000	27,000
Field Testing (20 sites x 2 visits, $700-$1200 / site)	28,000	48,000
Data Analysis	10,000	20,000
Reporting	8,000	16,000
Total	**$64,000**	**$121,000**

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A.1 Residential Central Air Conditioners

The major design differences between the standard and high efficiency units involved the size of the condenser and, in some units, the type of the compressor. The condenser size increase typically involved doubling the face area and minor changes to the condenser fan. PEG's engineering analysis of potential degradation mechanisms found that heat exchanger fouling could degrade the performance of both the standard and efficient units. However, the increase in face area for the efficient unit should lead to a lower rate of degradation primarily due to the lower sensitivity of systems with oversized heat exchangers to changes in heat exchanger capacity. The use of scroll compressors in some of the more efficient units was also examined and again the efficient unit was found to be less likely to experience degradation than the baseline unit.

PEG did conclude that the small percentage of efficient units which utilize tighter fin spacing on the evaporator may experience some relative degradation from increased fouling. In addition, some efficient units have TXV instead of orifice refrigerant metering. TXVs may experience positive or negative degradation depending on the circumstances. PEG concludes that the potential magnitude of relative degradation due to fin spacing and TXVs on a modest percentage of units is likely to have a much smaller impact on overall savings than the long-term superior performance expected from the other design changes. PEG also examined other performance factors such as refrigerant charge problems, duct leakage, and evaporator air flow and no relative degradation for the efficient unit was indicated.

Based on detailed component and system level analyses of design differences, PEG concludes that the high efficiency residential central air conditioners rebated in 1994 are unlikely to experience relative performance degradation compared to baseline units. In fact, they are more likely to exhibit superior long-term performance.

A.2 Commercial Package Air Conditioners

Commercial package air conditioners are similar in many ways to their residential counterparts. However, instead of increasing face area, cost and space constraints led the manufacturers to increase heat exchanger surface through additional tube rows. Heat exchangers with more rows may foul more rapidly, causing relative degradation. Insufficient information was found to identify the net impact of this design change on degradation and therefore PEG concludes that additional research is needed. A research plan for obtaining the needed information is provided in section 3.1.

A.3 Oversized Evaporative Cooled Condenser

This measure involves replacing air cooled condensers with evaporative cooled condensers in supermarket refrigeration applications. Oversized evaporative cooled condensers may suffer from scaling. The rate of scaling depends on proper water treatment, bleed rates, and spray patterns. Monthly maintenance contracts with water treatment companies are common. Industry sources provided widely varying estimates of the frequency and severity of scaling problems and the effectiveness of standard maintenance practices. The potential impact of scaling is severe and can lead to failure to meet the required loads. Air cooled condensers can also degrade due to fouling and, in coastal areas, corrosion. PEG concludes that there is insufficient information to assess the relative degradation of evaporative cooled condensers. A research plan to collect the needed information is provided in section 3.2.

A.4 Residential Refrigerators

The major design differences between the efficient and standard units involved compressor efficiency and motors. Some units also increased heat exchange area and one unit used an improved defrost control. Research on compressor degradation found that compressor performance is fairly constant over time and that the design differences between the efficient and standard compressors are unlikely to lead to relative degradation. The higher efficiency motors are also unlikely to lead to any relative degradation. Other minor design differences were also examined and again no relative degradation mechanisms were found.

While no relative degradation mechanisms were identified directly from the design differences, PEG did locate information indicating that refrigerators may suffer a significant performance degradation and usage may increase by 5-10% early in the life of newer units and perhaps much more over the life of older units. Therefore, PEG examined degradation mechanisms common to new efficient and baseline units in order to assess whether some mechanism may affect the two types of units differently. PEG performed a detailed analysis of insulation R-value degradation and gasket leakage as two potentially significant common degradation mechanisms which could explain the usage increases. That analysis indicated that degradation of foam insulation R-value may increase energy usage by 5%-10% over the first one or two years and perhaps by 20% over the life of a refrigerator. However, because the high efficiency units have more efficient compressors and motors, this degradation would lead to increasing energy savings over time when compared to baseline efficiency units (“negative” relative degradation). The same conclusion would hold for any factor which increased cabinet loads (e.g., gasket deterioration) because identical increases in cabinet loads lead to essentially equal percentage increases in energy usage for both units, which leads to a larger absolute difference in usage.

