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Prepared by:
Proctor Engineering Group, Ltd.
San Rafael, CA 94901
(415) 451-2480

Statewide Measure Performance Study #2 An Assessment of Relative technical Degradation Rates

Submitted to:
CADMAC Persistence Subcommittee
Pacific Gas and Electric
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Contributors:
George Peterson, P.E.
John Proctor, P.E.

Creators of CheckMe!®

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EXECUTIVE SUMMARY

The Statewide Measure Performance Study #2 (*Persistence 2*) was the second project, sponsored by the CADMAC subcommittee on persistence, to examine the relative technical degradation of demand side management (DSM) measures compared to standard efficiency equipment. This project covered eleven major DSM measures; the previous project (PEG 1996 *Persistence 1*) covered thirteen measures. The project focused on assessing existing information. There were two primary stages of work. The first stage performed an exhaustive search for existing information from published and unpublished sources and synthesized this information into an engineering analysis of technical degradation factors (TDFs). This analysis forms Section 2 of this report. The second stage of the study involved developing research plans for assessing relative technical degradation for those measures where substantial uncertainty was found in stage one. The research plans are the content of Section 3 of this report. The reference bibliography is Section 4.

Stage 1 - Degradation Analysis Findings

Proctor Engineering Group (PEG) with assistance from Marlene Vogelsang at the PG&E Energy Center conducted a broad search for information concerning the relative technical degradation of the eleven (11) 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, manufacturers' literature and product specifications, internet search facilities, and fee-based on-line search services. The project team also discussed these measures and data availability with manufacturers, industry associations, utilities, government agencies, national laboratories, and researchers.

This second study owes much to the first. The analytical approach developed in *Persistence 1* to determine relative technical degradation rates with limited empirical data was re-employed. For several measures the *Persistence 1* results were leveraged to help provide the results of this study. For example, the wall and floor insulation analysis benefited from the previous analysis of ceiling insulation, and the two adjustable speed drive measures (ASD) in process applications benefited from the previous study of ASDs on heating ventilating and air conditioning (HVAC) systems.

As expected, existing data on performance changes over time were very limited. However, PEG was able to utilize the available information 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 technical degradation factors (TDFs) and identify key uncertainties for each of the measures. The results of this analysis are summarized in Table 1 and Table 2.

The engineering analysis found that relative degradation is very unlikely for five of the eleven measures. Indeed, two measures (adjustable speed drive applied to waste water pumps and agricultural pumps) are likely to degrade less than their standard efficiency counterparts, resulting in increasing savings over time, or "negative" degradation. By CADMAC directive negative degradation rates are set equal to one.

Table 1. Summary of Findings		
Efficiency Measure	**Baseline Technology**	**Relative Degradation**
LED exit signs	Incandescent exit signs	none, retention issue
Process adjustable speed drives — waste water pumps	Inlet vane throttling on waste water pumps	none or negative
Process adjustable speed drives — injection molding machines	Standard injection molding machines	much possible
R-13 fiberglass batt wall and floor insulation	Fiberglass batt R-15 wall and R-19 floor insulation	none
Daylighting controls	Standard manual lighting controls	much possible
Agricultural pump repair or replacement	Existing agricultural pump	negative or none
Variable air volume HVAC distribution system	Constant air volume HVAC distribution system	uncertain
Energy management systems	Manual operation	much possible
New air compressors	Existing air compressors	compressors — none system — much possible
High efficiency compressed air distribution system	Standard efficiency compressed air distribution system	much possible
13 watt hard-wired compact fluorescent downlights	Incandescent downlights	none

For waste water pumping, the ASD and motor combination is not likely to experience any changes in savings. Because of slower speed operation, the pump itself should wear slower. Negative technical degradation is estimated due to decreased pump wear.

The efficient and standard agricultural pumps are the same equipment with different times in service. The specific shape of the efficiency versus time in service curve determines if relative technical degradation exists. This curve was not fully characterized in pre-existing sources. PEG's analysis of a utility pump test database indicates negative relative degradation.

For three measures (LED exit signs, wall and floor insulation, and compact fluorescent downlights) annual energy use is stable for both the efficienct and standards technologies so the TDF is estimated as one (1.0) for all years.

For three measures the first stage analysis found that potentially significant relative technical degradation could occur largely due to human factors and the possibility of system bypass. These measures were adjustable speed drives applied to injection molding machines, daylighting controls, and energy management systems.

Energy savings from ASD applications to injection molding machines (IMM) may decline due to lessening optimization of control settings. IMMs need control setting adjustment and optimization for each new production run. Production rates and quality are of prime importance. Operators need special training to utilize ASD settings for control rather than the hydraulic valves. The hydraulic oil bypasses that allow continuous pump operation must continue to function. Operator reversion to standard operation is possible from drops in operator competence after personnel changes or from reduced operator attention. An estimate of TDF was made and a research plan produced.

Problems with optimizing energy savings from daylighting with dimmable fluorescent lighting systems in office buildings are well documented. Office workers are sensitive to the quantity and quality of lighting. Worker productivity is of prime importance. Daylighting systems are complex with several weak spots in the control system. Good initial commissioning and continuing maintenance can achieve high savings. Control system problems are likely to result in system bypass and degradation of savings. An estimate of TDF was made and a research plan produced.

Human interactions are particularly prominent with energy management systems (EMS). Problems from poor commissioning and/or maintenance are common in published literature. A long-term study found that energy usage increased steadily for three years after installation. Another study found building operations unstable more than a year after completion. Long-term savings from EMSs are likely to differ from first year estimates. An estimate of TDF was made and a research plan produced.

Compressed air distribution systems are notoriously inefficient. Lack of information and responsibility has created an industrial culture that doesn't understand, tolerates, ignores, and/or even encourages compressed air wastage. On average only 37% of compressed air is used appropriately and productively. Changes in operation and equipment can provide significant savings. Without a comprehensive air management program (AMP) energy savings from operational changes are likely to degrade quickly. Energy savings from equipment changes will also degrade steadily without an AMP. An estimate of TDF was made and a research plan produced.

In the case of air compressors relative degradation was deemed unlikely compared to standard air compressors. However, decreasing measure energy savings was deemed likely due to degradation of the distribution system initiated and masked by the compressor. The increased air power of the compressor can increase the abrasive energy experienced at leakage sites causing them to enlarge faster. The increased pressure can contribute to artificial demand and increased air wastage. An estimate of TDF was made and a research plan produced.

For the variable air volume HVAC measure existing data was deemed inconclusive. On the one hand, VAV systems are likely to experience higher degradation relative to constant air volume systems due to greater system complexity, more interactive effects among building system components, and a larger number of failure mechanisms. On the other hand, constant air volume systems experience greater degradation due to comparable temperature measurement error. Which factor will predominate could not be determined. Rate and degree of degradation for both the CAV and VAV will be highly dependent on the quality of initial commissioning and the quality of operations and maintenance procedures. An estimate of TDF was made and a research plan produced.

Stage 2 - Research Plans

Research plans for assessing relative degradation for the those 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 the particular technical degradation mechanisms which were identified. 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.

In *Persistence 1*, two measures were found liable to experience relative degradation. This study found five. In *Persistence 2* there was a higher number of measures that subject to previously unstudied human factors.

According to CADMAC protocols performance studies are not required for any measures within the industrial process end use element. (CADMAC, Table 9A) Therefore, performance studies are not required for ASDs on IMMs, compressed air distribution systems, and air compressors. Optional research plans were developed for these measures.

The ASD-IMM research plan involves two phases. Phase one utilizes previous studies by other organizations. The degree of non-optimization is remeasured and compared to the previous result. This testing may find that no degradation occurred, and the research will be complete. If the testing indicates the occurrence of degradation, but does not sufficiently quantify it, then a second phase may be needed to derive an adequately reliable TDF.

The daylighting controls research plan involves testing the operation of the controls in a sample twenty building to determine if the controls are functional or disabled.

A study of relative technical degradation between VAV and CAV HVAC systems is suggested. This study would track the deviations in critical control points over a longitudinal field study. The results of this field study would be used in simulation models to estimate the energy consumption effects of the control point changes.

The persistence of savings from HVAC EMS systems can be studies through billing data analysis. Proctor Engineering Group recommends that study.

A combined research plan for compressors and compressor systems is suggested. This plan approaches the question from two directions. First, an estimate of the rate of leakage increase can be derived from analysis of data from existing air management programs. Second, longitudinal monitoring of air and electrical usage at selected sites will yield estimates of persistence for supply and/or demand side conservation with/without an AMP.

Summary

A technical degradation factor (TDF) was estimated for each measure. These estimates are displayed in Table 2.

Table 2. Summary of Technical Degradation Factors

Section #	2.1	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12
YEAR	LED exit	ASD Pump	ASD IMM	Wall Floor Insul	Day Lighting	Ag Pump	VAV	EMS	Cmpr w/o AMP	CADist w/o AMP	CFL Downlite
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	1.00	1.00	0.98	1.00	0.73	1.00	1.00	0.80	0.71	0.85	1.00
3	1.00	1.00	0.91	1.00	0.61	1.00	1.00	0.60	0.50	0.70	1.00
4	1.00	1.00	0.74	1.00	0.54	1.00	1.00	0.40	0.35	0.55	1.00
5	1.00	1.00	0.57	1.00	0.48	1.00	1.00	0.20	0.25	0.40	1.00
6	1.00	1.00	0.50	1.00	0.43	1.00	1.00	0.10	0.18	0.25	1.00
7	1.00	1.00	0.48	1.00	0.39	1.00	1.00	0.10	0.13	0.25	1.00
8	1.00	1.00	0.47	1.00	0.36	1.00	1.00	0.10	0.09	0.25	1.00
9	1.00	1.00	0.47	1.00	0.33	1.00	1.00	0.10	0.06	0.25	1.00
10	1.00	1.00	0.47	1.00	0.31	1.00	1.00	0.10	0.04	0.25	1.00
11	1.00	1.00	0.47	1.00	0.29	1.00	1.00	0.10	0.03	0.25	1.00
12	1.00	1.00	0.47	1.00	0.27	1.00	1.00	0.10	0.02	0.25	1.00
13	1.00	1.00	0.47	1.00	0.26	1.00	1.00	0.10	0.02	0.25	1.00
14	1.00	1.00	0.47	1.00	0.24	1.00	1.00	0.10	0.01	0.25	1.00
15	1.00	1.00	0.47	1.00	0.23	1.00	1.00	0.10	0.01	0.25	1.00
16	1.00	1.00	0.47	1.00	0.23	1.00	1.00	0.10	0.01	0.25	1.00
17	1.00	1.00	0.47	1.00	0.22	1.00	1.00	0.10	0.00	0.25	1.00
18	1.00	1.00	0.47	1.00	0.21	1.00	1.00	0.10	0.00	0.25	1.00
19	1.00	1.00	0.47	1.00	0.21	1.00	1.00	0.10	0.00	0.25	1.00
20	1.00	1.00	0.47	1.00	0.20	1.00	1.00	0.10	0.00	0.25	1.00

1. INTRODUCTION

This study: Statewide Measure Performance Study #2 (*Persistence 2*), is a continuation of the work performed by Proctor Engineering Group (PEG) in the first Statewide Measure Performance Study (*Persistence 1*, PEG 1996).

1.1 Project Research Objectives

The persistence studies are part of a multi-faceted approach to estimating the persistence of energy savings from demand side management (DSM) programs in California. These studies focused on one aspect of the persistence of savings -- technical degradation. The general research question that these studies are 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 technical performance of the standard measures they replace?*

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 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. The performance and useful life of most efficient and baseline measures depends upon installation, and operation & 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. 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 Contents and Report Structure

There were two primary stages to this study. The result of stage one is a set of Technical Degradation Factors (TDFs). The TDFs are a series of yearly numbers which when multiplied by the first year savings yield an estimate of the energy savings in years subsequent to the first year. Specifically the TDF is defined as: "A scalar to account for time and use related change in the energy savings of a high efficiency measure or practice relative to a standard efficiency measure or practice." (CADMAC 12/17/97)

The approach employed does not involve collecting new data, but is based on identifying, acquiring, and analyzing available data for the target measures. If sufficient data were available, then the analysis and conclusions were documented. If existing data were insufficient for drawing reliable conclusions, then engineering judgment was used to make the best estimate of the TDF. TDF results are found at the end of each analysis in Section 2 and are summarized in Appendix A.

The second stage of the study involved developing research plans for improving estimates of relative technical degradation for those measures where substantial uncertainty was found in stage one. The research plans 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 research plans are optional because the committee may chose to accept the TDF estimates from this study. These research plans are Section 3 of this report.

PEG with assistance from Marlene Vogelsang at the PG&E Energy Center and a technical research assistant at MIT conducted a broad search for information. The data collection process included the use of in-house expertise and resources combined with a broad literature search utilizing journal and periodical indexes, manufacturers' literature and product specifications, 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. There were extensive efforts to locate unpublished "gray" literature from researchers and manufacturers. As expected, existing empirical data on performance changes over time was limited for most measures. References and sources are listed in Section 4.

1.3 Study Measures

This study analyzes the technical degradation potential of eleven major DSM measures. Measures were selected for inclusion in this project by the sponsoring utilities on the CADMAC persistence 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 1-1.

Table 1-1 Study Measures

Efficiency Measure	Baseline Technology	Section #
LED exit signs	Incandescent exit signs	2.1
Process adjustable speed drives — waste water pumps	Inlet vane throttling on waste water pumps	2.3
Process adjustable speed drives — injection molding machines	Standard injection molding machines	2.4
R-13 fiberglass batt wall and floor insulation	Fiberglass batt R-15 wall and R-19 floor insulation	2.5
Daylighting controls	Standard manual lighting controls	2.6
Agricultural pump repair or replacement	Existing agricultural pump	2.7
Variable air volume HVAC distribution system	Constant air volume HVAC distribution system	2.8
Energy management systems	Manual operation	2.9
New air compressors	Existing air compressors	2.10
High efficiency compressed air distribution system	Standard efficiency compressed air distribution system	2.11
13 watt hard-wired compact fluorescent	Incandescent downlights	2.12

downlights		

1.4 Analytical Approach

The overall analytical approach to this project is based on the knowledge that there is little data available concerning measure degradation and that available data often represents 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.

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.

If the result of the above process indicated substantial uncertainty, then the engineering analysis was 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 allowed these plans to focus on just one or two critical factors. 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.

1.5 Findings

The findings from the literature search and engineering analysis are provided in detail in Section 2. Brief summaries of these findings and recommendations are also provided for each measure in Appendix B.

There are four categories of results from the analysis of the energy efficiency measures :

- measures where a defensible conclusion that relative technical degradation is zero or near zero can be made, that is the Technical Degradation Factor equals one (1.0)..
- measures where a defensible conclusion that relative technical improvement of savings does exist can be made. By CADMAC directive, for measures with relative technical improvement, a TDF of one (1.0) is used.
- measures for which reasonably accurate estimates of relative technical degradation can be made.
- measures for which technical degradation is likely, but a fully defensible estimate of the TDF was not yet possible, and a research plan was developed.

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 energy management system 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 study.

This report does not cover "retention" issues. For instance, if a measure is removed before the end of its rated life, the decrease in energy savings is captured in the estimate of retention. The boundary between "retention" and "degradation" can potentially be drawn at different places. An example helps to clarify this. If a device is made inoperable, such as turning off an energy management system, that could be considered non-retention or technical degradation. The specific definition of "Technical Degradation Factor" was clarified by CADMAC on December 17, 1997. The clarification states if the device is physically present but not in operation, it is considered to have experienced technical degradation (TDF = 0). Only if it is no longer physically present or inoperable is it considered non-retained.

The potential impacts and interactions of operation and maintenance practices with measure performance were considered in the analysis of relative degradation. In five 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., LED exit signs, ASDs on waste water pumps, wall and floor insulation, agricultural pumps, and CFL downlights). The degradation analysis assumes that maintenance would be comparable for such comparable products.

For six measures, the human effects captured in operation and maintenance procedures (O&M) were considered the primary degradation mechanisms (ASDs on IMMs, daylighting controls, VAV systems, EMSs, air compressors and compressed air distribution systems). In these cases the O&M factor was found to be poorly defined in available literature. This resulted in higher uncertainty in the TDFs for these measures. Research plans were developed for each of these measures.

While CFL downlights are unlikely to experience technical degradation, a retention study was recommended based on significant differences in estimated service life. The retention study is described in Appendix B.1.

1.7 Conclusions and Next Steps

The study and analysis in this report has provided Technical Degradation Factor estimates for eleven important DSM measures. *Persistence 1* and *Persistence 2* cover a significant portion of the total resource value claimed by participating utilities. CADMAC has acknowledged this and stated:

> Because the existing statewide studies have covered the vast majority of the measures, there is no performance study requirement for any measures not included in the statewide performance studies. (CADMAC 12/17/97)

Research plans were developed for each measure where substantial uncertainty was encountered in developing the TDF estimate.

The next phase of this study involves:

1) CADMAC assessing whether the potential improvement of a TDF estimate justifies the time and expense of a further study.

2) For qualifying measures, the Persistence Subcommittee securing funding from both subcommittee members and appropriate outside sources.

3) Conduction of the funded research studies by the selected contractor(s).

2 ANALYSIS OF TECHNICAL DEGRADATION

2.1. LED Exit Signs

Codes require exit signs in commercial, industrial, and institutional buildings. As an essential safety device they operate continuously for a total of 8760 hours per year. Because of their many hours of use, they represent a significant source of potential savings even though the connected wattage is low.

The measure baseline is an Exit Sign with two 20 watt incandescent bulbs operating continuously. The efficient measure is an LED Exit Sign with two 2 watt LEDs light sticks operating continuously.

2.1.1. Exit Sign Typology

There are three types of exit signs in general use: incandescent, fluorescent, and LED. "Self-luminescent" signs powered by the radioactive decay of tritium are also available.

Incandescent-Lighted Exit Signs Until the energy crisis in the 1970s, incandescent lamps were the only light sources for exit signs on the market. Estimates are that they still represent the vast majority of signs in use. (May 1997) Incandescent exit signs are typically lit with two 20- or 25-watt lamps for a total energy consumption of 40- to 50-watts.

Under continuous operation 20 watt incandescent bulbs will last 3,000 hours or about four months. Long-life exit sign lamps are available that are rated at 7000 hours. These longer life bulbs cost more and many users purchase the standard life bulbs.

Incandescent exit signs have the lowest first cost. Their drawbacks include hot spots, short bulb life, high maintenance costs, and excessive energy use.

Fluorescent-Lighted Exit Signs With the advent of increased energy awareness in the 1970s, fluorescent-lighted exit signs became available as original equipment and retrofit kits. Fluorescent-lighted exit signs are typically lit with two 5 watt or two 7 watt fluorescent tubes. Total power consumption with ballast losses is 19-20 watts. Fluorescent lamps are rated for 10,000 hours or about 1.1 years. Ballasts are also occasionally replaced.

Fluorescent exit signs have problems operating properly at low temperatures.

The price of LED exit signs has decreased to the point that they compete directly with fluorescent signs on first cost alone. The LED signs have a definite operating cost advantage and one manufacturer believes that the fluorescent market will soon disappear.

LED Exit Signs LED Exit Signs became available in 1985. Since then, the aesthetic appeal and efficiency have increased while the price has fallen.

LEDs vary widely in efficiency from 0.01 to 25 lumens per watt. (E. Source, 1994) LED exit sign energy consumption rates per face vary from 1 to 8 watts. Lighting strategies vary from spelling "EXIT" with LEDs to backlighting the lettering.

2.1.2. Operation

LEDs were invented in the 1960s. They are made out of semiconductor materials. When a current is passed through the LED, electrons in the material move between higher and lower energy states releasing visible light. There is a large variety of LEDs.

2.1.3. Energy Savings Mechanism

LED exit signs achieve energy savings by using an efficient LED light source and by concentrating the light output only were it is needed so there is less light lost in the fixture. Exit sign incandescent light sources produce about 4.5 lumens per watt (they are optimized for longer life) as compared to 5-20 lumens per watt for LEDs.

The greatest savings from LEDs come from using the light more efficiently. In order to obtain red letters the incandescent design filters out all wavelengths but red, essentially throwing the majority of the light away. On the other hand, the red LED only produces red light. The LED cap is spectrally designed to direct the light to the viewer. In the lowest wattage exit signs the LEDs are strategically placed along the letters. By using almost all of the light produced, the LED can achieve brightness comparable to or exceeding an incandescent source at much lower power.

2.1.4. Degradation

<u>LED Energy Consumption</u> An LED's power dissipation remains essentially constant over its life. Over time, the LED watt draw varies slightly (randomly with no upward or downward trend). (Forte, 1997; Grimes, 1997) The LED is excited by external solid state circuitry that maintains a constant current. The voltage drop is determined by the current flow. A typical LED is rated for 10-50 ma excitation; at 20 ma it might have a 2 volt drop for 4 watts of power. The external control is believed to be stable over years of operation according to all available sources.

> **PEG concludes that there is no increase in power usage expected during the life of the LED exit sign.**

<u>LED lumen Output</u> While the LED's power dissipation remains constant, the LED's light output decreases over time.

LEDs last longer than incandescent or fluorescent lamps and usually do not fail like incandescent or fluorescent lamps. Their light output decreases over time. The factors that determine how rapidly the LED's light output will degrade include:

- Type of LED
- Milliamp excitation
- Ambient temperature
- Ambient humidity

LED technology is changing and developing rapidly. The type of LED most recommended by several major manufacturers for LED exit signs (AlInGaP) only became available in 1995. It has higher light output and better long term stability.

The light output of an LED is approximately proportional to the excitation amperage. In order to double the light output a manufacturer can either double the number of LEDs or double the excitation. Doubling the excitation will approximately double the rate of lumen depreciation. At high excitations the rate of lumen depreciation is quite high. One manufacturer stated that they use both strategies (in their high end sign they create brightness with more LEDs, in their cost competitive sign they use increased excitation on fewer LEDs).

Higher ambient temperature and higher ambient humidity also shorten LED life.

Estimates of the useful life of LEDs vary widely. All estimates were significantly longer than incandescent or fluorescent bulbs. Estimates varied from 5-500 years. Table 2-1 summarizes the estimates and their sources.