Based on the analysis of design differences and common degradation mechanisms, PEG concludes that efficient refrigerators will not experience relative degradation compared to the baseline efficiency units. Instead, the savings from high efficiency units is likely to increase over time due to degradation mechanisms which affect both units by an equal percentage.

A.5 Electronic Ballasts

The superior performance of the electronic ballasts arises from high frequency operation (which improves lamp efficacy) and reduced losses from solid-state circuitry. Neither of these performance enhancements will lead to relative degradation. High frequency operation provides a fundamental improvement which will not degrade. Transformer and other losses are generally stable in both types of ballasts (some magnetic ballasts may experience a small increase in usage from capacitor failure). All sources contacted noted that the power draw of a fluorescent lighting system is very stable over time. Although system power draw does vary with lamp bulbwall temperature, no long term usage trends occur. In terms of light output, poor electronic ballast designs may adversely affect lamp lumen maintenance and life. However, most newer ballasts have overcome these problems. PEG concludes that electronic ballasts will not suffer from relative degradation.

A.6 T8 Lamps with Electronic Ballasts

T8 lamps have improved efficacy compared to standard T12 lamps because of their smaller diameter and superior phosphor composition. Fluorescent lamp efficacy improves as the tube diameter decreases. In addition, smaller diameter tubes allow more of the lumens produced to exit the fixture, providing for better illumination of the space per lumen. These performance benefits from a smaller diameter tube will not lead to relative degradation. T8 lamps also use rare earth phosphors with fundamentally better efficacy than standard phosphors. These improved phosphors also provide for better lumen maintenance over time. Lamp manufacturers take advantage of this fact, along with the improved luminaire light output per lumen, to further reduce lamp wattage. The net result is that T8 lamps typically provide fewer initial lumens than comparable T12 lamps, and may even provide fewer mean lumens, but will tend to provide the same average level of illumination to the space. PEG concludes that T8 lamps with electronic ballasts will not suffer from relative performance degradation compared to standard T12 lamps with efficient magnetic ballasts.

A.7 Optical Reflectors and Delamping

Not surprisingly, the energy savings from delamping after reflector installation are unlikely to degrade. The retrofit may increase the power draw of the remaining lamps due to thermal effects, but this change occurs immediately, not over time. The CADMAC subcommittee was more concerned with relative degradation in light output from reflector retrofits.

PEG examined surface depreciation, dirt depreciation, and interactive effects as the key factors which may cause relative light output degradation. Both reflectors and standard luminaire surfaces may depreciate over time. The little data available (from one manufacturer performing a limited range of tests) suggests that their front-reflective silver film reflector surfaces do not significantly depreciate due to ultra-violet, moisture, temperature cycling, or dirt build-up. These tests did not examine potential depreciation caused by abrasion or chemical attack from improper cleaning. In summary, PEG concludes that, while existing data are encouraging, there is insufficient information available to determine whether reflector surfaces may experience a relative degradation in light output over time compared to standard luminaires. However, PEG did identify a potentially more important light output degradation mechanism. Much of the apparent ability of reflector retrofits to maintain pre-retrofit illumination levels is due to lens cleaning and installation of new lamps. The impacts of these actions will degrade over time as standard maintenance schedules are re-established.

Overall, PEG concludes that energy savings from reflector retrofits will not degrade over time. However, light output may experience relative degradation due to reflector surface depreciation and, perhaps more importantly, the short-lived benefits of lens cleaning and relamping performed during the retrofit. The CADMAC subcommittee recommends that light output issues be explored in retention studies.