Table 2-1 LED Life Estimates

Life	Source	Source Description
100 years	Charles May, Vice President of Marketing, AstraLite	LED exit sign manufacturer
25 years	Evenlite Century	LED exit sign manufacturer
5-100 years	The Center for Renewable Energy and Sustainable Technology	Renewable Energy Organization Cooperative
50 years	Central Vermont Public Service Corporation	Electric Utility
80+ years	Budget Lighting	Retail lighting supplier
80-500+ years	Environmental Building News	periodical on environmentally sustainable design and construction
80-100 years	AstraLite	LED exit sign manufacturer
20 years	Marchetti, Manager Dual-Lite	LED exit sign manufacturer

Explanations for this large range in estimated life include:

- Different LED technologies -- Newer types have longer lives.
- Different standards of end-of-life
- Inaccuracies in advertising

Until recently, standards did not exist for minimum exit sign brightness. Various manufacturers have probably used different definitions of end-of-life of the LED leading to varying lifetime estimates.

Some LED exit sign manufacturers make claims that are disputed by other exit sign manufacturers and the manufacturers of LEDs. Examples include:

> "LEDs are guaranteed to maintain quality illumination throughout their long rated life."
>
> "[Manufacturer X] signs deliver high-quality illumination with no lumen depreciation throughout a long-rated service life of up to one million hours."

In response to such claims one engineer of a large LED manufacturer stated, "These claims are absolute idiocy."

Analysis

One manufacturer stated that the 25 year warranty did not cover any guaranteed light output level. Another manufacturer's engineer when asked about the company's claim about light output stability stated that he did not know anything about lumen depreciation in LEDs.

> **PEG concludes that LED signs will show lumen depreciation. This lumen depreciation is the prime determination of service life.**

<u>Incandescent Lumen Depreciation and Wattage Reduction</u> The lumen output of an incandescent lamp depreciates during the life of the bulb. This happens because the tungsten filament slowly evaporates. As it evaporates, the filament diameter becomes smaller and resistance increases. At a higher resistance the lamp uses fewer watts, operates at a lower temperature, and produces less light. The evaporated tungsten condenses onto the bulb wall further reducing the lumen output. Over its rated life an incandescent lamp depreciates about 18% in lumen output and uses about 5% less wattage, see Figure 2-1.

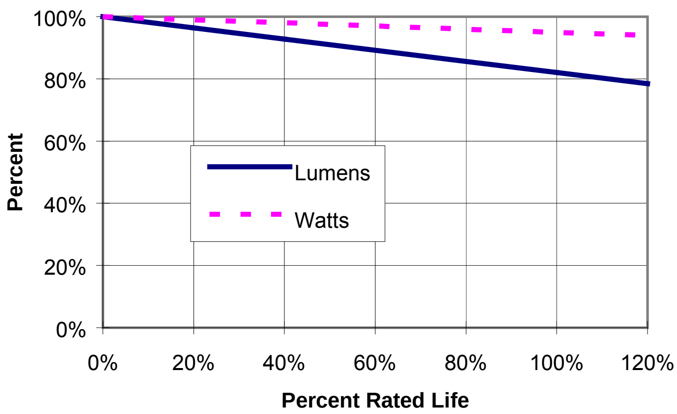


Figure 2-1 Incandescent Efficacy

The base power draw is a combination of incandescents in various stages of their life span. The diversified power draw will remain constant as they burn out and are replaced.

> **PEG concludes that there is no change in power usage expected in measure baseline on a diversified basis.**

<u>Battery and Backup Circuitry</u> Many exit signs have battery backup for power outages. The technology for this battery backup is the same as for conventional incandescent-lighted exit signs. No differential power draw or life is expected.

> **PEG concludes that there is no relative change in power usage between the baseline and efficient technology due to battery and backup circuitry.**

2.1.5. Conclusions

> **PEG concludes that savings from LED Exit signs are unlikely to show relative technical degradation over time.**

> **Lumen depreciation determines the service life of the LED. Many manufacturers' claims are misleading or inaccurate. Retention studies will determine the actual life for the measure.**

2.1.6. Estimate of Persistence

The energy use of both the baseline and efficient measure are expected to remain constant over time. The TDF is one (1.0) for all years.

2.2. Process Adjustable Speed Drives -- General

2.2.1. Operation

The speed of an induction motor changes based on the frequency of the input current. An Adjustable Speed Drive adjusts the operating frequency and voltage to match the load requirements.

Electronic ASDs are solid state devices with no moving parts. ASDs convert the AC input power into filtered DC power and, using a power inverter, synthesize the desired frequency AC waveform. There are a variety of different inverter strategies to create the AC current.

While each inverter type has some unique benefits and problems, most exhibit the following traits:

- The shape of the generated output is not as smooth as the waveform found on most power distribution systems.
- ASDs have low harmonics and high power factors at reasonable loads.
- ASDs 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 a common retrofit expense.

The most common type of ASD for motors up to 200 horsepower is pulse width modulation (PWM). PWM ASDs chop the filtered DC power into variable width pulses that synthesize the desired variable frequency and voltage AC waveform.

ASDs are usually controlled automatically by sensors monitoring the process or manually at a control panel (if frequent adjustments are not required).

2.2.2. Energy Savings Mechanism

Many fan, pumping, and process applications use induction motors to supply motive power. Induction motors have a nearly constant output speed. Thus many applications are operated at constant speed or if variable flow is desired the control is exercised at the application. The speed of an induction motor is controlled by the frequency of the electrical current. Drives have been developed which can control motor speed by varying the frequency and voltage of the supply current.

The relationships between torque, power requirements, and speed vary with the type of load. Processes such as hoists, winches, drilling, and milling, have constant torque requirements. The power required varies linearly with the speed. At half speed the process requires half power. In processes such as low viscosity mixing, the torque is proportional to the speed and power varies with the square of the speed. (In some highly viscous mixing processes the substance becomes less viscous at higher speeds and the torque requirements decrease after a certain speed, for example, bread dough mixing.)

In fan and pumping applications the power requirement is proportional to the cube of the flow rate. The pressure necessary to move the gas or liquid down ducts or pipes varies with the square of the flow rate. If the flow rate is halved, the necessary pressure is cut to one-fourth. One-fourth pressure at one-half flow equates to one-eight power requirement. Small reductions in flow result in significant power savings. A 21% reduction in flow rate cuts the power used by over half.

Many applications have varying flow requirements. However, one of the most common arrangements is to set the flow rate at the maximum and leave it there. For example, many chilled or hot water circulating loops in HVAC systems are operated at the design flow rate even though this is needed only a small percentage of the time. Common methods of flow reduction include flow throttling or flow bypass Both methods are energy inefficient. A throttling valve raises the pressure so that the power required at the reduced flow continues to be higher than necessary. Flow bypass can reduce the pressure, but it still wastes energy embodied in the bypass flow.

ASDs save energy by reducing the motor speed to just match load. This produces higher motor efficiency and eliminates the excess energy associated with throttling or bypass.

2.2.3. Degradation

Degradation of ASD energy efficiency was analyzed from three perspectives: ASD degradation, motor degradation, and sensor/control degradation.

ASD Degradation Additional contacts were made and literature searches were expanded over the ASD investigation in *Persistence 1* (PEG 1996). The results are unchanged from that report. Manufacturers, field service personnel, and researchers were asked about potential ASD degradation mechanisms.

The Adjustable Speed Drive does not degrade any appreciable amount over time. According to a field service company specializing in ASDs, the most common problem is total failure of the capacitors, which sometimes explode in the enclosure. The system runs well until there is a component failure, which results in the loss of operation.

Another source noted that ASDs themselves can be damaged by harmonics, which may effect 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 cause total failure, not degraded performance. If any loss mechanism increased significantly, the unit would overheat and fail.

> **PEG concludes that increases in energy consumption due to technical degradation of an ASD are unlikely.**

Motor Degradation The motor and adjustable speed drive must be considered as a unit. In a retrofit situation it is often necessary to replace the motor at the time the adjustable speed drive is added. Whether or not the existing motor can be utilized with the ASD depends on a variety of factors.

A potential exists for the ASD to harm the motor. However, this will result in motor failure rather than an appreciable degradation of the motor efficiency.

While not leading directly to decreased motor efficiency, ASD damage to a motor may indirectly lead to decreased motor efficiency. If the motor’s stator windings are damaged by an ASD, it is usually less expensive to rewind the motor than to buy a new one. This is particularly true in the larger motors (50 HP and larger). Several studies have shown that rewound motors often are less efficient than the original. (E. Source 1993) Ontario Hydro tested eleven standard efficiency 20 HP motors for efficiency. It then intentionally damaged ten of the motors, had them rewound at ten different rewind shops, and retested their efficiency. An average efficiency loss of 0.9% was recorded after rewind. Only one motor increased in efficiency after rewinding. BC Hydro conducted a similar test with eleven 20 HP premium efficiency motors. An average of 0.5% efficiency loss was found, with all ten test motors losing efficiency after rewinding. General Electric measured in-field motor losses. (McGovern 1984 and Evans 1984) The results from 70 motors were presented. For the 43 motors that had never been rewound, losses averaged 98% of nameplate information, indicating that there was no degradation over time. The 27 motors that had been previously rewound showed a 16% average increase in losses over the nameplate. This data is in line with other GE tests of core losses in previously rewound motors. For more information see Section 2.10.6 in *Persistence 1* (PEG 1996).

A potential retention (service life) problem is the generation of extra heat and reduced cooling capacity. Extra heat is generated because the synthesized waveform is not purely sinusoidal. The non-sinusoidal portion of the waveform does not contribute to useful mechanical energy and is converted into heat. The motor's life will be shortened if the rated design temperature of the motor winding insulation is surpassed. It is estimated that for every 10°C above design rating, the insulation's and motor's life is halved. However, even though a motor operating at a higher temperature may fail more rapidly, it is unlikely to experience declining efficiency. (Maase 1997)

In constant torque applications overheating potential increases. At lower speeds the motor's integral cooling fan runs slower, significantly reducing its cooling capacity. An independent motor cooling fan can be added to prevent overheating. Motors specifically designed and marketed for adjustable-speed service are often equipped with a separate constant speed motor cooling fan. New premium-efficiency motors inherently run cooler than standard efficiency motors and often do not need additional cooling with ASD drives.

Increased stress on motor insulation can occur because of voltage spikes. Voltage spikes are produced when an electric current is interrupted. The magnitude of the spike is proportional to the amount of current interrupted and speed of interruption. The high-frequency interruption from an ASD can produce spikes that two or three times the supply voltage that can rapidly break down conventional motor insulation. High voltages may also be produced by resonance in the line between the motor and control. There are a variety of solutions to this potential problem. Certain ASD designs are less susceptible to voltage spikes and can be used where spikes are a problem. Line reactors, which act as voltage spike chokes, can be installed between drive and motor. The insulation integrity of an existing motor can be tested before the installation of an adjustable speed drive and the windings can be reinsulated using motor stator dip if necessary. (Atkins 1996)

Decreased stator insulation integrity will cause a very small decrease in motor efficiency as stray currents increase. At any appreciable stray current the insulation and motor will fail.

An ASD can also cause bearing wear due to common mode voltage. The ASD is not referenced to ground and a DC voltage can develop between the stator and ground. This voltage can travel through the motor bearings causing excessive wear through increased frictional losses and decreased motor efficiency. This loss is small until catastrophic bearing failure occurs. (Howe 1995)

Solutions exist for most ASD caused motor problems. Motor failure is primarily due to misapplication of the technology or failure to take appropriate precautions. (Howe 1993 and Howe 1995)

The impacts of ASDs on motors that were designed for a fixed speed and voltage are not fully understood. However, motors do not lend themselves to significant degradation mechanisms without failure. Motors designed for operation with ASDs are available and their use is recommended on new applications or motor replacements.

No comprehensive database or field test of motor degradation with ASDs was found. The Army Corps of Engineers, Construction Engineering Research Laboratories has started a motor degradation field test of motors fitted with ASDs. (Maase, 1997) This research is in progress and the results are not yet available.

> **PEG concludes that increases in energy consumption due to motor rewinding after motor failure could be a significant issue that should be addressed in retention studies.**

Degradation of Sensors and Controls ASD control systems are subject to degradation. The process being controlled must be monitored with sensors. These sensors are connected to a process controller that initiates a signal to the adjustable speed drive. Sensors are subject to drift. ASD savings depend upon proper sensor performance and can degrade from accumulating sensor error.

The process controller is subject to operator error. Improper adjustment of control settings by building operators can cause 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). In processes where speed control is critical to product quality (such as film manufacturing or textile weaving) oversight of sensor accuracy will be tight. (Snyder 1991) In processes where speed control is optional, such as chilled water circulation in HVAC systems, the control might drift considerably before it is corrected. 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, which eliminates energy savings. These issues would be best addressed in studies specific to each measure. Studies will need to note control settings and check sensor calibrations over time at the sites visited. Studies will also need to be industry specific as operation and maintenance opportunities and practices differ significantly among applications.

> **PEG concludes that increases in energy consumption due to sensor and control drift or failure could be a significant issue that may need to be addressed in studies.**

2.2.4. Conclusions

> **PEG concludes that 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 may need to be investigated through measure specific studies. ASDs may contribute to motor failure and retention studies should address the frequency of motor rewinds compared to baseline.**

2.3. Process Adjustable Speed Drives -- Pumps

The baseline measure is a pump in a waste water treatment facility for which variable flow rates are controlled by inlet throttling. The efficient measure is the same pump with an adjustable speed drive to vary flow rates.

2.3.1. Degradation

Potential degradation mechanisms are as stated and analyzed in Section 2.2. An additional potential mechanism is the interaction with the pump.

Pump Degradation An ASD runs a pump slower under conditions of lower load. At slower speeds many of the wear characteristics are reduced, specifically:

- Impeller wear increases in proportion to the cube of the speed
- Vibration limits are inversely proportional to speed
- Required net positive suction head increases in proportion to speed
- Shaft run out increases in proportion to the square of the speed

(O'Keefe 1991) Pump wear increases clearances and reduces pump efficiency. By slowing pump wear, the ASD will maintain the pump efficiency longer than a conventional constant speed drive.

> **PEG concludes that pump efficiency will be maintained over a longer period than the baseline application. A pump driven by an ASD controlled motor is likely to experience negative relative technical degradation due to decreased pump wear.**

Sensors and Control Settings The installation of an ASD on a waste water pump is unlikely to experience degradation due to sensor drift and operator control because of inherent leeway in pumping rates, and because the process was already controlled to a variable rate with inlet throttling. If pumping rates were too high, liquid drawdown would proceed too quickly and initiate operator intervention. Control problems with inlet throttling are expected to be similar to ASD control issues. No technical degradation is expected on ASD pumping applications to this process. No further studies are recommended.

2.3.2. Conclusions

> **PEG concludes that savings from ASDs are unlikely to degrade over time due to changes in measure performance.**

> **PEG concludes that savings from ASDs are likely to improve over time due to changes in pump efficiency.**

2.3.3. Estimate of Persistence

Negative technical degradation is estimated due to decreased pump wear. By CADMAC directive, negative degradation rates are set equal to one. The TDF is one (1.0) for all years.

2.4. Process Adjustable Speed Drives -- Injection Molding

The baseline measure is an injection molding machine with a continuous operation hydraulic pump with bypass control. The efficient measure is the injection molding machine retrofitted with an adjustable speed drive. The bypass remains in place, but bypassing is minimized by adjusting the ASD.

2.4.1. Savings Mechanism

Injection molding forms thermoplastic and thermoset materials into molded products of intricate shapes. The process involves the injection, under high pressure, of a metered quantity of heated and plasticized material into a relatively cool mold--in which the plastic material solidifies. The machines function as follows:

> For each batch of parts, an injection molding machine goes through a cycle which generally lasts 20 - 60 seconds. It consists of six steps: mold close, injection high, injection low, screw rotate, idle or cooling, and mold open. Although pressure and flow requirements vary drastically between different steps of the cycle, the input power to the motor under constant speed operation does not, as the pump must overcome the frictional resistance of throttled valves or bypass fluid pathways. A VSD (*ASD*) dynamically modulates motor speed (thus hydraulic pressure and flow) to that required to perform the task of each part of the cycle. Motor speed, as well as acceleration rate (or ramp time) can be finely tuned for each phase of the cycle to optimize efficiency. In addition to improving efficiency, a VSD also improves the power factor for injection molding machinery because motors designed for peak machine capacity often run at lower loads. (Englander and Remley 1994)

2.4.2. Degradation

Potential degradation mechanisms are as stated and analyzed in Section 2.2. A critical potential degradation mechanism is the set up of the ASD specific to each mold and resin.

<u>Control Settings</u> Injection molding is a complex process and retrofitting an injection molding machine is more difficult than most other ASD applications. The application of ASD in injection molding requires special applications engineering without which the installation may fail. EPRI Adjustable-Speed Drive Demonstration Office conducted an applied research effort that showed ASD retrofits could be successful when properly designed and implemented. (EPRI, 1995)

As with any ASD application, the control is critical to the persistence of savings. The application to injection molding is complicated by two items. Each mold and resin will have unique settings for optimum energy efficiency and the original control system (bypasses, etc.) remain in place.

One study monitored twelve installations at seven sites. (Englander and Remley 1994) That study noted the critical nature of setup for each mold: “Each of the employees who changes molds must be trained to setup and optimize the VSDs, or else savings may deteriorate.” The authors did not have data on how widespread setup problems might be, but they did observe in one facility that systems and procedures for rapid and optimum set up were not in place. They also noted; “Plant personnel accustomed to adjusting the hydraulic valves as a means of tuning machine operation may continue to do unless they are comfortable with adjusting VSD settings, and find it easier to do so.”

Analysis

Two types of controls are used on ASDs for injection molding machines, manual and memory. Manual controls need to be reset for each new part. Controls with memory store the settings and can be reset more easily. The length of injection, cool-down, release, etc. varies from part to part. Optimizing for energy efficiency takes time and is less important to the operator than optimizing for speed. The sensitivity of long term energy savings to machine operation is a concern that should be technical degradation studies. A research plan is presented in Section 3.2.

2.4.3. Conclusions

PEG concludes that savings from ASDs are unlikely to degrade over time due to changes in measure performance.

ASD control settings during mold setup may affect the persistence of ASD savings on injection molding machines if the level of operator attention or competence drops after the first year savings are measured. This should be investigated through technical degradation studies.

2.3.4. Estimate of Persistence

Estimate Methodology No data was found on which to base an estimate of persistence for this technology. No technology similar enough to provide a reasonable basis for comparison was found either. Therefore, the estimate of persistence is based solely on engineering estimates of reasonableness.

Calculation The baseline technology of continuous operation will have constant energy use. A motor under continuous full speed operation by an ASD would dissipate about 4-6% more energy during operation because of internal ASD losses (Howe 1993). Therefore full degradation could generate an energy increase of that magnitude — 106% degradation of energy savings.

The greatest error would occur if the relative degradation were estimated in the opposite direction of its actual occurrence. If full degradation were predicted and no degradation occurred, or visa versa, maximum error would result. By estimating one half degradation, the possibility of an error greater than half is eliminated. Without supporting evidence for another estimate, minimizing the greatest potential error is the safest and fairest estimate. A degradation of one-half of 106% is 53% degradation.

The shape of the degradation curve was chosen as a logic curve by the following reasoning. Initially original operator pays close attention to details and parts for which the ASD was optimized are still produced, therefore initial degradation is slow. Over time original operators are replaced or regress to old habits and production of new parts complicates ASD operation. In the middle period both operator change and production changes accelerate degradation. Finally operation settles into an improved average The logic curve is a standard degradation curve that fits this profile; the half-life is estimated as 4 years. Table 2-2 lists the estimated TDFs.

Estimate of Persistence

Table 2-2 TDF of ASDs on IMMs

YEAR	Overall Multiplier
1	1.00
2	0.98
3	0.91
4	0.74
5	0.57
6	0.50
7	0.48
8	0.47
9	0.47
10	0.47
11	0.47
12	0.47
13	0.47
14	0.47
15	0.47
16	0.47
17	0.47
18	0.47
19	0.47
20	0.47

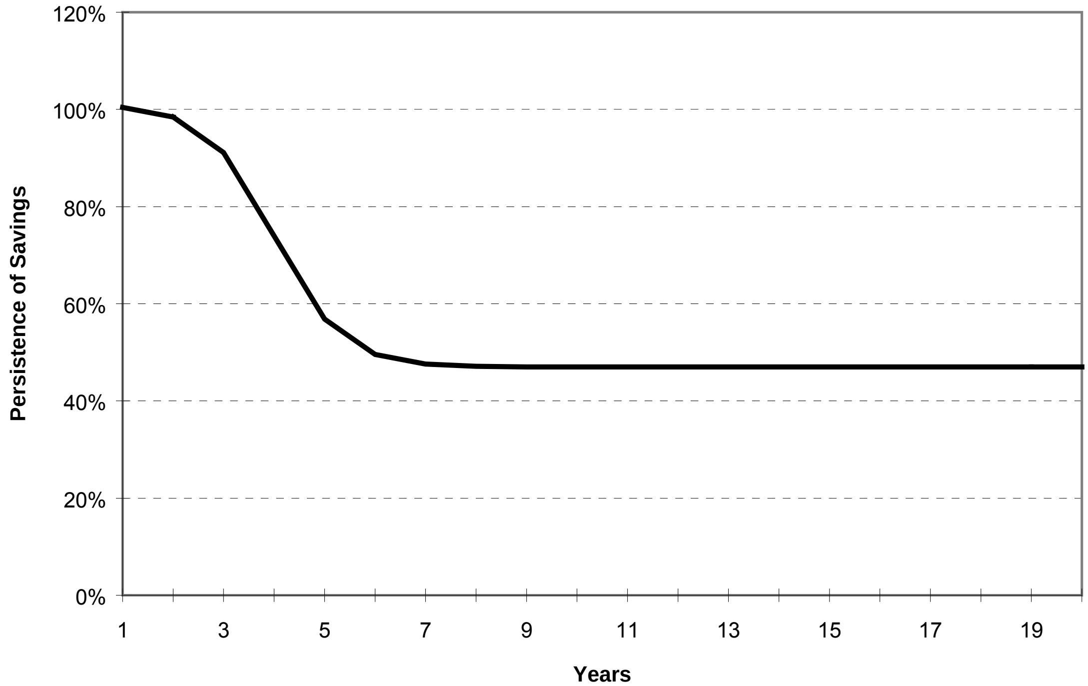


Figure 2-2 Persistence of Savings Curve for ASDs on IMMs

2.5. Wall & Floor Insulation

The baseline measures are R-13 fiberglass batt wall insulation and floor insulation in residential new construction. The efficient measures are R-15 fiberglass batt in the walls and R-19 in the floor.