A.8 HID Interior Metal Halide Lamps

Metal halide and mercury vapor lamps are two types of high intensity discharge (HID) lighting. The primary difference is that the metal halide lamp contains certain combinations of metals in addition to the mercury vapor in the discharge gas. These metals improve lamp efficacy and shift the radiation spectrum to provide better color rendering. HID lamps are operated using ballasts with a variety of designs, making generalizations difficult. The most common lamp / ballast combinations for mercury vapor lamps produce a constant power draw over the life of the lamp. However, metal halide lamps experience rising arc voltage over time. This increase in arc voltage will lead to increased power draw of about 3-5% over the life of the lamp. Lower wattage systems (<175 W) will not experience these energy usage increases due to differences in ballast design.

The net effect of the increasing energy usage over time will be a modest reduction in average savings of about 4%. The values of specific degradation factors for use in adjusting annual savings estimates depend upon not only the actual rate of usage increase, but also the nature and timing of the first year impact evaluation, the annual lamp operating hours, the lamp life, and relamping strategies. A table showing degradation factors under a variety of assumptions is provided in section 2.8.1.

In terms of light output, metal halide systems have comparable initial and mean lumen ratings as the mercury vapor systems which they replace. Differences in rated lamp life, variations in lamp / ballast / fixture combinations and interactions, and differing shapes to the lumen depreciation curves provide a complex set of factors for comparing light output over time. However, manufacturers and lighting experts all consider the lumen maintenance characteristics of metal halide lamps superior to those of mercury vapor.

A.9 Occupancy Sensors

The performance of an occupancy sensor may be considered unsatisfactory if it fails to turn and keep the lights on when the space is occupied or fails to turn and keep the lights off when it is unoccupied. The former situation has been known to create annoyances to occupants and may lead to the system being defeated, but does not otherwise reduce energy savings. The latter situation may occur due to false detection of occupancy and would reduce energy savings. Both major types of sensors (passive infra-red and ultrasonic) are subject to both types of problems. However, this study is only concerned with factors which may change sensor performance over time.

The only direct technical degradation mechanism identified was dust or dirt accumulation on the detection ports, leading to decreased sensitivity. While no data on this effect were found, reduced sensitivity would not reduce energy savings because the lights would turn off more often. But if this reduced sensitivity caused occupants to over-ride or tamper with the system, energy savings would be compromised. The CADMAC subcommittee recommends that these potential occupant interaction problems be explored through retention studies.

A.10 Motors

High efficiency motors have lower losses than standard efficiency units due to many changes in materials, design, and manufacture. Core losses are reduced by the use of high grade silicon steels, thinner gauge material, improved interlaminer insulation, and changed core dimensions. Stator and Rotor I^2R Losses are reduced by improved slot designs, increased copper content, and increased cross-sectional areas of the rotor bars and end rings. Friction and Windage losses are reduced by modifications to the ventilation system. Stray load losses are reduced through maintaining a concentric air gap, the use of coil spans in the winding, and improved casting of the squirrel cage. These design differences between standard and high efficiency units are primarily due to fundamental changes in materials and dimensions which are unlikely to degrade over time.

Researchers and manufacturers agree that motors do not degrade in efficiency over time unless they are improperly rewound. Operational problems which reduce the efficiency of the motor (e.g., bearing and insulation failure) rapidly lead to motor failure, not continued operation at reduced efficiency.

A key study which supports these conclusions measured actual in-field efficiency of older motors and found that there was no performance degradation (in units that had never been rewound).

Manufacturers and researchers state that high efficiency motors are more reliable and less prone to problems than standard efficiency units because of their design, materials, and lower operating temperatures. In one manufacturer’s accelerated life and extreme operating tests, high efficiency units had double the expected life of standard efficiency units. These tests also found that high efficiency motors are better able to withstand overloads, frequent starting, voltage and frequency variations, high ambient temperatures, and high elevations.

PEG’s analyses of relative and absolute performance degradation mechanisms and other operating factors which may influence energy savings from efficient motors all indicate that there will be no relative degradation in energy savings over time when compared to standard efficiency motors.