2.5.1. Savings Mechanism

Wall and floor insulation save energy by reducing the heat loss rate through the building envelope. 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 across the envelope.

The fiberglass itself is not an insulator; glass is a relatively good conductor. A single pane glass window for example provides little insulation. It is the air films on the glass pane that are insulating. Similarly, it is the air around the fiberglass that provides insulation. Similar to the air space in a thermal pane window, the fibers of glass trap air, which is a poor conductor. The air provides the insulation effect. The R-value of fiberglass is dependent of the proper entrapment of air.

2.5.2. Degradation

Performance degradation may occur over time if the ability of the insulation to maintain air pockets is reduced. The mechanisms include removal, compression, increased pressure difference across the insulation driving air through it, moisture, and moisture damage. This investigation identified a limited amount of data on these items.

In inspections of homes weatherized in the Bonneville Regional Weatherization Program, investigators found degradation mechanisms on some wall and floor insulation seven years after installation. The investigators found that some homes had been remodeled and the wall insulation had been disturbed during a remodel. They also found that it was “normal” for floor insulation to sag 1 to 3 inches from its original position. In some cases the floor insulation had been disturbed by human activity. (West 1996)

A 1 to 3 inch sag in a floor batt will have no effect on the insulation effectiveness unless another heat loss mechanism is present. If the sag only produces a large dead air space, the air space will not impact the performance of the insulation. If, on the other hand, potential exists for a wind wash blowing between the floor and insulation batt, sagging can produce the air flow pathway. The rate of sagging is unknown, but it is generally believed to occur soon after installation and rapidly reach equilibrium. The authors’ inspections of new construction before occupancy lend credence to this belief.

> **PEG concludes that it is unlikely that sag in floor insulation causes savings degradation after the first year.**

Rodents can nest in fiberglass floor insulation. In addition, fiberglass batt insulation apparently provides an appealing nest-building material for squirrels and plundering of insulation for this purpose has been reported (although it is uncommon).

> **PEG concludes that it is unlikely that rodent activity will cause any measurable savings degradation when viewed across a program of any significant size.**

Analysis

The potential impacts of human activity disturbing the wall or floor insulation can be reasonably estimated using standard heat transfer theory.

A "worst case" scenario was developed:

- if 10% of the homes disturbed 10% of the wall insulation over 10 years making it totally ineffective
- and if 20% of the homes disturbed 10% of the floor insulation over 10 years making it totally ineffective
- then the wall savings relative degradation in year 10 would be 1% of the savings (not 1% of the consumption).
- and the floor savings relative degradation in year 10 would be 2% of the savings (not 2% of the consumption).

While some known degradation mechanisms exist, their effect appears to be extremely small. Persistence studies of weatherization measures have a difficult time distinguishing between the persistence of different measures (since they are generally installed in combinations).

Homes with insulation measures installed have shown more consistent performance over time than homes with lesser retrofits (termed "General Heat Waste" (GHW) in low-income weatherization). For example, in a study of 848 participant homes, those with only GHW lost all their savings between the first and second year (an increase of 1% to 5% of total consumption). The savings loss for all participants (all of which had GHW) from year one to year two was 0.5% to 0.8% of total consumption. The best performing group was the group with GHW, Attic insulation, wall insulation, and floor insulation. That group showed a savings increase of 0.2% to 1.2% of total consumption between years one and two. (Gregory 1989).

While wall and floor insulation degradation mechanisms exist, they are believed to have a very small effect. Available studies support the belief that wall and floor insulation savings persist over time.

2.5.3. Conclusions

> **PEG concludes that savings from wall and floor insulation are unlikely to show any measurable amount relative technical degradation after the first year.**

2.5.4. Estimate of Persistence

The energy use of baseline and efficient measures are expected to remain constant. The TDF is one (1.0) for all years.

2.6. Daylighting Controls

The baseline technology is standard manually operated fluorescent lighting in an office building. The efficient measure is a standard office building retrofitted with photosensors controlling dimmable fluorescent lighting.

2.6.1. Daylighting Control Typology

There are three primary types of daylighting controls: switched, stepped, and dimmable. (Ander 1995)

Switching or on/off controls turn lights off when daylight provides sufficient illumination. They are the simplest and least costly, but provide the least energy savings because savings only occur when daylight alone fully satisfies the lighting needs.

Stepped controls provide intermediate levels of electric light by progressively switching groups of lights off as daylight intensity increases. Control is relatively simple, resulting in a more flexible and aesthetically pleasing environment. Stepped controls provide greater energy savings potential because lights can be switched off at intermediate daylight levels.

Dimmable controls adjust electric light output continuously to supplement available daylight. Maximum energy savings are possible because only the minimum necessary electric lighting need be used. The controls are the most complex, and the system requires special lighting equipment capable of producing adjustable light output.

2.6.2. Operation

Daylighting control selection is strongly influenced by lighting quality requirements. A shopping center atrium with a large amount of glass may function well with on/off controls if the environment is designed to resemble the outdoor environment.

A warehouse employing skylights and stepped controls is a common and acceptable arrangement. Significant variation in interior light levels are well tolerated as long as all areas have a minimum.

By contrast, only dimmable lighting systems have been found generally acceptable for office environments. Requirements for quantity and quality of light are strict - the dimming system must be nearly transparent to office occupants.

<u>System Components and Control Strategies</u> The control system has three components.

- Photosensor
- Controller that converts the photosensor input to a control output
- Lighting fixture - with ballast for dimmable fluorescent systems

There are two basic control strategies: open-loop and closed-loop. In an open-loop, the photosensor is installed so that the system only responds to exterior light levels. In a closed-loop, the photosensor measures light at the work surface and adjusts the luminaries accordingly. Care must be taken with either system to ensure interior light levels do not oscillate, yet still respond to external light levels.

Switched and Stepped Control Systems Switched and stepped control systems use a photosensor to measure available ambient light. A time delay and deadband are often added to reduce rapid changes in light levels on partly cloudy days. On a year round basis, a switched or stepped daylighting system can typically reduce the daylit area's electrical demand and usage by 25-33%. (Booz Allen & Hamilton 1987).

Daylighting systems can also enhance space aesthetics while saving energy as illustrated by the successful switching system inside a retail mall atrium that mimics the outdoor environment as described below.

> The retail stores are organized around a linear plan that utilizes three anchor stores at either end of the center and one opposite the entrance. A barreled dome and diffusing panels are used to allow daylight to penetrate the linear circulation spine. The daylight not only illuminates the circulation spine but also provides enough light for the live trees and plants in the space. The barreled acrylic dome permits reflected daylight to reach the open spaces, whereas the diffusing panels control direct beam penetration. During certain seasons, a thin linear slice of light enters the building and hits the floor, which helps direct shoppers through the circulation spine while adding visual contrast and interest. The combination of reflected, diffuse, and direct daylight improves the visual quality of the interior environment and, in addition, reduces lighting, HVAC and peak demand loads. (Ander 1995)

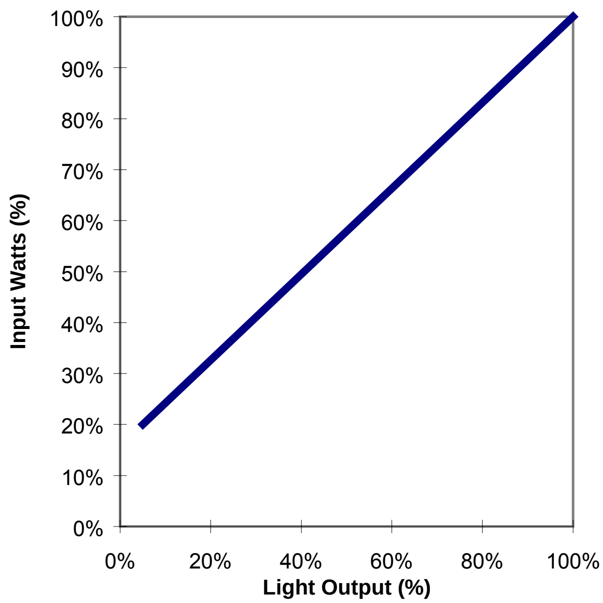
Dimmable Fluorescent Systems There are a number of technical and operational reasons that complicate the use of daylighting in office buildings. Direct daylight is too strong and produces discomfort due to shadowing and glare. Daylight must also be transferred from vertical, exterior windows to horizontal, interior surfaces where it is needed. Dimming the fluorescent lighting system must be automatically controlled to provide the correct light levels under highly variable environmental conditions.

An office daylighting system can be as complex as designing an office building to incorporate and take advantage of daylighting potential. In a building specifically designed for daylighting, the shape of building takes advantage of available sunlight and maximizes useful light penetration to interior spaces. Windows are chosen that transmit the visible portion of the light spectrum while excluding the heat content of sunlight. Electric lighting fixtures are installed to permit dimming in banks with careful attention given to luminaries located near windows. A control system is installed that brings all of the parts together and controls the fluorescent lights as supplemental lighting. On a year round basis, a dimming daylighting system can typically provide 35-50% of the daylit areas lighting needs.

The heart of a daylighting system in an office building is the dimmable fluorescent ballast. Incandescent lights are inherently dimmable. Dimmer switches that use various techniques to alter the current waveform and achieve dimming are cheap, readily available, and reliable. However, the arc in a fluorescent light is more difficult to maintain. A ballast must maintain the arc and limit the wattage simultaneously.

There are two reasons for dimmable fluorescent ballast systems: architectural effect and energy savings. Systems optimized for each have been developed. Architectural dimming systems have the ability to reduce lighting accurately down to very low light levels, as low as 1% of full brightness. These systems tend to be expensive. Dimming for energy savings to 10-30% of full brightness is acceptable. The eye is relatively insensitive to light level differences so minor fluctuations are acceptable; however flicker and hunting are not.

The ratio of watt output reduction to light output reduction varies among products. Figure 2-3 illustrates a typical ballast and lamp. The light output is always reduced more that the watt input, i.e. the lamps are operated less efficiently when dimmed.



Source: Advance Transformer Company (Mark VII)

Figure 2-3 Light Output vs. Input Watts for a Dimmable Ballast

2.6.3. Energy Savings Mechanism

Energy savings from daylighting are achieved when the electric lighting system's power is reduced by taking advantage of ambient light. The electric lighting system must be sized to supply adequate light at night. Therefore at full brightness, the electric lighting system will over-illuminate whenever significant daylight is available.

The daylighting system measures the available light either at the work surface or at the glazing. The daylight controls adjust the lighting system to deliver the minimum necessary artificial light to obtain the correct light level at the work surface.

There are three mechanisms to reduce the power consumption of artificial lights.

- Daylight supplemented lighting
- Lumen maintenance
- Scheduled light levels

Daylight Supplemented Lighting In switched and stepped control systems lights are switched off when adequate natural light is present.

Dimming systems are used in conjunction with fluorescent lighting to save energy and reduce peak demand. Ideally the dimming control system operates unnoticed by the occupants, but often this is not the case. The primary problem is maintaining light quality as humans are very sensitive to it. Reduced workplace productivity from poor lighting quality would quickly negate any financial benefit from reduced lighting costs.

Lumen Maintenance The light output of a fluorescent lighting system is reduced over time due to lamp lumen depreciation and dirt buildup on the lamp, lens, and reflector surfaces. In order to compensate for this reduction, the system is designed to provide adequate light levels even at minimum output. Therefore, except at full lumen depreciation just before lamp replacement, the light is too bright in its full on position. A dimmable lighting system can adjust for variations in lumen output. Lumen maintenance works best with group relamping because this typically provides more uniform lighting levels.

Scheduled Light Levels Nighttime light levels do not have to be as high as during the day if only maintenance and cleaning crews are working. Switching on every other light can leave unacceptable dark spots. Uniform dimming of fluorescent lights can save energy and provide even illumination. When connected to a lighting controller, the system can dim on any appropriate schedule.

2.6.4. Degradation

Degradation of Fluorescent Light Source Output Daylighting controls adjust the fluorescent luminaries to compensate for any shortage from the daylighting. Consequently, anything that reduces the efficacy of the artificial lighting system will increase power usage.

As lamps age, their light output decreases 10-15%. Dirty lamps and fixtures result in an additional 15-25% lumen reduction. Conventional practice includes this light loss factor into the design, so that the system provides sufficient light at full depreciation. As the ambient light level goes down, the daylighting system compensates for lumen depreciation. When the system is newer, lights are dimmed to design level. As the system ages, the illumination level remains constant and power draw increases.

Since lamp lumen depreciation and fixture efficiency depreciation due to dirt are anticipated events, saving calculations from daylighting controls could be based on average values incorporating these events. If the savings calculations includes and anticipates this light loss factor then further degradation of savings would not occur. The full light loss effect takes 3-5 years and would not be completely measured in first year savings.

In a test of advanced lighting strategies including lumen maintenance, Rubinstein (1990) found a 21% increased light level from cleaning and relamping fixtures. He describes a lumen maintenance cycle as fixtures age or are relamped.

> Using the light measurements from the reference zone before and after relamping (data not shown), we estimated that the increase in light output *due to relamping and cleaning alone* was approximately 21%. … Clearly, a significant portion of the base energy savings from the daylighting/lumen maintenance/scheduling control scenario is attributable to the fact that the power levels could be set to 75% of full power and still supply essentially the same light level as was provided prior to the retrofit (approximately 50 fc). As time passes, however, the lamps will age and gradually produce less light. As the photo-electric controls automatically compensate for this drop in efficacy, the ballasts will have to supply more lamp power to maintain the same light level. Thus, under similar daylight conditions a year from now, the lighting demand (and daily energy use) is expected to be slightly higher. This trend should continue until the system is relamped and cleaned at which time the savings pattern should repeat itself. (Rubinstein 1990, *italics original*)

In later follow-up study, Rubinstein (1991) found that energy usage increased 9.5% after 11 months for the same zone and similar ambient light conditions. This result corresponds to the expected 5% decrease in light output due to lamp lumen depreciation and 5% decrease due to dirt accumulation.

A typical light loss factor is 30% depreciation (Philips Lighting Co. 1984). On a diversified basis the average depreciation would be half of this — 15%. Over 3 years this would result in a diversified wattage increase of 15%. If first year savings captured 5% depreciation, the average of 0-10% that occurs in the first year, the technical degradation would be an additional 10%.

PEG concludes that light loss factors would lead to a 10% differential technical degradation in closed loop dimmable daylighting systems in which savings estimates are based on original lamp output or measured first year savings.

Photosensor Failure Photosensors are subject to failure. A photosensor failure that resulted in inadequate lighting would be expected to be corrected more quickly than a photosensor failure that resulted in continuous operation. A switching or stepped system would return to full power. Because dimmable ballasts draw more power at full brightness than standard ballasts (see "Higher Ballast Losses" below), a photosensor failure resulting in continuous operation would increase the energy usage of the system to above the standard system watt draw for those fixture connected to the sensor.

PEG concludes that daylighting systems are likely to experience relative technical degradation due to photosensor failure.

Ballast Failure Electronic dimmable ballasts can fail in a variety of ways: full off, stuck at one level, flicker or strobe, or full on. Usually the ballast fails in an obvious discernible way that will cause it to be replaced. A full-on failure would diminish savings. One manufacturer stated that the two most common failure modes were failure to ignite lamp and diminished light output with a reduced power draw. Failure in the full-on condition was considered extremely unlikely. (Droho 1998)

Initially dimmable ballasts had problems and higher failure rates. Several sources reported that the newer ballasts operate with fewer failures. Loisos (1997) estimated failure rates to be equal to electronic ballasts in general. PG&E estimated the effective useful life of dimmable ballasts as 8 years, only half that of electronic ballasts — 16 years. (CADMAC, 1996, Table 1 items 14 & 15) Rubinstein (1991) found 10 out of 54 ballasts failed within two years of installation. However, these ballasts were hand built prototypes and probably atypical; he considered the failure rate much higher than would be expected in commercial production.

Various sources estimate the life of a dimmable or electronic ballasts as 8 to 16 years, Table 2-3. SCE estimates the effective useful life of daylighting systems as 10 years. Thus, dimmable ballasts failures would be expected to cause higher energy use infrequently during the rated life of the system.

Table 2-3   Measure Life Estimates of Electronic and Dimmable Ballasts

Measure	**Measure Life Estimates**	**Source**
Ballast — Electronic	10 Years	SCE, CADMAC 1996: Table 1 #15
Ballast — Electronic	16 Years	PG&E, CADMAC 1996: Table 1 #15
Ballast — Electronic	16 Years	SDG&E, CADMAC 1996: Table 1 #15
Ballast — Electronic & Dimmable	50,000 Hours (12.5 years @ 4,000 hr/yr)	Advance Transformer Co., 1998
Ballast — Dimmable	No estimate given	SCE, CADMAC 1996: Table 1 #14
Ballast — Dimmable	8 Years	PG&E, CADMAC 1996: Table 1 #14

PEG concludes that ballast failure rates are reasonably low and that the primary ballast failure modes result in lights off or reduced power draw. PEG concludes that daylighting systems are unlikely to experience technical degradation due to ballast failure.

Control System Degradation and System Bypass of Dimmable Systems The most often cited reason for savings degradation is control system problems that lead to system bypass. Humans are sensitive to the quality of illumination in the work environment. In a study of workers' response to office conditions, the quantity and quality of light were consistently rated as very important. (Ne'eman 1984) The ideal daylighting system would operate smoothly without drawing occupant attention. Daylighting controls are complicated and difficult to adjust properly. Annoying operation of a lighting system is usually quickly dealt with by disabling it. A constant artificial light level is familiar and accepted. Bypass is often easily accomplished. If tape is applied over the photosensor, the control system will see pitch black and become inoperative. One researcher found a daylighting system 80% bypassed within 2 years. (Rubinstein 1998) Most practitioners contacted had anecdotal stories of system malfunctions and creative bypass solutions. (Loisos 1997; Rubinstein 1998; Mapp 1998)

Critical control points in the daylighting system that could result in unacceptable operation and encourage system bypass include photosensor, controller signal output, and the dimmable ballast.

Occupant Response to Daylighting Sometimes the system may be bypassed because of perceived rather than real problems. One researcher reports that during a daylighting installation the photosensors were installed in the ceiling tile before they were hooked up to the lights. When the researchers came back for the final installation and system activation, one of the photosensors was already taped over. (Rubenstein, 1998)

Occupant acceptance is key to successful daylighting. And the key to occupant acceptance is a control system that operates the lights unobtrusively. The control of dimmable daylighting systems is improving rapidly, but is not a fully developed and reliable technology at this point.

> "According to Dr. Rea, daylight dimming did not fare as well [as manual dimmers] in performance because of the lack of occupant acceptance, which resulted in NCAR adjusting the photosensors until they became much less effective than the manual dimming. After complaints that the photosensor dimmed the lights too quickly, in-house engineering personnel returned to each office to increase the set-point of the minimum desired light level, reducing the sensor's effectiveness. They also increased the ratio of response of the sensor, so that one unit of electric light was removed only after a geometrically increasing number of units of daylight was sensed. This satisfied the occupants to a large extent but reduced the effectiveness of the photo sensor at saving energy. Recalibrations took a half-hour for each sensor. (Dilouie, 1997)

In an analysis of a successful project that greatly increased the dimming response of the fluorescent lighting system at a large office building built with explicit daylighting design features, Benton et al. (1990) report that occupants were unaware when maximum dimming was increased from 5% to 72% dimming.

> "Our revisions have been successful in establishing proper lighting system operation for summer, equinox, and winter conditions and in clear and cloudy weather. … it is clear that the test zone system is now performing properly and using the appropriate amount of lighting energy to maintain an accurate target illuminance. … We can provide an anecdotal report that occupants of the test zone are largely unaware of the increased dimming as it occurs during the brighter portion of the day. (Benton et al., 1990)

Higher Ballast Loses System bypass will result in a greater watt draw than the standard system because dimming electronic ballasts draw more energy at full light output than non-dimming electronic ballasts. Negative savings will occur at continuous full light output levels, Table 2-4.

Table 2-4 Electronic Ballast with Two T8 Lamps

Ballast	Watts
Non-dimming rapid-start electronic ballast	60-62
Non-dimming instant-start electronic ballast	58
Dimming electronic ballast	64-65

Photosensor response Currently available photosensors are difficult to work with for several reasons. During calibration the presence of the worker obstructs the sensor's field of view. The calibration screw is often small and poorly located making it difficult to adjust. Standards do not exist, so different ballast/photosensor combinations result in unpredictable performance.

Photosensor response can be affected by a temporary object within their field of view. In one study a photosensor was strongly affected by light reflected from the top of a bald man's head. (Wisconsin Energy Bureau, Tale of Two sensors)

> "Photosensors can be a weak link in a dimming system: (E Source 1995)

Photosensor drift and calibration error Photosensor calibrations can drift over time.

One element that could contribute to photosensor calibration error is dirt accumulation on the sensor. Dirt accumulation would cause the sensor to see a darker room and increase the light level in response, resulting in diminished savings. One source reports that this has not been observed to be a problem. (Loisos, 1997) He reasons that the photosensor points down and is unheated so there is no mechanism to draw dirt into it.

Lack of Standard Component Specifications No standards exist for system components and configurations. This can cause significant maintenance problems when components are replaced. Exact replacement parts may be unavailable because they are no longer manufactured or difficult to get. Alternate components may not function the same as the originals. If a set of ten ballasts are controlled by a single photosensor control signal and nine respond at one level with the tenth behaving differently, the potential for bypass is great. Even new installations might have incompatible components if the whole number needed couldn't be supplied as specified.

> "While all of this can be complicated, there is yet another hidden problem that can complicate (or even eliminate) energy savings. Among those electronic ballasts controllable by low-wattage signals, there is a wide variety of responses to the same signal." (E Source)

> **PEG concludes that for dimmable systems: 1) there are a variety of maintenance and control problems that could lead to poor system operation; 2) that field experience has demonstrated a high potential for system bypass; and 3) that energy savings from dimmable daylighting systems are likely to experience relative degradation due to system bypass.**

Window coverings If window orientation is such that direct sunlight can enter it is usually necessary to provide some form of glare control such as blinds or drapes which are usually occupant controlled. If blinds are closed, for instance because of early morning sunlight entering the office, they may remain closed into the afternoon. This would reduce daylighting, increase electric lighting, and reduce savings.

In one test of daylighting, offices with occupant operable blinds were found to use 38% more lighting energy than similarly oriented offices without blinds in the same building. (FSEC, 1997) In a test of an innovative daylighting strategy, Rubinstein et al. (1991) found 48% savings from daylighting in the office building's North zone but only 33% savings in the South zone. The researchers concluded that the South zone's savings where less in spite of the greater available daylight because the occupants regularly closed the drapes to reduce glare and thermal discomfort. Pigg et al. (1996) found that offices on the South side of the building often kept the blinds closed and concluded that daylighting controls on the North side might have been more effective.

> The use of blinds was also found to be a significant factor in savings from the daylighting controls. … The use of the blinds was almost certainly a factor for some of the rooms with continuous daylighting. We found that only half of the 12 rooms that had continuous daylighting controls showed any evidence of dimming during the 11 months of monitoring. The walk-through surveys indicated that occupants in three of the six rooms in which the lights never dimmed kept their blinds closed nearly all the time. It is notable that all of the offices in the continuous daylighting group were along the south face of the building. The blind management data suggest that considerably more savings would have been obtained if the daylighting controls had been installed in rooms on a different face of the building. (Pigg, 1996)

While window coverings have been shown to significantly reduce the savings from daylighting strategies, the effect of window coverings is expected to be captured in estimates of first year savings. Changes in window covers or their management after the first year could change savings. However, PEG does not expect window coverings to change systematically and on a diversified basis, and no change in energy use should result.

> **PEG concludes that on a diversified basis daylighting system watt draw is not likely to vary over time due to the effects of widow coverings and their management.**

<u>Interaction with Occupancy Sensors and other Lighting Controls</u> Occupancy sensors are becoming a more common office lighting control. The potential exists for the lighting system to have four interacting control systems. These controls may interact in ways that enhance or degrade savings.

- Manual on/off control
- Occupancy sensor control
- EMCS control
- Daylighting control

In a study of the interaction of occupancy sensors and daylighting controls in a University office building, Pigg et al. (1996) found that the presence on automatic controls changed occupant behavior in such a way to significantly diminish the amount of savings produced by the controls. The researchers found that the occupants of offices with occupancy sensors began to depend on the sensors to turn off office lights when they left. Occupants of offices with motion detectors were less likely to manually turn off the lights when they left for an extended period; instead they relied on the motion detector. Since they had been fairly conscientious about turning lights off when they left and since the occupancy sensor had a delay that wasn't present with manual switching, the effect was to reduce the savings. The lack of manually switching and time delay of the motion detector was found to reduce savings by 30%.

> "The results showed that people in offices with occupancy sensors were less likely to turn off the lights when they left the room. Instead they relied on the occupancy sensors to control the lights for them. They were also somewhat less likely to choose a switch setting other than full illumination from the overhead lights. Both of these findings suggest that in this kind of setting, people modify their behavior in the presence of an occupancy sensor in ways that reduce the savings potential from

> the device. The tendency to rely on the sensors to control the lights was estimated to reduce the savings from the occupancy sensors by about 30% in this case. Overall, the occupancy sensors were not cost effective in these individual offices from the standpoint of saving lighting energy, because people managed the lights in their offices fairly diligently. The use of blinds was also found to be a significant factor in savings from the daylighting controls. (Pigg et al., 1996)

While degradation potential exists from the interaction of daylighting controls with other controls, the presence of multiple controls is expected to be infrequent and its effect should be captured in measures of first year savings.

PEG concludes that the savings from daylighting system are unlikely to experience relative degradation due to the interaction of daylighting controls with other lighting controls.

<u>Commissioning Dimmable Daylighting Controls</u> PEG expects standard installation practices to be adequate for switched and stepped daylighting systems.

No accepted standard of components, installation, or commissioning for dimmable daylighting systems yet exists. Standard lighting system are not commissioned which may carry over to a belief that no lighting systems need commissioning. However, daylighting systems do need to be commissioned. Without commissioning parts of the system may operate inappropriately with the result that the system is quickly found unacceptable and bypassed.

A number of researchers found daylighting systems to be operating poorly as originally installed. The researchers commissioned the installation and found significantly increased savings. (Benton et al. 1990; Reed et al. 1995; Rubinstein et al. 1997; Warren et al. 1986)

> The large increase in savings in mid-July was entirely due to adjusting the sensors so they would operate properly. It is clear from looking at the data that commissioning of the sensors was extremely important. If these sensors had not been commissioned, they would have provided almost no benefits. … When the controls in the SWAB were properly adjusted, savings were two to four times greater than when they were installed without adjustment. … Our experience suggests that installation and commissioning may be the most important factors in determining whether daylighting system have good paybacks. (Reed et al., 1995)

Lack of commissioning is expected to lead to poor initial operation, low savings, and system bypass. As the daylighting controls are bypassed, the low initial savings will be reduced even further. Some, but not all, of this effect will be captured in estimates of first year savings.

<u>Human factors</u> Human factors in control operation are very important but difficult to quantify. In one facility, one shift manager switched the lights to continuous-on while the other shift manger switched them to automatic. (Booz et al. 1987)

PEG concludes that adequate commissioning is unlikely to occur in the absence of a direct utility programmatic requirement for commissioning.

PEG concludes that the savings from dimmable daylighting systems are likely to experience relative degradation due to the lack of commissioning.

2.6.5. Conclusions

> **PEG concludes that the energy savings from dimmable daylighting systems is likely to degrade over time due primarily due to control problems resulting in system bypass.**
>
> **PEG concludes that the achievement and persistence of energy savings from daylighting systems is likely to be highly variable between different installations due to commissioning factors and human factors.**
>
> **PEG concludes that switched and stepped daylighting systems have few degradation mechanisms and are less subject to degradation than dimmable systems.**

2.6.6. Calculation of Persistence

Switched and Stepped Daylighting Systems Switched and stepped daylighting systems have fewer failure mechanisms and operate in a more tolerant environment where they are less prone to bypass than dimmable systems. Photosensor or relay failure are expected to be the primary degradation mechanisms. Too little light is much more problematic than more than enough. Failures that result in insufficient light are expected to be fixed quickly; failures resulting in continuous operation are expected to be fixed more slowly. Some degradation of savings is expected due to equipment failure. No data on this degradation rate was found.

Problems with Daylighting Persistence Calculations The research of the persistence of savings from dimmable daylighting systems is made particularly problematic by the evolving nature of the technology. Systems installed in the late 1980s and early 1990s were plagued by electronic ballast failures; problems that have been solved with improved technology. Investigations of persistence necessarily have long time horizons. Measuring persistence from 1980s' installations would capture ballast failure rates and other failures which may not reliably indicate the functioning of today's components and systems. Systems installed recently do not have long post-installation energy use histories.

Adding to the above general problem of obtaining or interpreting results; very little data is available on daylighting components and their performance in place.

> Also, predicting savings from dimming can be complex due to the intricacies of dimming hardware …" (E Source 1995)
>
> … it is still difficult to find studies of the energy performance of buildings with active daylighting systems, and the studies that do exist have limitations. … A number of problems appear to be inherent in the studies that have been conducted. A major problem with nearly all of the studies is a generalization of the results. The characteristics of the buildings — orientation, size and placement of windows, ceiling heights, and existence of light shelves — can all significantly influence energy savings. Also, most metering studies have been conducted for short periods, and it is difficult to know how to generalize the results beyond the monitored period. In addition, some projects mix technologies so that the energy savings contributions of individual technologies are difficult tot identify. (Reed et al., 1995, page 11)

Calculation Methodology The primary degradation mechanism for dimmable daylighting systems is estimated by PEG to be system bypass. The primary cause of system bypass is uneven performance resulting in occupant dissatisfaction. The two primary causes of poor system operation are inadequate commissioning and inadequate maintenance. Proctor Engineering reviewed a number of studies that detail saving and/or persistence of saving from daylighting installations. PEG has found it useful to divide these studies into groups based on the estimated degree of commissioning and degree of maintenance, Figure 2-4. Buildings that were properly commissioned and carefully maintained (1), had a high persistence of savings. These buildings are estimated to be a distinct minority. Buildings that received good or poor commissioning and poor maintenance were not studied often so data is generally not available (3&4). Buildings that received poor commissioning and were later received good maintenance by researchers (2) formed the bulk of studies. The reports indicate that these buildings were generally saving very little from daylighting when the research effort began.

	Good Commissioning	Poor Commissioning
Good Maintenance	1	2
Poor Maintenance	3	4

Figure 2-4 Commissioning and Maintenance

<u>Estimation of Persistence of Savings</u> Two factors were included in the estimate of TDFs. A degradation of savings from light loss factors of 15% was estimated to occur in three years with the first 5% captured in estimates of first year savings. System bypass was modeled as an exponential decay with a 4 year half-life. The minimum savings was estimated as 20% based on research studies of poorly performing sites. TDF estimates for daylighting are considered highly tentative and a research plan is presented in Section 3.3.

Table 2-5 Daylighting TDFs

YEAR	Overall Multiplier
1	1.00
2	0.73
3	0.61
4	0.54
5	0.48
6	0.43
7	0.39
8	0.36
9	0.33
10	0.31
11	0.29
12	0.27
13	0.26
14	0.24
15	0.23
16	0.23
17	0.22
18	0.21
19	0.21
20	0.20

2.7. Agricultural Pump

The baseline measure is a standard vertical turbine agricultural pump that has worn and is operating at lowered efficiency. The efficient measure is an agricultural pump retrofitted with a new impeller and bowl assembly. Only the hydraulic efficiency of the pump bowl-impeller is considered. High efficiency electric motors are discussed elsewhere. (PEG 1996)

Replacement of an agricultural pump will result in immediate energy savings due to the improved efficiency of the new bowl and impeller over the old worn bowl and impeller. The lifetime of the measure is determined by when the worn pump would have been replaced without the intervention of the program.

2.7.1. Agricultural Pump Typology

There are four types of agricultural irrigation pumps in common use.

1) Lift pump or axial flow propeller pumps: They are used to transfer large volumes of water across a low head such as from an irrigation canal.

2) Horizontal centrifugal pumps: These pump are typically single stage units mounted at the surface that draw water up the intake. A suction lift of 15-20 feet is possible.

3) Submersible turbine pumps: Submersible turbine pumps have the motor at the bottom of the well and the electric power is fed down the well.

4) Vertical turbine pumps: The vertical turbine pump has the motor at the surface and is powered by a rotating shaft mounted in the bore hole between motor and pump.

Agricultural wells to 400-500 feet are common in some areas of the country. For lifts greater than 20 feet there must be positive suction pressure and turbine pumps are used. The pumps may have single or multiple stages, and very high lifts are possible. Deep well submersible pumps are generally used for lower flow rates and vertical turbine pumps for higher flow rates though there is a great deal of overlap in available sizing.

2.7.2. Operation

An agricultural deep well is constructed by boring a hole into which a large diameter pipe is fitted. The deep well turbine pump is attached at the bottom of a second pipe which is lowered into the well one section at a time, typically 10 foot sections. A rotating shaft runs inside this pipe; it transfers the power from the motor at the surface to the pump below. A stabilizer bearing is installed at each pipe section break.

Water from the aquifer enters into the bore hole. The pump bowl and impeller are set below the water surface. As it rotates the pump's impeller forces the water out and the bowl converts the kinetic energy into pressure which causes the water to rise to the surface. If the rise is over 100 feet, there would typically be multiple stages.

Often the aquifer has sand and gravel since it is precisely these subterranean layers that hold the water. The pump has a screen which filters out larger rock, but the sand can enter the pump.

2.7.3. Bowl and Impeller Energy Savings Mechanism

Pump efficiency is affected by pump hydraulics, application conditions, manufacture, and wear.

Hydraulics Hydraulic design refers to the design and manufacture of the bowl and impeller. The hydraulics of the pump's interior are complex. Energy is lost and efficiency decreased from a variety of mechanisms including: turbulence, eddies, surface friction, shape turns, and restrictions.

Application conditions Choosing the correct pump for the required head and flow is important. Similar pumps by the same manufacturer are optimized for different conditions. For example, Table 2-6 lists two pumps by the same manufacturer. The first pump is correctly sized for the application conditions of 60 feet head and 500 gpm and has an efficiency of 82.5%. The second pump has a greater maximum efficiency, but it would only achieve 70.5% under the stated application conditions. "Bigger is not better." In addition, a pump that is over-sized will draw the well down too quickly and will increase the chance of cavitation. Proper application is not directly covered by utility programs nor this report.

Table 2-6 Comparison of Application Efficiencies

Goulds Pump Model Number	Maximum efficiency	Efficiency at 60 ft head and 500 gpm
11WAHC, 1770 RPM	83.0%	82.5%
12RJLO, 1760 RPM	85.5%	70.5%

Pump manufacture The efficiency of the pump is improved by the design and machining of the bowl and impeller. Precise design and manufacture result in higher efficiency. The efficiency gain from the improved design and manufacture can be further enhanced by coating the water contact surfaces with porcelain. This coating reduces friction and reduces impeller and bowl wear.

Wear Pump hydraulics, application conditions, and manufacture are considered equivalent between the baseline and efficient condition. The potential exists for relative technical degradation between the old pump and the new pump as they would both wear. This is covered in the following section.

2.7.4. Degradation

Degradation Mechanisms All experts contacted agree that agricultural pumps experience significant efficiency degradation over their time in service. Wear in the bowl and impeller are the primary efficiency degradation mechanisms. The wear is due to abrasion from sand and other particles in the well water, cavitation, and near end-of-life to vibration.

Pump operating in clean water, such as building HVAC circulation pumps, can last 20-40 years and are usually limited by the bearing life. Agricultural pump life is strongly influenced by the abrasive quality of the groundwater, and pumps in some areas are known wear more quickly. (Williams 1998,) Start/stop cycles influence wear by kicking up debris in the well.

Degradation Curve The specific shape of the efficiency versus time in service curve will determine if relative technical degradation exists. There will be positive degradation if efficiency decreases rapidly at the beginning of pump service and then drops more slowly later. There will be an improvement in savings if efficiency decreases slowly at first and then drops more rapidly. A linear degradation, measured as percentage efficiency loss per year, would result in negative relative degradation — savings increase —. Figures 2-5 shows some potential curves.

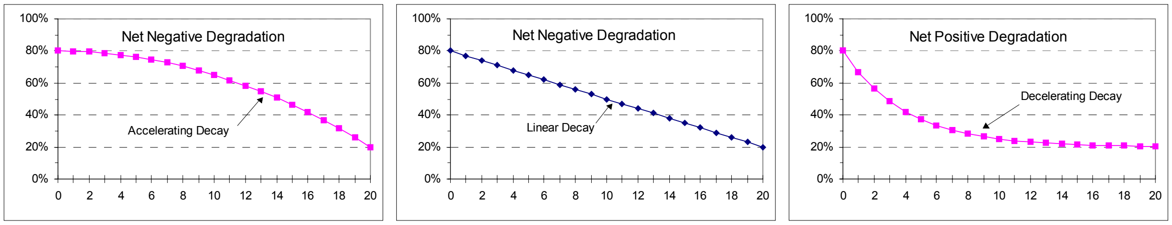


Figure 2-5 Illustration of Potential Efficiency versus Time in Service Curves

PEG used three methods to determine the efficiency versus time in service curve:

- Literature search
- Pump wear research
- Database analysis.

The literature search found no references that quantified the curve.

Pump wear research has mostly concentrated on slurry and dredge pumps for which wear is a very important issue. For slurry and dredge pumps, wear out is more important than efficiency and wear was measured as the rate of pump material loss. If a correlation of material loss versus time in service were combined with a correlation of cumulative material loss to efficiency degradation, the needed efficiency versus time in service curve could be derived. However, while the former is partly available in the research literature, the latter is not. While the shape of the curve could not be determined from this research, it was helpful in identifying wear factors and checking for reasonableness.

A database of utility pump tests was used to estimate the efficiency degradation curve. This analysis is covered in section 2.7.

As the pump wears, its hydraulic characteristics change and efficiency decreases. Factors that affect the wear rate include: particle characteristics such as size, shape, hardness, concentration, and density; pump characteristics such as materials, coating, and hydraulic design; and operating characteristics such as cavitation, flow rate, best efficiency point, and specific speed. (Ingersoll-Rand Research, Inc. 1983)

<u>Particle Characteristic Effects on Wear Rate</u> Four mechanisms has been identified for the wear of pumps from solids in suspension. (Clark 1993)

1. Grinding wear produced by the compression of particles between rotating surfaces.
2. Sliding bed, frictional wear.
3. Directional impact as a result of a stream of particles hitting the wall.
4. Random impact due to the motion of particles in turbulent fluid.

Grinding wear has been shown to contribute little to wear. Sliding bed wear is not important in dilute concentrations. Therefore in agricultural pumps, directional impact and random impact wear are the primary mechanisms.

The rate of wear has been found to be directly proportional to the rate of dissipation of the impacting particles' kinetic energy and inversely proportional to the wear resistance characteristics of the removed material. These are affected by the particle mass, velocity, and impact angle. (Ahmad 1986, Clark 1993, Addie et al. 1996) However, at this point accurate predictive models are not yet available.

> Unfortunately, those who conduct laboratory erosion tests are not able to describe the particle impact conditions under which mass loss is taking place, even under what are in principle, well-understood, controlled conditions. Until such information is available, laboratory tests will have little to offer

except broad rankings of material performance to the engineer attempting to cope with erosive wear in industrial hardware. (Clark 1993)

Little information was found that quantified the abrasive characteristics of particulates in well water in California.

PEG concludes that wear rates are proportional to the abrasive characteristic of particulates passing through the pump. PEG further concludes that these characteristics are not now quantified for California agricultural wells.

Wear Due to Cavitation Cavitation wear is caused when gas pockets collapse on pump surfaces. The collapse causes the liquid to impinge on the surface and creates wear.

There are three sources of cavitation. The net positive suction pressure (NPSP) is the pressure at the pump inlet necessary to avoid cavitation. This is more critical on suction lift pumps than turbine pumps which are set into the water column. Water falling down the bore hole sides can entrain air and create cavitation. Local wear phenomena can create low pressure points inside the pump leading to cavitation.

Rayan (1985) found that cavitation wear followed an "S" shaped curve. Wear was initially slow in an apparent incubation period. This was followed by a maximum wear rate and finally a period of slowing erosion.

PEG concludes that the effect of cavitation on wear, measured as material loss, is non-linear and probably accelerates after an incubation period.

Pump Characteristics Effects on Wear Rate Some pump manufacturers coat the inside water contact surfaces of the bowl and impeller with a porcelain coating. This coating creates a hard slick smooth surface that reduces the friction of the water traveling through the pump. The reduced friction results in increased efficiency. The porcelain coating is harder and more wear resistant than exposed cast iron. Therefore the pump may last longer than an uncoated alternative. A manufacturer estimated that the coating lasts about 10 years. (DeVore 1997) Williams (1996) measured a vortex sewage pump maximum efficiency as 51% without and 64% with a low friction coating. Though, he also noted that application of coatings are detrimental to the efficiency of some pumps. He estimated coating life as 5 years for waste water applications. Advanced coatings have been found to last over 15 years even in sewage system service. (Tucker 1986)

In slurry pumps resistance to wear is a critical pump characteristic. Slurry pump manufacturers have improved pump life through hydraulic designs that reduce wear. (Mistry et al. 1983) Hydraulic characteristics that enhance efficiency may decrease wear resistance. Addie et al. (1996) found that slurry pumps rarely achieve maximum theoretical efficiencies because of hydraulic compromises necessary to improve wear life.. One manufacturer reported that feathering the impeller tip of agricultural pumps improved published efficiency but was highly susceptible to wear degradation. Wear resistant hydraulic designs were not advertised as a competitive advantage by agricultural pump manufacturers.

Larger pumps with slower rotational speeds may experience less wear at the impeller inlet compared to smaller higher speed pumps. As flow increases, the location of maximum wear has been found to shift away from the tongue and towards the pump discharge. (Addie et al. 1996) Wiedenroth (1984) found measured impeller mass loss highly correlated to pump rpm. Total head is proportional to the impeller outside diameter tip speed; higher impeller outlet wear rates are expected at higher heads. (Ingersoll-Rand Research, Inc. 1983, Mistry et al. 1983) Mistry et al. (1983) derived formulas that showed pump life was longer at lower specific speeds.

> **PEG concludes that agricultural pumps' design and selection are not optimized to reduce wear.**

Operating Characteristics Effects on Wear Rate A pump can produce larger flows at lower lifts or lower flows at higher lifts. The pump operating efficiency changes with the flow and lift conditions. The condition that maximizes efficiency is the best efficiency point (BEP). Rates of wear change with operating conditions.

Operating a pump significantly below its BEP may result in water recirculation within the pump and gouging eddies which cause very rapid localized wear. (Addie et al., 1996)

Walker et al. (1994) tested the effect of flow rate and particle size on wear rates. They found the wear rate minimized at a flow rate about 75% and 80% of the best efficiency point for fine and coarse particle sizes respectively.

> The test work described in this paper shows that both particle size and slurry flow rate strongly influence pump wear. … The results indicate that traditionally held beliefs may need to be revised if pumps are to be designed and applied for minimum wear. … Further testing will also examine alternative pump geometries, as this is likely to strongly influence the effects of particle size and flow rate on wear. (Walker et al. 1994)

> **PEG concludes that operating a pump significantly below the best efficiency point increases wear. PEG concludes that wear rates are minimized at a flow rate 75-80% of BEP.**

Wear Rates over Time in service Wear changes the hydraulic characteristics of the pump and therefore affects the wear rate. (Addie et al 1996)

Rayan and Gadelhak. (1985) measured wear as impeller weight loss on an in-service dredge pump. Wear was highest at the beginning of time in service. They hypothesized that this might be due to the higher initial flow rates. Wiedenroth et al. (1987) measured wear in a dredge pump operating on 30% solid sludge in a laboratory setting. He found an "N-shaped" curve for impeller weight loss over time. The initial weight loss was highest, followed by a period of lower loss, and then increasing loss.