A.11 Adjustable Speed Drives for HVAC Fans

Pulse width modulating adjustable speed drives are solid state devices with no moving parts. The primary components, rectifier and inverter, are not subject to performance degradation, but may fail due to manufacturing defect or overheating (which is a well known problem, particularly when unit ventilation rates are low and/or air quality is poor). No efficiency degradation mechanisms were identified and any significant increase in losses would be quite unlikely without causing overheating and drive failure. Interactions between ASDs and motors were also explored and have been noted as a source of potential reliability problems. However, no evidence of motor efficiency degradation over time due to operation with an ASD was found.

While system efficiency is unlikely to degrade over time, overall energy savings may decline due to changes in control settings (e.g., from sensor degradation or changes in set points). One study identified changes in pressure control settings as a key factor in reduced energy savings at some sites with ASD control of VAV systems. No other information on sensor problems or improper control settings was located, but significant savings degradation could occur if these events are common. PEG concludes that ASD savings may degrade over time due to control problems and these issues would be best addressed in the context of measure retention studies.

A.12 Infra-red Gas Fryers

Infra-red gas fryers are more efficient than standard atmospheric designs due to three design differences: burner/combustion design, vat/heat exchanger design, and ignition system. The burner efficiency improvements account for approximately one third of the savings and may degrade if the combustion air inlet to the blower becomes blocked or fouled. However, the standard atmospheric burner design may also experience fouling such as dust and grease accumulation in the burner ports. Neither of these problems are believed to be common and the average net impacts on efficiency should be small. Vat and heat exchanger design differences account for nearly half of the savings and are unlikely to degrade over time. It is more likely that the standard immersion tube design will suffer from degradation due to fouling and difficult maintenance. Some infra-red units use a split vat design to achieve even greater energy savings. These additional savings should not degrade over time. Infra-red fryers also use an electronic ignition instead of a standing pilot light. While electronic ignition can suffer from reliability problems, the energy savings will not degrade.

In summary, the energy savings from infra-red fryers could degrade slightly due to some units experiencing problems with combustion air supply. However, other design advantages are at least as likely to create an offsetting amount of “negative” degradation. PEG concludes that infra-red fryers are unlikely to experience an overall average degradation in energy savings relative to standard atmospheric fryers.

A.13 Residential Ceiling Insulation

Energy savings from increased levels of attic insulation depend on proper coverage and performance of the material at rated R-value and may be reduced by parallel heat transfer mechanisms into the attic (air or duct leakage and other “thermal bypasses”). Performance degradation may occur over time if the insulation is removed, compressed, disturbed, or damaged. PEG investigated five mechanisms which may lead to these circumstances: human intervention, settling, wind shifting, moisture damage, and animal disturbance.

A literature review and discussion with insulation contractors and weatherization practitioners identified human intervention as the primary potential cause for degraded performance of blown and batt fiberglass (the most common material used in the California programs). In particular, the use of attic space for storage and disturbances / removal of insulation from contractor activities (e.g., cable TV, alarm, electrical, and HVAC contractors) were identified as two common causes for performance degradation. PEG used heat transfer calculations to assess a “worst case” insulation disturbance scenario involving these events. The calculations indicated that the absolute rate of heat loss will increase by about the same amount in attics with the higher and lower insulation levels. Therefore, while disturbances to attic insulation caused by human intervention may have a large impact on heat loss, no significant relative degradation should occur from higher insulation levels.

The lack of savings degradation from attic insulation is also supported somewhat from the encouraging results of billing analysis based persistence studies of residential weatherization (which typically have attic insulation as a key component). In particular, a DOE-sponsored persistence study of the Wisconsin weatherization program over a seven year period found that net savings were stable or increasing over time. While the stability of these savings over time may be due to many factors, including comparison group usage increases, they tend to refute the idea that insulation savings are significantly degrading over time. In summary, no mechanisms for relative degradation were identified and available studies support this conclusion. PEG therefore concludes that the energy savings from increased levels of attic insulation will not degrade over time compared to the standard levels.