In a review of the literature on predictive equations for pump life, Ingersoll-Rand (1983) noted that the equations included empirically derived constants, other parameters that would be difficult to determine for actual pumps, and questionable assumptions. They concluded that the equations were not useful for determining the life of actual pumps. Pagalthivarthi and Helmly (1992) found that models of wear rate over predicted actual wear rates up to five times. They conclude that wear coefficients are best obtained by testing the actual pump. Marscher (1987) reports that the effect of vibration on pump tribology has not been satisfactorily determined.

> **PEG concludes that wear rates change dynamically as pumps wear but that these changes have not been reliably quantified.**

Effects of Wear on Efficiency As pumps wear the hydraulics change. Engeda (1995) found that loss of efficiency was directly proportional to tip clearance in semi-open impeller pumps.

No literature was found that quantified the effects of wear as measured by unit weight loss of material on efficiency. Wear on different parts of the pump will have different effects on efficiency, i.e. wear on an impeller tip would have a different effect than wear on the shroud lining. The same pump exposed to the same abrasive particle will experience wear in different areas depending on the pump's operating point. Specific correlation of wear versus efficiency are not possible at this time. Diversified correlation is possible and is the important parameter for calculating persistence of savings.

> **PEG concludes that the effect of wear on efficiency cannot be accurately quantified at this time.**

Field Tests of Agricultural Pump Efficiency Smajstrla et al. (undated) tested 247 agricultural pumps in Florida from 1980-84. The pumps efficiencies were compared relative to standards developed by the Nebraska Tractor Test Laboratories (NTTL) — a standardized rating of equipment in good operating condition. Prime movers were 55.1% electric, 42.5% diesel, and 2.4% other. Relative to NTTL standards, performance varied normally with an average of 69%, high of 126.0% and low of 7.1%. Smajstrla et al. concluded that the average pump was in need of adjustment or repair.

> Although a detailed analysis including pumping time and repair costs would need to be made for each individual site to determine the need for repair, the average performance rating of 69 percent indicated that the average pumping system is probably in need of repair or adjustment. (Smajstrla et al. undated)

> **PEG concludes that in areas where well water contains abrasive particles, such as California, agricultural well pumps show significant degradation over their time in service.**

2.7.5. Conclusions

> **PEG concludes that abrasive qualities of well water significantly degrade the efficiency of agricultural pumps over time.**

> **PEG concludes that the efficiency versus time in service curve for agricultural pumps was not fully characterized in pre-existing sources.**

2.7.6. Calculation of Persistence

Calculation Methodology PG&E and SCE have provided agricultural customers with pump testing service for many years. To determine an efficiency versus time in service, a number of pumps must have known efficiencies at a minimum of two points in their time in service. Pumps tested more than ounce in PG&E's Ag. Pump MDSS database were analyzed to develop an estimate of the efficiency versus time in service.

Pacific Gas and Electric Company's pump test database was cleaned and sorted. One hundred and sixty pumps were identified that were tested at the beginning of their times in service and at other times over their service life. The average initial efficiency was 61.7%. The data are consistent with a linear decay curve for each pump. The overall results can be modeled by a daily linear efficiency decay of .0000328 times the maximum measured pump efficiency. The confidence interval on the decay estimate was ± .0000097 at 95%. Figures 2-6 through 2-8 show the efficiency decay as a function of the fraction of service life (where service life is estimated to end at 90% of the maximum tested efficiency) based on efficiency at most recent test.

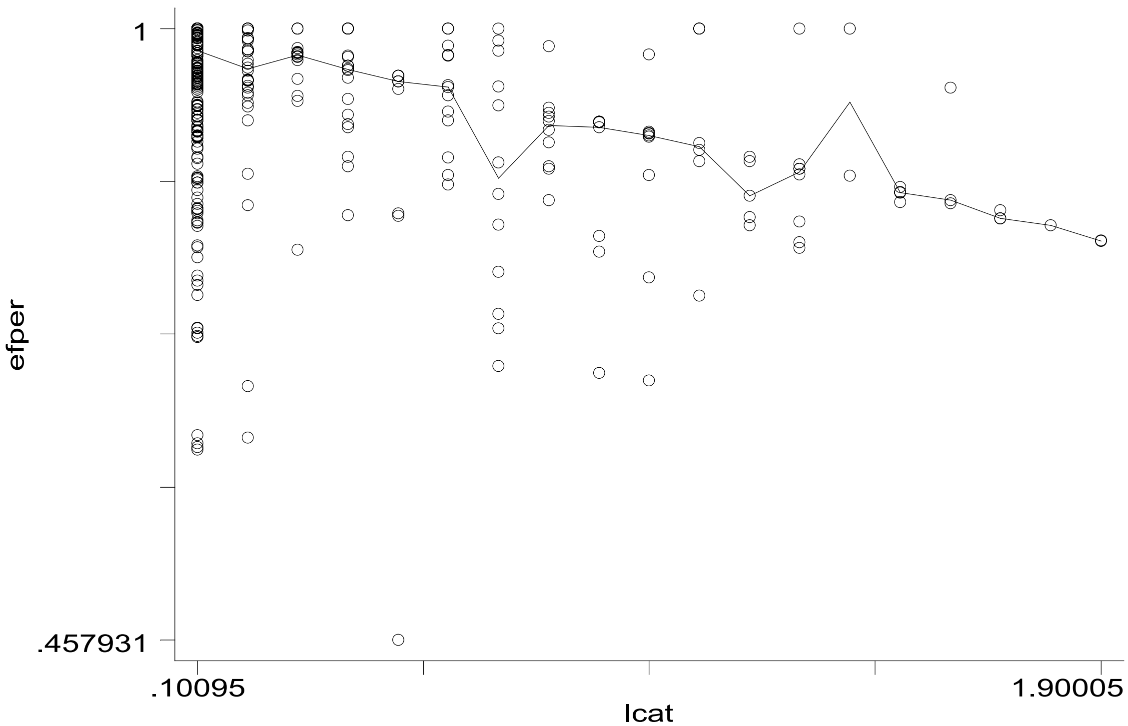


Figure 2-6 Efficiency Degradation vs. Time in Service (Pumps with three or more tests over time)

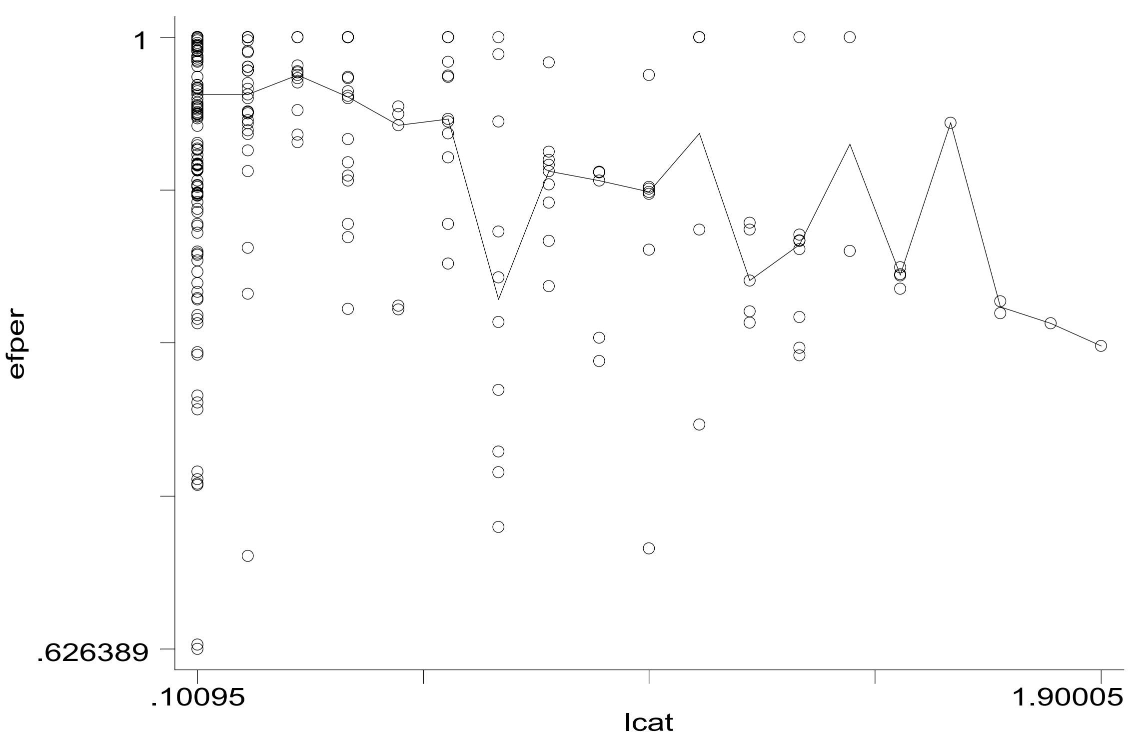


Figure 2-7 Efficiency Degradation vs. Time in Service (Pumps with four or more tests over time)

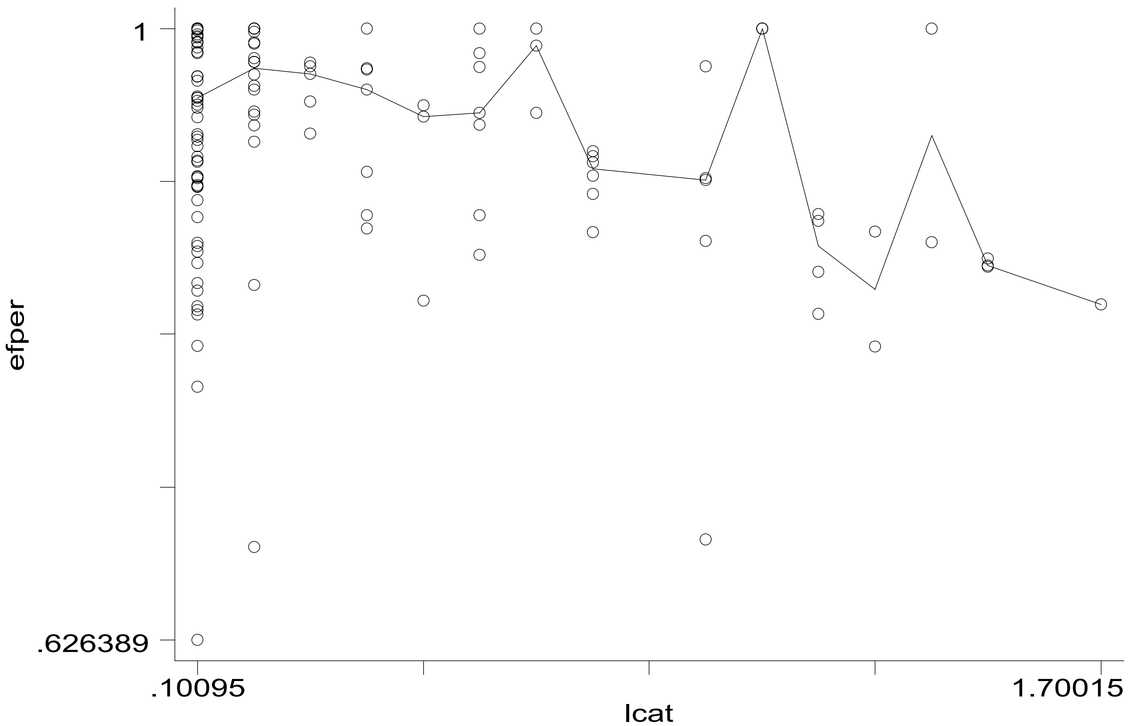


Figure 2-8 Efficiency Degradation vs. Time in Service (Pumps with five or more tests over time)

Seven pumps with good data were followed from their initial installation until the bowl and impeller were replaced. The average pump efficiency at the time of repair was 91.4% of their maximum tested efficiency. The tested efficiencies of these seven pumps over time are displayed in Figure 2-9.

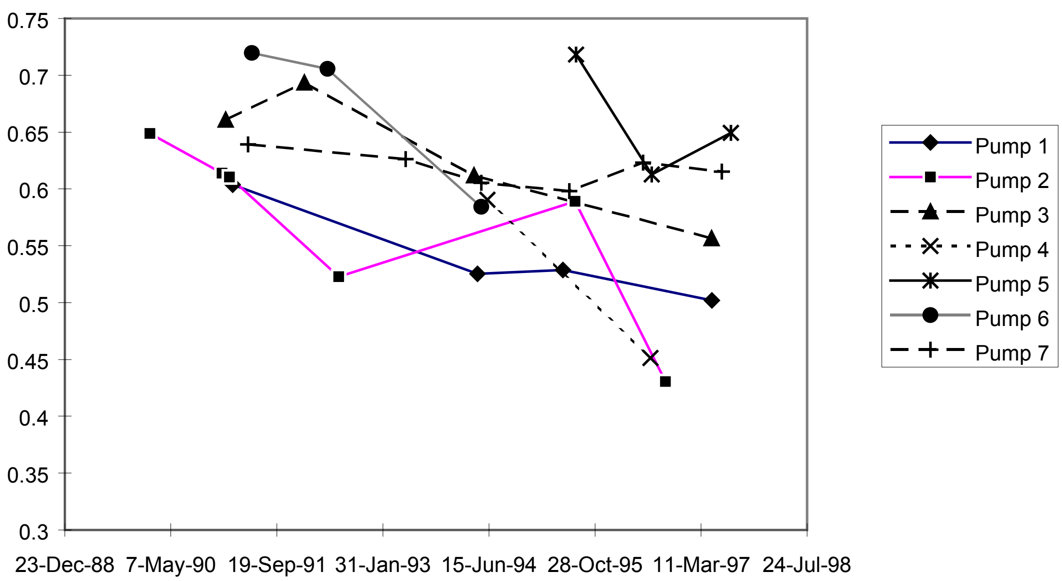


Figure 2-9 Efficiency Degradation vs. Time in Service (Pumps tracked to bowl and impeller replacement)

Analysis

PEG concludes that energy savings from replacement of the bowl and impeller on agricultural deep well turbine pumps is unlikely to degrade over time and may increase.

<u>Estimate of Persistence</u> PEG analysis indicates negative degradation rates. By CADMAC directive, the TDF of measures with negative degradation rates are set equal to one. The TDF is one (1.0) for all years.

2.8. Variable Air Volume HVAC Systems

The efficient measure is the installation of variable air volume HVAC distribution systems (VAV) in new commercial buildings. The baseline measure is installation of constant air volume HVAC distribution systems (CAV) in the same new commercial buildings.

2.8.1. System Typology

The primary division between all-air HVAC systems is single or dual duct. Single duct systems contain the main heating and cooling coils in a series and all distribution points receive a common supply air temperature. Dual duct systems have separate, parallel paths for the main heating and cooling air streams. The air is mixed according to space requirements at the distribution point or at a mixing box for the zone. Classifications can be further divided as shown in Table 2-7. (ASHRAE Systems 2.1)

Table 2-7 Classification of Air-based HVAC Systems

Variable Air Volume (VAV)
- Single Duct
  - Reheat
  - Induction
  - Dual conduit
  - Variable diffusers
- Dual Duct
  - Dual Duct
  - Multizone

Constant Air Volume (CAV)
- Single Duct
  - Single zone
  - Multiple-zone reheat
  - Bypass
- Dual Duct
  - Dual Duct
  - Multizone

2.8.2. Operation

Variable air volume HVAC systems meet changing building cooling and heating loads by varying the amount of air delivered to the conditioned space. The supply air temperature is held constant, adjusted for the season. A constant volume system changes the supply air temperature in response to the space load changes. VAV systems are common in new commercial construction because of their energy efficiency and the large amount of fan energy required in large buildings.

2.8.3. Energy Savings Mechanism

The energy required to move air increases by the power of three for each unit increase in air moved; doubling the air volume requires 8 times the energy. The system supply air fan is sized for the peak heating or cooling load. Maximum conditioned air flows are only needed during extreme weather conditions. A constant volume system provides the same maximum air volume all year, while VAV systems are designed to provide only the needed conditioned air. Significant fan energy is saved because of the reduced air volumes. Heating and cooling energy are also saved because the volume of conditioned air is reduced.

> Variable-air-volume (VAV) systems are commonly installed in new commercial, industrial, and institutional buildings. The primary reason for the popularity of VAV systems is their energy efficiency. In order to achieve the energy-efficiency level expected of the VAV system, two areas of high energy use must be precisely controlled — fan horsepower and tempering of outside air. Approximately 30% of a large building's electrical energy load is consumed by the air-conditioning

> fans. With this large electrical energy load concentrated at one point, fan control schemes should be given a good deal of consideration. (Smith 1990)

2.8.4. Degradation

While variable air volume systems have significant potential for saving energy, they have greater control requirements.

> Although reduced energy consumption is possible, VAV systems demand robust control schemes if they are to be as efficient as expected. (Hittle 1997)

> Controlling VAV systems may not be as simple and direct as many may have thought. There are many, many non-working or partially working systems, as a result of incomplete or non-functioning controls. (Williams 1988)

VAV systems are likely to experience higher degradation relative to constant air volume systems due to greater system complexity, more interactive effects among building system components, and a larger number of failure mechanisms.

- greater system complexity
- more interactive effects
- larger number of failure mechanisms

Failure modes can sometimes be dramatic but more often result in pernicious, less noticeable losses in efficiency.

> Problems were experienced with system stability, so it was decided to control the supply fan from duct static and the return fan from building static. The author was called to investigate the job after a window wall was blown out of the building and felt to be related to the fan control. (Kettler 1988)

System Complexity All else being equal, more complex systems are more prone to error, degradation, and failure. The probability of an error in a system is proportional to a statistical aggregate of the probabilities of an error in any one component. The more components there are, the more sensitive the components, and the more error prone those components; the higher probability that the system will experience errors. VAV systems are such complex, sensitive systems. Hittle (1997) discusses a number of VAV control challenges including:

- Controller gain changes with airflow
- Supply air reset interacts with VAV box damper settings
- Return and exhaust air quantities change constantly
- The exhaust fan must maintain a constant pressure ratio rather than just a pressure differential
- Minimum outside air intake must be maintained even at low supply air flows
- The return air fans, if installed, must work in tandem with the supply fan

Avery states that in particular the VAV outside economizer is the most difficult control problem.

> Because of the number and interaction of manipulated variables, the variable air volume (VAV) outside air economizer cycle is probably the most difficult problem facing engineers in the HVAC field. (Avery 1986)

Analysis

> Numerous papers and articles have been published that relate to the problems associated with the outside air economizer cycle when used with variable air volume (VAV) systems. Most problems with this cycle can be attributed to improper damper selection, intricate fan tracking control devices and so many interacting control loops that stable operation becomes impossible. (Avery 1989)

While more complex systems always present challenges, a critical point is reached when the complexity exceeds the expertise and capability of operating personnel. At this point, control degradation is almost assured.

> The personnel operating and maintaining the air conditioning and controls should be considered. In large research and development or industrial complexes, experienced personnel are available for maintenance. On small and sometimes even large commercial installations, however, office managers are often responsible, so designs must be in accordance with their capabilities. (ASHRAE Systems 1996 2.10)

In a paper describing field experiences with correcting VAV control problems, Kettler, 1988, describes successfully tuning a building's VAV system through considerable effort. After several years the system was again malfunctioning because the maintenance expertise requirements exceeded those available. He concludes, "Moral: Keep the controls simple so they can be understood and tuned by the level of expertise of people available."

> Case No. 1 After 30-plus man-hours of adjusting, testing, and resetting of the pilot positioner's settings, proper control was obtained. … the author learned that one or two years after tuning this job, the controls had drifted and stability was again a problem. When local people could not get the system back into control, the inlet vanes were manually set and locked, the system rode the fan curve, and the owner put up with the noise and energy waste. (Kettler 1988)

Kettler, 1988, also describes a fan tracking control run amuck from too complex of a control strategy. He concludes, "The lesson to be learned from this job is that more controls do not necessarily mean a more controllable system."

> This system had so much control interaction and hunting that it was almost impossible to keep the supply fans from cycling and shutting off on high static. The system had to be started manually, gradually increasing the control signals to supply and return fans and getting the system on-line manually before switching over to automatic operation. A change in airflow at a terminal unit would cause the floor static controller at the main trunk to change, which would cause a change at the supply fan. The return fan would adjust to track the change in flow at the supply fan, and the whole process would repeat itself when the duct static changed because of the action of the return fan. The system was in a continuous hunt. To reduce the continuos hunt and the problem of getting the system on-line, it was decided to eliminate some of the excess control and the interaction between loops. (Kettler 1988)

Variable air volume sensors are required to be more sensitive and be better calibrated than CAV systems. Sensors are required to operate over larger ranges and with variable controller gains. Air flow sensors in particular are required to measure ultra low pressure differentials.

Smith (1990) discusses the problem of signal errors at low flow rates.

> For example, in VAV fan control systems, turndowns of overall system operating to 25% of capacity can be experienced, While this condition represents a flow turndown of 4:1, it actually represents a 16:1 turndown in the operating span

> When a differential pressure transmitter is required to operate under system turndown, the inaccuracy of signal error, added to the thermal effect when the transmitter is not properly temperature compensated, can be several times greater than the magnitude of the operating input signal itself. (Smith, 1990)

Hittle (1997) discusses the problem of variable controller gains:

> For example, if the air volume flow rate over the cooling coil is only half the design maximum, then the change in valve position required to produce a given change in discharge temperature will be about half that needed at full flow. This has the effect of doubling the process gain. If a proportional only controller was used to control the cooling coil, and if the gain of the controller was set to provide stable control at full flow, the control system might be completely unstable at half flow because the overall loop gain would have nearly doubled. The problem is compounded by the more sluggish response of the temperature sensor under low-flow conditions. … proportional only control might work little better than no control at all. (Hittle, 1997)

PEG concludes that VAV HVAC systems are subject to degradation due to their complexity.

Interactive Effects VAV control components often interact in ways that make diagnosis and repair problematic.

> There are many, many non-working or partially working systems, as a result of incomplete or non-functioning controls. … it is often difficult to determine the exact problem, since a VAV system is inherently dynamic and , therefore, constantly changing its operating characteristics. (Williams, 1988)

Control interactions that individually would save energy can interact to increase energy use. In a simulation of various control strategies Mutammara and Hittle (1990) showed that cold deck reset on interior zones significantly increased required fan power because the warmer supply air had to be delivered at a higher volume. An economizer cycle in a humid climate increased cooling power requirements because even thought the outside air was cooler the humidity made the enthalpy higher and increased cooling requirements for dehumidification.

In discussing design variations for the outside air economizer cycle, Avery (1986) argues that interactive effects make many designs too unstable to control and designs that minimize interaction are more stable and preferable.

> Systems designed using duct or louver sized control dampers and return air fans, can consume more energy than a system without the economizer cycle. Such systems seem to operate properly if any one control loop is tested while the others are disabled. For example, the low monitoring manufacturer can demonstrate satisfactory supply-return fan synchronization while all other control loops are inoperable. The same demonstrations can be made by the control manufacturer and the fan manufacturer when the mixed air controls and supply duct static pressure controls are tested. Only when all loops are enabled, does the "system's" equilibrium become unbalanced due to loop interaction. (Avery 1896)

PEG concludes that VAV systems are vulnerable to degradation relative to CAV systems because of greater system interactions.

Failure Mechanisms Cappellin (1997) discusses common failure mechanism for VAV systems, Table 2-8. While many of these are also failure mechanisms for CAV systems, some are unique to VAV system, i.e. VAV boxes linkages, and static pressure control of fans.

Table 2-8 VAV System Failure Mechanisms

- Improper VAV design
- Improper VAV installation
- Improper design and installation of access requirements for service and maintenance
- VAV boxes, linkages tend to bind when actuator strokes
- Control sequence too complex for operating personal
- Building operators not sufficiently trained in system operation
- The supply air fan and return air fan controlled by the same static pressure switch
- Enthalpy sensor changeover of economizer
- Alteration of controls by maintenance personal to solve operating problems that exacerbate rather than fix problems
- Fan belt breakage
- Thermostat setting overlap between perimeter baseboard and VAV system. (Both systems can be operated by a single thermostat which prevents simultaneous operation.
- Very dirty filters, filter collapse
- Duct air leakage

A comprehensive energy efficiency retrofit was done on an occupied 311,000 ft^2 office building. Continuous commissioning of the system was performed to minimize operational problems. The retrofit included conversion of the HVAC system to VAV. The commissioning found 40% of the VAV boxes to originally be out of calibration. In a less closely monitored setting many of these calibration errors could have gone unnoticed. CAV system does not have terminal boxes so this problem would not occur.

> "Calibration and checkout of the VAV boxes, just after completion by the contractor, revealed that about 40% of the boxes had a calibration out of specification. This deficiency was decided to be by and large attributable to poor organization of the calibration process by the contractor. (Reichmuth & Fish 1994)

> **PEG concludes that VAV systems are vulnerable to degradation relative to CAV systems because they have a larger number of failure mechanism.**

<u>Sensor Error Effects</u> Sensor error can have a dramatic effect on building operation and energy consumption. Kao and Pierce, 1983, estimated that sensor error could increase annual energy consumption of a constant volume with reheat air handler by as much as 50% based on a computer simulation. They found that energy consumption was much more dependent on the accuracy of some sensors over others. The system studied was not very sensitive to outside air and return air dry-bulb sensors. Energy consumption was very sensitive to the mixed air temperature. Depending on the direction of error either cooling or heating use increased. Cooling energy consumption was increased 11% per +1°F error; heating energy consumption was increased 6.5% per -1°F error. Of the sensors tested, system energy use was most sensitive to errors from the cooling coil discharge sensor. If the cooling discharge temperature was too high, energy use was reduced but the system might not maintain adequate space conditioning. If the cooling discharge temperature was too low, excess cooling and extra reheat resulted. Per -1°F error, energy consumption for cooling and heating increased 8.5% and 11% respectively. They recommended careful purchase and frequent calibration of these sensors.

> A computer simulation was used to examine the effects of errors in the sensors of automatic controls for HVAC systems. Computer calculations using the BLAST program indicate that sensor errors can increase the annual energy requirements attributable to an air handling system by as much as 30 to

> 50 percent. Errors in the mixed air temperature sensor and the cooling coil sensor appear to be most critical for the type of HVAC studied. (Kao and Pierce 1983)

Kao, 1985 investigated the effect of sensor error on the energy consumption of a VAV air handler. Increase energy consumption was significant but not as high as with a constant volume system. An error in the mixed air temperature increased cooling energy consumption by 2.2% per +1°F error; heating energy consumption was increased 6.4% per -1°F error. A negative error in the cooling discharge temperature resulted in a 2.1% and 7.2% increase in cooling and heating energy per -1°F error respectively. Under some errors fan energy consumption also increased. Fan consumption increased 2.3% per +0.1″ W.G. error.

> The smaller energy waste in the VAV system resulted from the assumption that the terminal unit of the system could cut down the extra cooling capacity of the system by maintaining the desired space conditions accurately. (Kao 1995)

PEG concludes that CAV systems are vulnerable to relative degradation because they experience greater increases in energy consumption due to comparable temperature measurement error.

Commissioning and O&M Efficient HVAC system operation often depends more on operators and building occupants than the physical equipment. The human element involved in commissioning greatly affects the initial operation, and the sustainability of long term energy efficiency strategies. Ongoing training and a commitment to adequate operation and maintenance are key to achieving expected energy savings from the higher efficiency HVAC VAV systems.

2.8.5. Conclusions

PEG concludes that VAV systems are likely to experience degradation over time relative to constant air volume systems due to greater system complexity, more interactive effects among building system components, and a larger number of failure mechanisms.

PEG concludes that VAV systems are less likely to experience degradation over time relative to CAV systems due to lesser energy waste from comparable temperature measurement error.

The rate and degree of degradation will depend on the quality of initial commissioning and the quality of operations and maintenance procedures.

2.8.6. Calculation of Persistence

Problems with VAV Persistence Calculations Insufficient data were found on the persistence of savings from variable air volume or constant air volume HVAC distribution systems.

The great variety and changing nature of the systems and equipment installed complicates analysis.

System operation is very strongly affected by commissioning and O&M procedures. These are human factors which lead to widely variable performance. Therefore, savings from VAV systems are expected to be highly variable.

Analysis

Calculation Methodology The two major factors that could result in relative technical degradation between VAV and CAV systems are in opposition. Which factor is likely to predominant could not be determined.

Differences due to commissioning will be captured in first year savings. Half of the annual relative degradation per year will also be captured in estimates of first year savings.

Estimation of Persistence of Savings PEG estimates no relative technical degradation between VAV and CAV systems over time.

The greatest error would occur if the relative degradation were estimated in the opposite direction of its actual occurrence. By estimating no relative technical degradation, the possibility of an error in the wrong direction is eliminated. Without supporting evidence for another estimate, minimizing the greatest potential error is the safest and fairest estimate.

A system performance degradation per year is estimated to be equal for VAV and CAV systems. The TDF is estimated as one (1.0) for all years. A research study to refine this estimate is recommended. A research plan was developed in Section 3.5.

2.9. Energy Management Systems

The energy efficient measure is installation of an energy management system (EMS) to control a commercial heating, ventilating, and air conditioning (HVAC) system. The baseline measure is standard control of HVAC system including manually set thermostats and on/off controls.

2.9.1. Typology and Operation

The term energy management system refers to a broad spectrum of control systems. An EMS is often referred to as an energy management and control system (EMCS) or building automation system (BAS) to emphasize that non-energy control functions are usually included.

ASHRAE defines an EMCS as follows:

> Energy management control systems (EMCS). A computer/processor based hardware and software system with sensors, control devices and all the necessary components that perform some or all of the following functions:
>
> a. Measures conditions related to the use of various forms of energy by HVAC systems;
>
> b. Controls these conditions at selected set-points;
>
> c. Monitors and/or controls the energy use;
>
> d. Provides status reports on the HVAC system's performances;
>
> e. Provides information for the management of a building's environment, and/or its energy efficiency and/or HVAC system maintenance. (ASHRAE Standard 114-1986)

The Electric Power Research Institute (EPRI) describes a range of energy management equipment from simple timers to large distributed computer driven systems. (EPRI 1993) Timers, setback thermostats, and controllers can provide significant savings at reduced cost and complexity.

Timers can turn off loads when they are not needed.

Setback thermostats adjust temperature setpoints on a scheduled basis. They are safer than simple timers because they maintain minimum temperatures during unoccupied periods.

Controllers can provide a range of control functions such as setback, optimum start/stop, economizer control, and demand limiting. They are designed for specific situations with logic that is usually factory set and cannot be altered on-site .

Energy management systems provide for both local and remote control. Sensors and actuators are used to control the equipment. Most controls were pneumatic previous to the mid-1980s and transducers were used to convert the signals to digital form. Direct digital control with a microprocessor based controller using electronic sensors and electric actuators is more flexible and sophisticated. EMSs can often be linked to other systems such as billing or security.

Until recently, equipment and communication protocols were usually proprietary. With a proprietary protocol, equipment could only be purchased from the original system manufacturer. ASHRAE has recently developed a non-proprietary system, BACnet, to which system purchasers can standardize and obtain equipment from a broad range of manufacturers.

2.9.2. Energy Savings Mechanism

EPRI lists the following uses of an EMCS to save energy. (EPRI 1993)

Equipment Scheduling and Control

- Temperature Setback/Forward Thermostat
- Schedules On/Off controls — turn off HVAC equipment and lights during unoccupied times
- Occupant Overrides — override scheduled off times for intermittent after hours occupancy
- Tenant Billing — billing of tenants for system override
- Optimum Start/Stop — optimize the time a building is conditioned
- Night Purge — using night air for cooling
- Economizer Control — using outside air for cooling when possible
- Enthalpy Control — use outside air for cooling based on total heat content, sensible and latent
- Indoor Air Quality Control — use minimum outside air and maintain indoor air quality by active control

Utility Rate Structure Response

- Load Shedding — shed loads at a preset demand limit
- Load Cycling — cycling of shed loads to maintain comfort
- Temperature Scheduling — reset temperature during peak demand periods
- Generation — generate electricity on-site to reduce utility demand
- Dual Fuel — switching to alternative fuels to reduce demand
- Thermal Storage — production and storage of coolness at night by daytime use
- Cogeneration — capture and use of heat from electric generation
- Chiller Heat Capture — service hot water heating from rejected chiller heat
- Closed-Loop Water Source Heat Pumps — transfer of heat from interior to exterior zones

Coordinating Central HVAC Equipment

- Duty Cycling — sequencing loads to limit demand
- Sequencing Boilers/Chillers — using the minimum number of modules required
- Resetting Chiller/Boiler Temperatures — resetting delivery temperatures to minimum required
- Cooling Tower Control — minimize energy use and prevent freeze up
- Free Cooling — using a heat exchanger rather than chiller for cooling at low ambient

Controlling Lights

- Schedule Lights On and Off — timer/scheduler for lighting
- Override Time-out — automatic end to override control
- Occupancy Sensing — lights controlled by sensing occupancy
- Illumination Level Control — daylighting and dimming of artificial lighting

2.9.3. Degradation

The accuracy and reliability of an EMCS are the combined accuracy and reliability of each step in the system data and actuation process. The process includes all steps to gather the original information and transmit it to the operator. EMS end-to-end accuracy refers to the accuracy from the sensor to the display. HVAC system end-to-end accuracy also includes the errors that arise because the sensor does not fully describe the HVAC process. Room temperature sensors only measure the temperature in one location, while the temperature varies throughout the room.

> The general method of rating the accuracy of a given EMCS is to rate system end-to-end accuracy in engineering units of the measured variable. However, to do so quantitatively requires a method of converting the component accuracy's to system end-to-end accuracy's. The most direct way of doing this is to trace through the system from sensor to readout and to identify the achievable accuracy of each functional component . The functions of a system include: sensing, transducing, multiplexing, field conditioning to provide a value message, communications, and display. Specific system designs may combine several functions into a component with a single accuracy rating. The system end-to-end accuracy rating is based upon the combined accuracy of all the components actually used between sensing and display. … The accuracy or an EMCS has a direct effect on energy savings and owner satisfaction. (ASHRAE Standard 114-1986)

Sensor Reliability ASHRAE states that all sensors are subject to error over time and recommends periodic checking at six month intervals.

> All sensors need periodic maintenance and recalibration -some more often than others. Electronic sensors require less maintenance than pneumatic sensors and are slower to drift out of calibration. (ASHRAE Standard 114-1986)

ASHRAE lists the following sources of sensor error over time.

- Wire connections loosened by vibration and/or expansion
- Physical material changes with aging — drift
- Dirt accumulation
- Depletion of elements and solutions
- Physical damage
- Degradation of bearings and moving parts

ASHRAE lists the following as common sensor types:

- Temperature
- Humidity and moisture
- Air flow velocity
- Fluid flow velocity
- Electrical energy

Sensor accuracy and reliability are important to most automatic control systems.

The baseline measure is standard control of HVAC system including manually set thermostats and on/off controls. The functioning of the baseline is assumed steady. Operations will change with a change in personnel, but not on a diversified basis.

Field Conditioning of Value Message The sensor is typically hooked up to an analog to digital converter (A/D) which converts the sensor's analog signal into a digital one. The resolution of the A/D converter determines the accuracy of the conversion. An eight bit converter would have a maximum accuracy of 1 part in 254 (2^8) or 3.9 percent. These are the most common converters and they limit accuracy of temperature measurements to about one degree F. More recent equipment uses 12 bit or higher A/D converters, but these are still not in common use. The A/D converter is subject to drift due to temperature and humidity effects upon the electronic circuitry..

Communication and Display Communication, central processing, and display are digital function in a direct digital control system (DDC). While they are not subject to drift, operator control can degrade performance.

> The digital information produced in the signal conditioner can be transmitted by various means to the central processor … No loss of accuracy will occur as a result of such transmission although interference may destroy the integrity of the data and require it to be retransmitted.
>
> In microprocessor based EMCS designs, the design verification includes extensive software functional testing as well as hardwire testing. Good practice dictates that when changes are made in a program, a certain amount of regression testing (retesting of basic function) be done to ensure that no unplanned changes resulted. (ASHRAE Standard 114-1986)

Electronic interference or noise can degrade performance. Sources of noise include: (ASHRAE Standard 114-1986)

- I/O line signals
- Contact bounce from dry contacts
- Analog circuit white noise
- High frequency and 60 Hz noise within the EMCS itself

The display provides the systems interface to the important human control component. Without effective display of information, human control could be rendered ineffective.

> The effectiveness of an EMS depends to a large extent on the effectiveness of its interface to the operator. A display needs to present information in an easily understood format. It must highlight critical information, like alarms, to catch the operators' attention It needs to allow operators to create screens that show the information they want, preferably with options for both content and format. (EPRI 1993)

Human Operation The human interface provides the greatest opportunity for improvement or degradation of system performance.

An event that is particularly vulnerable to the degradation in the human operation is when new personnel take over the system. Much of what was originally communicated by the installers or learned from experience can be lost. Petze (1996) states that new personnel may need even more training than the original personnel.

> *Turnover of operations personnel:* Is the same effort expended training new operators as was invested in the original operators? New operators may actually be in greater need of training because they are new to both the facility and the automation system. A successful BAS project should include a plan for the training of new operations personnel. (Petze, 1996)

Commissioning and Maintenance Whether system performance will degrade, improve, or stay the same depends on the commissioning and level of maintenance, Figure 2-10.

	Good Commissioning	Poor Commissioning
Good Maintenance	1	2
Poor Maintenance	3	4

Figure 2-10 Commissioning and Maintenance

1) Good Commissioning and Good Maintenance: With good commissioning and good maintenance sensors and data transmission systems will start out and remain accurate. No degradation of performance would be expected. Unfortunately anecdotal evidence suggests that this is a minority situation.

2) Poor Commissioning and Good Maintenance: With poor commissioning many sensor and control routines will be inaccurate or un-optimized. These errors will gradually be corrected and the routines refined under a good maintenance program. System performance would be expected to improve over time.

> System optimization. It is important to realize that there is no system that is perfectly adapted to a facility at the time of its initial design and installation. The successful automation system will provide the trained operator with countless opportunities to improve the facility's operation through modifications to the initial control sequences. These opportunities need to be exploited. Analysis of information collected via the data logging capabilities of BAS can, and should, be used to identify opportunities for enhancements in the operation of the facility. (Petze 1996)

3) Good Commissioning and Poor Maintenance: With good commissioning and poor maintenance sensors and data transmission systems will start out accurate but degrade over time. System performance would show definite degradation over time.

4) Poor Commissioning and Poor Maintenance: With poor commissioning and poor maintenance system performance will start out compromised and remain so. Overall system performance could limp along at an inefficient but stable rate; or things could go from-bad-to-worse.

<u>Commissioning</u> The term commissioning has a range of meaning. A broad sense of commissioning is given by O’Neill & Radke, 1994. They state that commissioning is an activity that spans the entire life of a building from conception to demolition. Operations and maintenance are extensions of commissioning — continuous commissioning.

> [Commissioning is] In the broadest sense, a process for achieving, verifying, and documenting that the performance of a building and its various systems meet design intent and the owner and occupants’ operational needs. The process ideally extends through all phases of a project, from concept to occupancy and operation. (PECI 1992)

A more narrow definition is that commissioning is the phase in construction when the installed systems are tested to ensure that they operate as intended before the building is accepted as completed.

> [Commissioning is] In a narrower sense, the act of statistically and dynamically testing the operation of equipment and building systems to ensure they operate as designed and can satisfactorily meet the needs of the building throughout the entire range of operating conditions. (PECI 1992)

ASHRAE recognizes that the lack of careful and complete commissioning leads to many future problems in building operation. Numerous authors describe problems from inadequate commissioning and successful projects where design and construction flaws where corrected during a comprehensive commissioning process. (Koran 1994; Tseng et al 1994; Güven and Spaeth 1994)

> In recent years, commissioning of heating, ventilating, and air-conditioning (HVAC) and electrical systems has been in the forefront of ASHRAE initiatives to address a more efficient building turnover process. While the current practices followed by building owners and facilities engineers already include many of the elements of commissioning delineated in the ASHRAE guidelines, most do not have a comprehensive approach to the commissioning challenge for their facilities. (Tseng et al. 1994)

As a result of poor design and installation not corrected by commissioning, building occupancy often starts with a poorly operating system.

> Owners and facilities engineers engaged in the design and construction of buildings all have horror stories about buildings with serious flaws upon occupancy, such as HVAC systems not functioning correctly and temperature control systems with logic that would baffle the best of minds. Annoying problems such as unreliable temperature controls, overheating and overcooling of various zones, lack of credible air balancing, absence of building pressurization, and poor documentation continue to exasperate facilities engineers long after the building is occupied. (Tseng et al. 1994)

A comprehensive commissioning process often finds and corrects potential problems.

> The results revealed numerous system problems that were not known before. Installation and design problems that normally would have gone unnoticed have been discovered as a result of the commissioning effort. (Tseng et al. 1994)

Tseng states that a comprehensive commissioning process, preferable through an independent agent, is essentially for successful building operation. However, this comprehensive effort is an exception rather than the rule except in extremely critic applications such as research laboratories. (Coogan 1994; Rizzo 1994)

O'Neill & Radke state that future building operators are often not trained adequately during the initial commissioning process. The building operation will gradually improve as the operator gains familiarity and optimizes the controls, or it will gradually degrade as systems drift out of alignment or are improperly adjusted.

> During the design and construction of a building, a great deal of information is generated and transferred among all of the parties associated with the building. When the building is completed, it is often checked-out and handed over to the new owners with the warranty clock(s) ticking. Unfortunately, the new owners and future building operators are likely to have little or no information about how the building was designed, what was actually installed, and how the building should be operated and maintained. This problem is amplified when ownership changes throughout the life of the building. (O'Neill and Radke 1994)

<u>Operations and Maintenance</u> While poor operations and maintenance procedures can lead to EMS degradation, an EMS's data acquisition capabilities can also lead to improved O&M. The Texas Governor's Energy Office established the LoanSTAR program (Loan to Save Taxes and Resources), an

institutional loan program. Part of the program is monitoring and analysis to assure that retrofit achieve real savings. Claridge et al. report:

> One of the program's key objectives is to reduce energy costs by identifying operational and maintenance improvements. This requires communication with and cooperation of facility engineers and building operators. A key part of this process is the publication of a six-page monthly energy consumption report that is sent to each agency. This report summarizes energy consumption in different categories of savings (e.g., electricity, heating, cooling) and provides comments on the past month's performance. Plots of daily heating and cooling energy as a function of ambient temperature are provided along with two-dimensional, time-series plots of hourly electricity use, heating, cooling, ambient temperature and relative humidity … (Claridge et al. 1991)

As expressed in the byline to the report, "Energy conservation retrofits can be significantly improved by installing data acquisition systems to measure savings," such attention to detail may significantly contribute to realized savings and persistence of those savings, but it is beyond the capability of most operations.

2.9.4. Performance Studies

The installation of energy management systems has the potential to both improve or compromise a buildings energy efficiency. Whether degradation or refinement dominate will depend on the commissioning/maintenance ratio. Field studies of savings are the best way to determine what really happens. Measured savings from installed EMSs indicate that they most often initially save energy but sometimes have the opposite effect.

<u>Tanaka and Miyasaka</u> Tanaka and Miyasaka (1994) reported on eight remotely monitored buildings in Japan. Reliability was analyzed. An initial period of failures was found to be followed by increasing short term reliability until a period of stable operation was reached in which the mean time between failures (MTBF) was constant. During the fifteen months of monitoring after installation, aggregate problem alarms peaked at six months and stabilized thereafter. After fifteen months three buildings were stable, two buildings were almost stable, and three buildings were still in an unstable mode. This research indicates that operations and savings as measured by first year's savings may not be stabilized until after the first year.

> The period of initial failures for building equipment systems and machinery — right after completion of construction — is when MTBF is most likely to change. Depending on the degree of change, it will be necessary to evaluate the period of initial failure (unstable condition) to determine if the transition to a normal operation period (stable condition) has been made. (Tanaka and Miyasaka 1994)

<u>Wheeler</u> In a study of 20 buildings that installed EMSs, but almost nothing else, Wheeler (1994) found that EMS performance as measured by percent energy savings and simple payback was not significantly correlated to building age, area, EMS functions, or EMS cost. Three buildings had measured increases in energy use after installation of the EMS.

> Energy Management Systems (EMS) are computer-based control systems that operate building equipment. They can be expensive and don't always save energy. There are many studies and papers on EMS, but only a few include measurements of actual energy savings (or increases). There are reports of successes and failures, but there is generally little information on why they succeed or fail. Possible explanations for both successes and failures include hardware reliability, operator training, vendor support, operator sophistication, inappropriate applications, and too much or too little system.

> There are other factors that affect building energy use, such as ventilation, infiltration, architecture, and people. Building occupants and operators both affect energy; use and savings, but people are perhaps the most difficult to analyze. (Wheeler 1994)

Liu et al In a study of a systematic and thorough approach to O&M which included using metered hourly data and sometimes sub-metered data, engineering analysis, and site visit with facility personal, the Texas LoanSTAR program found substantial opportunities to recommission existing energy conservation measures. EMS systems in schools were particularly likely to suffer from disconnection.

> "In 1993, the LoanSTAR staff found that the EMCS control had been disabled in more than 100 schools in the Fort Worth area, and that the EMCS systems are being severely underutilized with an estimated potential savings of $1,658,000 per year.
>
> One major effort of the LoanSTAR O&M program has been the restoration and recommissioning of Energy Management and Control System (EMCS). LoanSTAR O&M staff found the following problems: 1) control Systems are disabled without the knowledge of EMCS personnel and/or facility management; 2) EMCS sensors gave incorrect values that caused the EMCS to perform poorly; and 3) EMCS control commands are not properly assigned or are being ignored. LoanSTAR O&M staff found that recommissioning of the EMCS system in one school district alone has the potential to reduce their energy bills by 27%, or $1,658,000/yr. In some of the LoanSTAR agencies with EMCS, it appears that little effort had been put into proper EMCS maintenance, which has led to total system failures within one year after installation. (Lui et al. 1994)

Greey, Ruth E. In the incentive program described, Ontario Hydro tried to capture DSM savings from the installation of EMSs that they considered an under-utilized technology. The program requires a five year maintenance contract.

> "A five year maintenance contract must be negotiated between the manufacturer and the customer. The contract must include: all control equipment; all labor and parts for repairs; and routine scheduled preventive maintenance. In addition, all other mechanical equipment must be covered by an existing maintenance contracts. …
>
> Initial results, which can be seen on Poster display illustrate that estimated and actual savings do vary. This can be attributed to a number of factors including; inaccuracies in the feasibility study or the energy analysis that are performed before a project is accepted (these are scrutinized both internally and externally so they should not be a major contributor to discrepancies); poor installation or commissioning; no or inadequate operator training; poor subsequent maintenance (this should be avoided since a maintenance contract is required)." (Greey 1992)

Diamond et al Multi-year monitoring was conducted of two newly constructed office buildings with EMSs that participated in a demonstration program of reduced energy usage in new commercial construction. (Diamond et al. 1992) Energy use increased by an average 85% over first year use by the end of the third year. After 3 years energy use appeared to level off, but monitoring was stopped, Figure 2-11. The average building in the study used half of the energy of conventional construction but after three years the EMS buildings were only savings 7.5% compared to conventional designs.

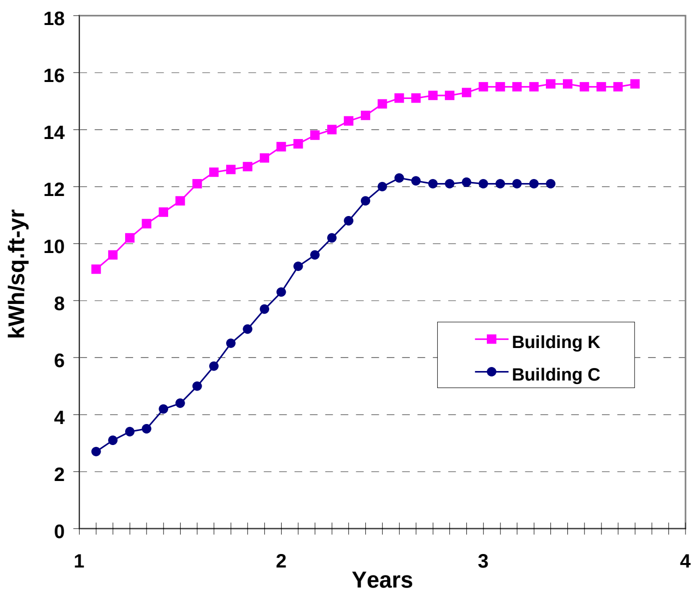


Figure 2-11 Multi-year Energy Use of Two EMSs

2.9.5. Conclusions

> **PEG concludes that performance studies indicate significant potential for relative degradation of energy savings from energy management systems. On a diversified basis, relative degradation is expected. Difficult to quantify human factors appear to be the main determinant of performance.**

2.9.6. Calculation of Persistence

The persistence of savings from the installation of EMSs is difficult to quantify due to large physical variations in equipment and the strong influence of human factors.

Field studies indicate a significant potential for both improvement and degradation of performance over time. There was a preponderance of references to degradation of performance which appear to predominate over increased efficiency. The time period over which degradation occurs is longer than one year (Tanaka and Miyasaka 1994) and will not be fully captured in estimates of first year savings. Multi-year monitoring of office buildings with EMSs by Diamond et al. (1992) showed increasing energy use for the first 2½-3 years with a final savings of only 7.5%.

These results suggest a strong initial degradation in performance for the first three years. PEG recommends a degradation estimate of 20%/year for five years with a permanent savings of 10%, Table 2-9.

Table 2-9 EMS — TDF

YEAR	TDF Multiplier
0	1.00
1	0.80
2	0.60
3	0.40
4	0.20
5	0.10
6	0.10
7	0.10
8	0.10
9	0.10
10	0.10
11	0.10
12	0.10
13	0.10
14	0.10
15	0.10
16	0.10
17	0.10
18	0.10
19	0.10
20	0.10

2.10. Air Compressors

The baseline measure is an existing lubricant-flooded rotary screw air compressor. The efficient measure is a new lubricant-flooded rotary screw air compressor, with or without various efficiency enhancements.

2.10.1 Air Compressor Typology

Air Compressor Classification The two primary classifications of compressor types are positive displacement and continuous flow machines. Positive displacement machines entrap air in a volume and then reduce the volume to achieve compression. Dynamic flow machines impart flow energy to the air and then convert the dynamic head to higher static head. Within each primary class are sub-classes, see figure 2-12.

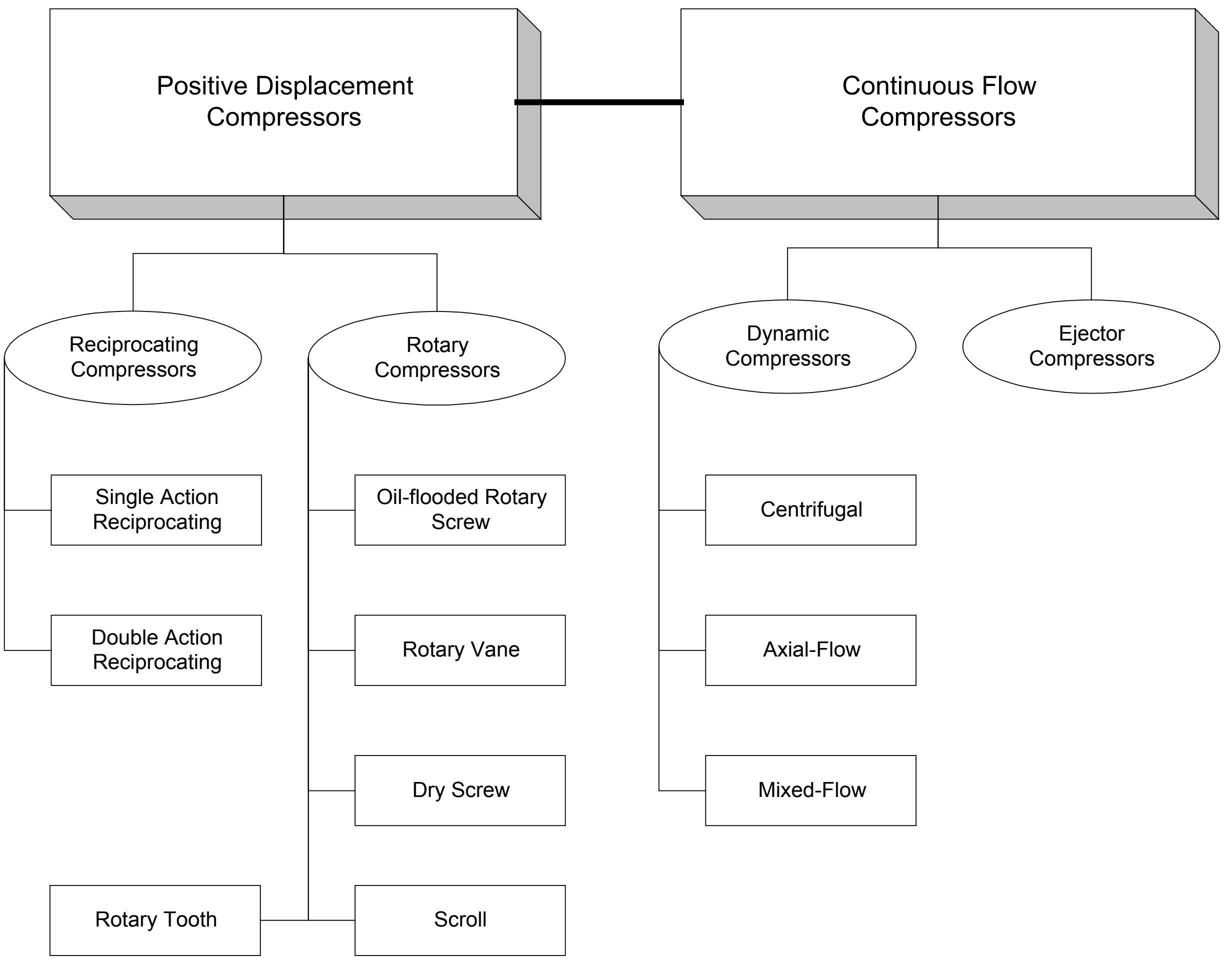


Figure 2-12 Types of Compressors

Air Compressor Selection The optimum compressor for a particular application will depend on many factors and particularly: application requirements, first cost, reliability, and operating costs.

Some applications, such as pharmaceuticals require inherently oil-free compressors. High pressure ranges can best be achieved with reciprocating compressors. Centrifugal compressors are best for high volume, continuous flow applications, such as snow making equipment.

After determining which types of compressors could perform the job, cost and reliability usually determine compressor selection. Dibbits (1992) ranks common compressor types for first cost and reliability, Table 2-10.

Table 2-10 First Cost and Reliability of Compressors

Compressor Reliability		Compressor Capital Costs	
• Rotary vane	Least reliable	• Rotary vane	Least expensive
• Reciprocating		• Reciprocating	
• Rotary Tooth		• Oil-flooded screw	
• Dry screw		• Rotary Tooth	
• Oil-flooded screw		• Dry screw	
• Centrifugal	Most reliable	• Centrifugal	Most expensive

Air Compressor Market Share Dibbits, ibid., estimates the market share for industrial compressors, Figure 2-13. The oil-flooded rotary screw is the most common type. The efficiency features of the oil-flooded rotary screw are investigated in depth in this report. Many efficiency features, such as premium efficiency motors apply equally well across most compressor types. Some features specific to other types are mentioned briefly.

> "The standard industrial lubricated screw compressor is highly reliable and has become the workhorse for general industry." (Dibbits 1992)

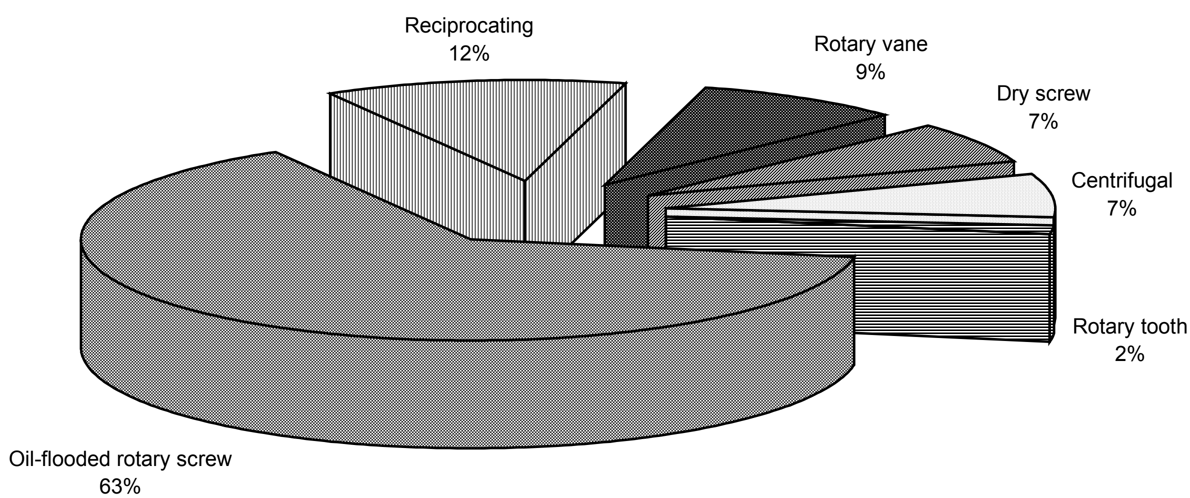


Figure 2-13 Industrial Compressor Market Share

<u>Reciprocating Compressors</u> Reciprocating compressors are positive displacement machines that move a piston up and down in a cylinder to compress the air. The basic reciprocating compressor sub-types are single action and double action. Single action compressors cause compressor only during upstroke of the piston while double action compressors cause compressor in both directions of piston travel. They were the most common equipment until the introduction of the rotary screw compressor. Single action reciprocating compressors are the least expensive and are still the most common type in small sizes for home and light commercial.

Reciprocating compressors are available in single or multiple stage units. When operating significantly above the normal 125-150 psi range, a reciprocating compressor is frequently the optimum choice; for the highest pressures, it is the only choice. Reciprocating compressors are rugged and durable in harsh environments. Double-acting reciprocating compressors are efficient , easy to unload and have very low unloaded horsepower.

Reciprocating compressors have more moving parts, more wear points, and require more maintenance than the rotary screw which has replaced them in industrial settings.

<u>Lubricant-flooded Rotary Screw Compressors</u> Rotary screw compressors use one or two screws or rotors to achieve compression. In the most common design of a rotary compressor, twin helical screw rotors enmesh in a dual bore cylinder. A trapped volume of air is compressed as a concave and convex rotor decreased the volume along the rotor. In a single-screw design the rotor meshes with the casing and air flow is controlled by gates. An oil or water based lubricant is injected which provides lubrication, heat removal, and chamber sealing.

Rotary compressors require less maintenance than reciprocating compressors. They are available in lower capacities and are easier to unload than centrifugal compressors.

Separation of the lubricant from the air can be a problem. If very pure air is needed, an oil-free model is used.

<u>Rotary Vane or Sliding Vane Compressors</u> In a rotary vane air compressor the rotor is mounted eccentrically in a housing. As the rotor turns the entrapped air volume is reduced and the vanes slide in and out to maintain the seal. The machine can be lubricated or oil-free.

<u>Oil-free or Dry Rotary Screw</u> Oil-free or dry rotary screw compressors are not just lubricant-flooded machines without lubricant. The seals are created by very close tolerances. Because of the heat of compression, high single-stage compression ratios are not possible and multi-stage machines are used for all except low pressure applications. Timing gears are used to prevent rotor contact. Seals on the bearing shaft prevent bearing oil from entering the compression chamber.

The oil-free rotary screw is more complex, more expensive, and has higher maintenance than the lubricant-flooded designs. It is used in applications where very clean air is needed such as pharmaceuticals and electronics.

<u>Centrifugal Compressors</u> The centrifugal compressor uses an impeller to create air velocity and a diffuser to change the velocity into pressure. Three stage are usually required to achieve useful pressures although some two stage compressors are available.

Centrifugal compressors have few component parts and are oil free. They are especially cost effective at very large sizes.

Unloading is more difficult for centrifugal compressors. They usually cannot be operated below 70% of full capacity. Operations that require high volume continuous air, such as snow machines, are ideal centrifugal applications.

Scroll Compressors Scroll compressors use a rotating spiral within a stationary spiral to compress the air. They offer several advantages. Scroll's inherent compression design makes it more efficient than conventional compressors. Scroll compressors have few component parts. They use no compression valves, pistons, piston rings, or cylinders which are subject to wear. Maintenance and unexpected downtimes are reduced. Scrolls also operate at low noise levels.

However, scroll compressors are now commonly available only in sizes less than 10 HP which limits their application.

2.10.2. Operation

There are three sectors in a compressed air system: production, distribution, and end-use. In production the air is compressed and conditioned for use which usually includes cooling, drying, and contaminate removal. Efficient control during the production of compressed air presents a large opportunity for energy savings. For a facility with only one compressor that would mean focusing on the efficiency of that compressor. Most larger facilities have multiple compressors and the control and sequencing of these compressors is often more important than individual compressor efficiencies. Other potential areas of energy savings include coolers and dryers.

2.10.3. Energy Savings Mechanism

Energy is the largest component in the total cost of compressing air. After verifying that the compressor can produce the required air, the next consideration is the efficiency of the air compressor — how many cfm can the compressor produce at the required pressure for a given kW input. In most applications, the load varies considerably and part-load efficiency is more important than full-load. A rule-of-thumb is an average load of 60% of peak load.

The primary methods of increasing compressor efficiency are list in Table 2-11.

Table 2-11 Efficient Compressor Features

- Rotor design: geometry and tolerances
- Multi-stage or high coolant injection
- Capacity unloading
- Control sequences
- Motor efficiency
- Cooling and heat recovery
- Drive
- Lubricant

Rotor and Chamber Design The two basic rotor and chamber designs are twin or single rotor. A variety of geometric shapes are available for the rotor or chamber. Efficiency will vary based on the geometry chosen. Because manufacturers do not rate equipment under standard conditions, it is not possible to directly compare efficiency ratings. It appears that all major manufacturers use more efficient computer designed profiles. The rotor profile does not change appreciably with wear. Rather bearing wear can lead to equipment failure. A sampling of manufacture claims follows:

"The asymmetrical osmiroid rotor profile used 4 male lobes working against 5 female cavities to achieve the shortest possible sealing line. This unique design used by Curtis minimizes internal power loss and maximizes efficiency to pressures of 175 PSI." (Curtis-Toledo 1997)

"The innovative SIGMA profile was developed by Kaeser. The design produces more compressed air for less energy and provides significantly reduced operating costs." (Kaeser 1997)

"Exclusive KYPHO Rotor Profile returns greater efficiency over its operating range and delivers a 3% to 5% operating efficiency advantage over standard rotor designs. Its asymmetrical rotor shape inherently provides a tighter seal between the grooves of the rotors to reduce slippage, eliminate vibration and increase efficiency." (Gardner Denver 1997)

"Optimized rotor profile design for unsurpassed efficiency." (Quincy 1997)

PEG concludes that rotor and chamber designs are fundamental design and material differences which should not degrade over time.

Tolerances The compressor takes in air, compresses the air, and then expels the air at a high pressure. In practical applications several inefficiencies are inherent in this process. With each cycle of compression, some of the compressed air remains in the chamber. It is then re-expanded in the intake cycle. This causes inefficiency because the energy used to compress it is lost and the chamber is at a higher pressure on the intake cycle so less new air can enter. The amount of re-expanded air is determined by the machine tolerances. At the height of the compression cycle, zero clearance is ideal. In practical applications, this is impossible. Metals expand with temperature and changes in alignment demand a degree of tolerance to avoid metal to metal contact which would quickly deteriorate the machine. More efficient equipment has tighter machine tolerances. The rotors wear little over time. The chamber is sealed by the lubricant and a small amount of wear will not lead to chamber air leakage. It is bearing failure that leads to equipment failure. A differential change in tolerances is not expected to change efficiency.

PEG concludes that machining tolerances are fundamental design and material differences which should not degrade over time.

Multi-stage or high coolant injection As air is compressed, it gets hotter; heated air expands and is harder to compress. By lowering the temperature of the air during compression, compression can be achieved more efficiently. Manufacturers use two techniques to accomplish this — two-stage compressors and high coolant injection. (The same fluid is both the lubricant and the coolant.) In two stage air compressors the air is compressed part way then it passes through a chamber where the lubricant/coolant reduces its temperature before it enters the second compression chamber. In high coolant injection there is a single compression chamber. The coolant is sprayed into a chamber designed for higher air/coolant contact and keeps the air cooler during compression.

Multi-stage or high coolant injected lubricant-flooded rotary screw air compressors are more efficient than single stage units. Manufacturers claim a 2-12% efficiency advantage over standard designs. However, multi-stage units are more complex and more expensive than single stage units.

Intensive Injection pays an immediate dividend through lower energy costs. This ingenious design improves efficiency 6 to 8% over the conventional lubricant injection. Lubricant injection into the compression chamber of a rotary screw compressor has three major functions: cooling the heat of compression, lubrication of the rotors, and sealing the internal running clearances.

> Of these, cooling the compression cycle is the key factor in controlling power consumption. Intensive Injection feeds the coolant into the compression chamber as a dense mist through four injection ports. The dense mist accelerates the rate of heat exchange between the air/oil mixture, with most of the injection and heat transfer occurring when the air has reached its highest pressure and greatest temperature. Hot spots are eliminated. The discharge air is pulsation-free and ready to use immediately, due to the steady continuous intermeshing of the rotors and the cooler discharge air temperatures. (Gardner Denver, 1997)

The high temperatures create stresses and accelerate wear on compressor components, seals, and lubricants. Rates of wear are often closely tied to temperature of operation. Two stage and intensive injection air compressors that increase efficiency by compressing at lower temperatures may therefore wear slower than less efficient models.

> Due to the dissipation of heat between stages (because of the inter-cooler), above 100 psig, two stage units allow for more efficient and cooler operating compressors, which increases compressor life. (Scales, undated)

PEG concludes that the differences between a single-stage and multi-stage and high coolant injection compressor are fundamental design and material differences which should not degrade over time.

PEG concludes that energy savings from two stage or intensive injection air compressors are likely to experience a small negative relative degradation compared to the baseline.

Capacity Unloading Plant air demand is usually below rated compressor capacity. Full load is needed rarely. Surveys indicate that most air compressors operate at 60-70% of full capacity on average, with full loading only occurring during peak demand periods. (Gardner Denver 1997). A compressor's efficiency can drop off dramatically at part-load conditions. Various methods are employed to meet part-load conditions and increase part-load efficiency. Methods of reducing compressor capacity include, Table 2-12.

Table 2-12 Methods of Capacity Unloading

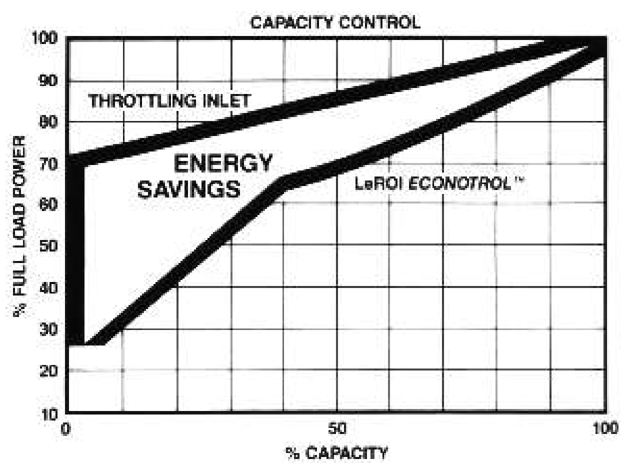
- Start/Stop Control
- Geometric unloading
- Inlet Valve Modulation
- Load/No-load Control
- Variable Speed Control
- Load/Unload Control
- Multiple Control Sequencing
- Multiple Compressor Sequencing

Start/Stop Control The simplest method is start-stop operation. The compressor is always under full load when operating which is its most efficient point. However, there is a loss of partially compressed air when it stops. Also cycling is hard on equipment; and it is not viable for large, high demand operations. Start-stop operation is useful for small compressors and larger compressors with low, intermittent demand. Adding extra storage reduces compressor cycling.

Inlet Valve Modulation In rotary screw compressors that operate at fixed speed, capacity control is usually either by inlet throttling or rotor length unloading. Typically in inlet throttling a butterfly valve across the air intake is modulated based on demand. The pressure across the compressor is artificially increased which reduces capacity but at a significant energy penalty because of the increased pressure. The horsepower required reduces slower than the reduction of capacity. At 50% load about 86% of peak brake horsepower (BHP) is needed; at 10% load, 75% of peak BHP is needed, see Figure 2.14. Inlet throttling is inexpensive to implement and provides good capacity control, but causes a significant drop in efficiency.

<u>Rotor Length Unloading</u> Some rotary screw compressors use rotor length unloading rather than throttling to control capacity. By opening ports along the chamber length, the effective rotor length is shortened and compression per rotation is reduced. Manufacturers claim higher part load efficiencies for rotor length unloading, Figure 2-14.

An energy penalty occurs during unloading when the compressed air is vented. The effect of this is greater at higher part-loads where part-load efficiencies may be similar to inlet valve modulation. The unloading ports themselves can add inefficiencies if they trap, leak, or bypass air.



Source: LeRoi Compressors

Figure 2-14 Part Load Efficiency of Inlet Throttling vs. Cylinder Unloading

<u>Load/No-load Control</u> In load/no-load control the butterfly valve at the inlet to the compressor is set either full open or fully closed. The motor continues to operate without any load which prevents start/stop cycling. One manufacturer claims that load/no-load control is comparable to rotor length unloading at lower capacities.

<u>Variable Speed Control</u> Adjustable speed drives are very effective at maintaining high efficiency under intermediate load conditions. They have had only limited market penetration so far, but are becoming more common as prices decrease and acceptance increases. Few manufacturers were found that offered an adjustable speed drive as an original equipment manufacturer (OEM) capacity control.

Adjustable speed drives consume more power at full load because of the ASD's internal power dissipation. They should only be used on systems that operate at partial load the majority of the time — which includes most industrial systems.

<u>Load/Unload Control</u> In load/unload control a relief valve opens to exhaust compressed air when the system is satisfied. Inlet modulation is used to reduce the volume of air vented. This system is more common on centrifugal compressor which depend on the impeller speed to create the required pressure and are more difficult to unload. It is also sometimes used on rotary screw compressors.

Advanced Controls and Sequencing Microprocessor based controls allow advanced control strategies. The capacity control that provides the best characteristics varies with the fraction of capacity needed at the time. The unloading that works well at high fractional loads, 99-95% capacity, may be different that that which works well at low fractional loads, 5-1% capacity. Many manufacturers offer automatic control sequences which optimize their capacity control for the various capacity ranges.

One manufacturer uses a stepped automatic control sequence to take advantage of the different control strategies. Between 100-60% load, inlet valve modulation is used; from 59-3% load, load/no-load is used; below 3% start/stop control is used.

Multiple Compressor Sequencing In most large facilities more than one compressor is used. The compressors may be distributed throughout the plant or combined together in one location. Compressor sequencing can be arranged such that only one compressor is operating at reduced capacity at any given time while the others are either off or at full load. The mixture of compressors can be optimized to provide low initial cost and superior operating efficiency. Centrifugal compressors are highly efficient only when fully loaded. A potentially good application might include a base centrifugal compressor to supply the continuous needs of a plant in conjunction with a variable capacity rotary screw to handle the variable portion.

Differential Degradation Techniques of capacity unloading are fundamental material and design characteristics. Most are not subject to differential degradation, though some potential does exist. The base case is considered to be inlet valve modulation. If a high efficiency model with rotor length unloading had a poppet valve fail closed, the superior benefits of rotor length unloading would be reduced and the failure might go unnoticed for some time. This is, however, expected to be rare.

> **PEG concludes that energy savings from efficient air compressors unloading strategies are fundamental design and material differences which should not degrade over time.**

Energy Efficient Motors Energy efficient motors supply the same brake horsepower at reduced kW draw. A straight forward way to increase compressor efficiency is to use an energy efficient motor. 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. All of the changes to achieve higher efficiency are fundamental design and material improvements which should not degrade over time. One manufacturer claims that the high efficiency motors will have double the life of standard efficiency units according to accelerated life testing (McGovern 1984). Many sources indicated that efficient motors provide numerous benefits in terms of reliability, time in service, 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.

In a previous PEG report on energy efficient motor, PEG found: (PEG 1996)

> 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.**

Cooling and Heat Recovery The lubricant/coolant in a lubricant-flooded rotary screw provides primary cooling as well as lubrication and chamber sealing. The lubricant itself must then be cooled using an air cooled radiator or liquid-liquid heat exchanger. An air cooled radiator is an additional load. For a 100 HP unit the fan is usually 3-5 HP. The coolant pump on a water cooled system will also be an additional load.

An indirect way to make the production of compressed air more efficient is to recover the heat of compression given off by the compressor. About 94% of the heat of compression is recoverable, Figure 2-15. (Chemical Engineer, 9/12/91) This heat is fairly high quality; it is available at 170-212°F (77-100°C), hot enough for service water or space heating or some process needs. It will be available whenever the compressor is operating; therefore, its availability may be highly coincident with end use needs. In closed loop systems, little fouling would occur; open loop systems would need only routine maintenance.

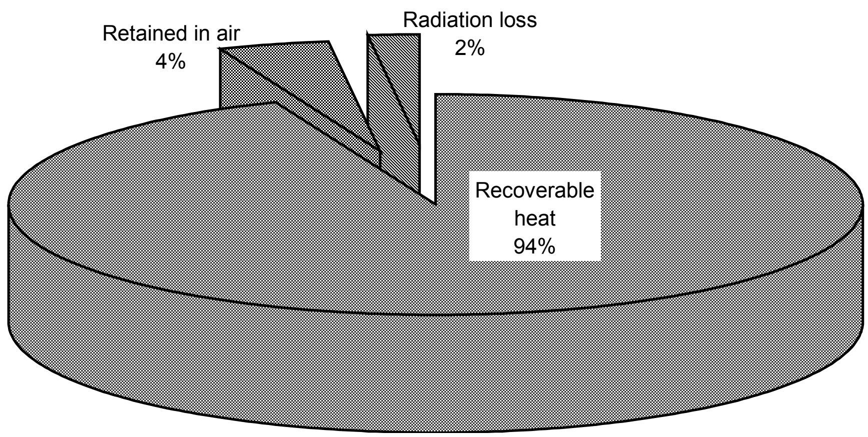


Figure 2-15 Heat Recovery Potential

> **PEG concludes that energy savings from heat recovery is a fundamental design and material change which will not decline over time due to technical degradation.**

Lubricants Lower friction lubricants can reduce horsepower input, but the effect is small. Some higher quality lubricants may have higher viscosity and increase power requirements somewhat. Proper maintenance of changing oil when necessary is the main factor. Because the lubricant has direct air contact, in dirty environments the lubricant needs to be changed frequently, and therefore, less expensive lubricants are usually used.

The rotary screw compressor is a rugged machine. While degradation due to inadequate oil quality maintenance is an issue; it is expected to be slow and not to differ between standard and high efficiency equipment.

> **PEG concludes that energy savings will not decline over time due to lubricant choice or maintenance.**

Drive The drive linking the motor to the compressor proper will dissipate some power. Direct drives are best, then gear driven, then belt driven. Differential degradation between drive types is not expected.

> **PEG concludes that drive mechanism is a fundamental design and material option and energy savings will not decline over time due to technical degradation.**

2.10.4. Degradation

Bearing Degradation The primary wear point in lubricant-flooded rotary screw compressors is the bearings. As the bearings wear the rotors develop some play. The rotors can then rattle against each other and the cylinder wall. Because the rotor bearing is such a significant stress point, rotor shafts with double or triple bearings are common. Rotor replacement is usually done at the factory.

Bearing design is more important to equipment life than to efficiency.

> **PEG concludes that new air compressors are unlikely to experience relative technical degradation due to bearing wear.**

Wear Degradation All sources contacted agreed that the modern lubricant-flooded rotary screw compressor is a harder, reliable, long-lasting machine. Efficiency loss due to wear was not noted as a problem by any expert source. End of life was considered due to bearing failure not loss of compression efficiency. Documentation of efficiency degradation at end of life was not found.

> **PEG concludes that new air compressors are unlikely to experience relative technical degradation due to wear.**

Degradation of Distribution System and End Uses A new air compressor is often purchased to remedy a perceived lack of capacity. End users complain about inadequate air supply and the existing equipment is set at maximum so new capacity is added. Usually the capacity shortfall is actually due to problems with the distribution system and end uses. Increased capacity from new equipment will tend to exacerbate and mask these conditions leading to increased degradation “downstream”.

For example, a perceived capacity shortfall may actually be too many leaks. The added compressor capacity will increase system pressure — its primary purpose. This does temporary fix the symptom of insufficient pressure, but ultimately only results in more air wastage and exacerbated supply problems. The increased pressure will accelerate the escaping air and entrained particulates which then abrade and enlarge the holes faster. It might take several years before the leaks fully absorb the added compressor power and the effect would not be completely captured in estimates of first year savings. Increased end use due to other mechanisms such as over pressurizing cylinders would be captured in first year savings estimates.

An air management program (AMP — a comprehensive package of measures aimed at production, distribution, and end uses) may eliminate most or all this degradation. An important part of an AMP is an expander valve. An expander valve maintains the distribution main header pressure separate from the air compressor. Then, increased compressor power does not translate directly into increased supply pressure and does not increase leak rates. It is the most important and effective device to brake the degradation mechanism of added compressor power.

> **PEG concludes that new air compressors are likely to increase losses in the distribution system unless an expander valve is present.**

2.10.5. Conclusions

> **PEG concludes that relative technical degradation between existing air compressor and replacement air compressor is unlikely.**
>
> **PEG concludes that decreasing measure energy savings are likely due to degradation of the distribution system initiated and masked by the replacement compressor.**

2.10.6. Calculation of Persistence

All of the most significant changes to achieve higher efficiency at the compressor are fundamental design and material improvements which should not degrade relatively faster than the standard compressor over time.

Without an air management program, the increased air flow will degrade the distribution system and go into uncontrolled uses. Field measurements of the effects of capacity increase on system losses were not found. Increased capacity would be similar to leak repair and all authorities agreed that leak generation and enlargement is rapid. This estimate of persistence assumes that increased capacity is absorbed by leaks and increased air wastage with a half-life of 2 years, Table 2-13. An AMP may greatly reduce or eliminate this degradation. Further research to strengthen these estimates is recommended, and a research plan is presented in Section 3.7.

Table 2-13 Air Compressor — TDF

YEAR	TDF w/o AMP
1	1.00
2	0.71
3	0.50
4	0.35
5	0.25
6	0.18
7	0.13
8	0.09
9	0.06
10	0.04
11	0.03
12	0.02
13	0.02
14	0.01
15	0.01
16	0.01
17	0.00
18	0.00
19	0.00
20	0.00

2.11. Compressed Air Distribution Systems

Header pressure in the baseline distribution system is supplied directly from the compressors. The piping system is marginally sized and leaky. Many regulators are set at maximum. Filters are clogged. Air is often used inappropriately.

In the efficient system, the main header pressure is controlled by an expander from an adequately sized storage tank. The system is tight with few leaks and no large ones. The piping system is adequately sized to provide the rated flows. Regulators are set at the appropriate pressure to provide supply to the specific end-uses. Each end use is appropriate in function and quantity of air used.

2.11.1. Components of Compressed Air Distribution Systems

Compressed air systems have much in common with electrical systems. There are generation, transmission and demand parts. The system is supplied with air from an air compressor — generation. In large facilities there is often multiple compressors at one or several sites in the system. The air compressors are typically set to maintain a constant pressure and experience a varying load — maintain constant voltage and experience varying demand. The compressed air is distributed through a system of distribution pipes — transmission. Regulators drop the pressure down to the needs of local branches — transformers. Finally the compressed air is used in a myriad on end uses in the plant or facility.

Each of the system components — generation, distribution, and demand — has a set of energy savings opportunities.

2.11.2. Operation

Compressed air systems transfer energy from the electrical connection to the points of use through compressed air. There are several advantages to compressed air systems. Most rotary tools come in electric and pneumatic models. Pneumatic tools can be lighter and more maintenance free than conventional electric tools. Pneumatic tools are safer than electric tools in damp environments. Pneumatic tools are inherently variable speed, and the armature is less massive and can respond faster to calls for greater speed. Some end uses utilize the compressed air directly, i.e. blowing out debris.

2.11.3. Energy Savings Mechanisms and Degradation

Compressed air usage is notoriously inefficient. Based on 42 audited systems, Foss (1993) estimates that in a typical system only 37% of the compressed air is used appropriately in production. Table 2-14 shows the typical components of compressed air demand.

Table 2-14 Component of Compressed Air Demand

Component	Average Percent	Description
Appropriate End Use	37%	Appropriate usage in end-use application, quantity, and pressure.
Inappropriate use in production	10%	Applications that would be more appropriately accomplished with a different power source.
Open blowing	15%	Air used for moving, drying, cooling, etc. where

		blowers or low volume nozzles would be more efficient.
Artificial Demand	9%	Excess usage by unregulated users because of excess supply pressure.
Leaks	23%	Leaks in distribution piping system, drops, and internal to production equipment.
Drainage	6%	Air used in conjunction with the removal of water or lubricants from the system

<u>Inappropriate Use in Production and Open Blowing</u> Compressed air is often used wastefully. Because it is available, convenient, and has low initial cost for the end use equipment, compressed air is used for end uses that could be accomplished with far less operating costs by other means. For example, compressed air can be used to agitate liquids when an electric stirrer is less expensive to operate and would quickly pay for itself. It can be used to blow off a bench when a brush would do as well; or an intermittent need may be supplied with a continuous air flow. Open blowing is the most wasteful inappropriate use.

Decreases in inappropriate usage from education and operation are likely to have low persistence unless reinforced with an on-going training and over-sight function. Decreases in inappropriate usage that involve equipment changes, i.e., the addition of automatic control of intermittent needs etc., are likely to be more permanent. Decreases in inappropriate use where the compressed air usage is stopped altogether due to equipment changes are likely to have high persistence. For instance, a low pressure blower can be substituted for high pressure air in some cases. Table 2-15 lists some common wasteful practices with compressed air. (List condensed from Howe and Scales, 1995.)

Table 2-15 Common Wasteful Practices with Compressed Air

Inappropriate Uses	Remedy / Retrofit	Persistence
Use of compressed air unnecessary and discretionary such as blowing off workbench	Use appropriate tool such as brush	Low persistence without ongoing training and oversight by management
Low pressure air sufficient	Use blower	High persistence with equipment change out
Continuous use for intermittent requirement	Install automatic controls	Moderate persistence, control bypass possible
Excessive pressure at end point causing over use	Lower pressure	Low persistence, pressure increase are common occurrences
Air supplied simultaneously to all points of a multipoint sequential process	Sequence air usage with automatic controls	Moderately high persistence. Control bypass possible but no obvious advantage to bypass.
Distribution supply pressure too high	Lower distribution pressure	Low persistence, pressure increase are common occurrences

Distribution kept high to satisfy only one or two pieces of equipment with higher pressure needs	Install pressure booster to specific equipment	Moderately high persistence with equipment change out, pressure increases still possible
Distribution pressure high due to intermittent lower pressures caused by large uses	Increase storage, either system or local; use feed forward control; use demand control	Moderate persistence with equipment change out, pressure increases still possible
End use pressures too high	Decrease regulator setting for proper pressure	Very low persistence, pressure increase are common occurrences especially at operator's end
Compressed air system on without any load	Turn off system when not in use	Low persistence, without management training and oversight

PEG concludes that air usage is in continuous flux. Without a comprehensive air usage management program, energy savings from appropriate air use are likely to experience relative technical degradation.

PEG concludes that energy savings from reducing compressed air consumption in inappropriate end uses that involve major equipment changeovers are likely to degrade towards baseline only slowly.

<u>Artificial Demand and Excess Supply Pressure</u> Artificial demand is the excess usage caused by excess supply pressure. Operating personnel often attempt to solve system performance problems by increasing the system pressure. While it is often the first response to complaint, increasing the system pressure is rarely the correct solution. It can sometimes cover-up other problems, but at a severe energy penalty. For instance, if an end use has a short periodic need for a large amount of air, it can reduce pressures to below setpoint throughout the system. Increasing system pressure will reduce this effect. Adding local storage at the device would solve the problem without any system pressure increase.

The setting of the distribution pressure has a significant impact of compressed air usage. While demands that have individual regulators will not be affected, many demands are directly correlated to the distribution pressure. The most obvious are distribution system leaks. Some end uses use unregulated pressures. Regulators are often set at maximum, effectively giving pressure control to the distribution system. Increasing the pressure from 80 psig to 120 psig, 50% increase, increases the uncontrolled discharge through a 1/4" orifice by 42%. (Compressed Air and Gas Institute 1989)

<u>Storage</u> In most systems the distribution header is supplied directly from the compressors. The storage tank cannot perform its intended function because it needs a pressure differential to operate. Adequate storage reduces system pressure fluctuations and reduces compressor cycling. Inadequate storage often results in calls for higher pressures.

<u>Expander Valve</u> An expander valve can be used between the storage tank and distribution piping to control distribution pressure. It can pass a large amount of air at a low pressure drop. Rather than operating at whatever pressure the compressor produces, the system will operate at the defined minimum pressure. Demand spikes are supplied from storage rather than from increasing pressure. By

limiting the pressure, the waste from unregulated uses or uses with regulators set a maximum is minimized.

While adding system storage and an expander valve are fundamental equipment changes, the pressure setting on the expander valve can be easily reset. An expander valve is a critical component to a comprehensive demand management program, but used alone resetting is likely. A comprehensive system of training and oversight could maintain these savings.

<u>End-Use Pressure Regulation</u> The pressure of the distribution piping is reduced for end-use at the drop. The pressure should be set to the minimum necessary at each end use. Often it is set higher than needed. Turning up the pressure is a common first fix for many problems. Even if the problem is later discovered to be something else, the pressure may not be reset to its original setting.

Dickson (1997) states that virtually all end uses should have pressure regulation to step down the mainline pressure to the minimum required end use pressure. He estimates that 20-30% of end use points have no pressure regulators; Foss (1993) estimates 50%..

Turn-up-the-pressure is a common factory floor folk lore as evidenced by this statement published in "Air Compressor Tips":

> To get better efficiency from your air tools, turn up your output pressure 5-10 lbs. HIGHER than is recommended by the air tool manufacturer.

Higher drop pressures increase leaks in the drop system (the most frequent location) and uses more air per event.

A comprehensive system of training and management oversight can decrease the factory floor culture of excessive pressure usage. However without ongoing support, the training and operational changes will lapse.

> **PEG concludes adequate storage and/or an expander valve are basic equipment changes and are unlikely to experience relative degradation.**
>
> **PEG concludes that pressure is often uncontrolled and is easily reset. Energy savings from reduced artificial demand are likely to experience relative technical degradation.**

<u>Leaks and Leak Reduction</u> Leaks are a major source of inefficiency in compressed air system. Unlike liquid leaks, air leaks usually leave no trace. This reduces the obviousness of the leak and the impetus to fix it.

> "You can't see them. You probably won't hear them. But they are costing you -- a lot." (www.wkpower.com)

PG&E presented the following introduction to air leak reduction measures in their January 1995 Advice Filing.

> Compressed air systems are among the most common and least efficient electrical end- uses in industrial plants. After lighting, motors and HVAC, compressed air systems offer the greatest electricity savings potential in these facilities. Based on available research, over 50% of plants use centralized compressed air. The American Council for an Energy- Efficient Economy (ACEEE) has estimated that, nationwide, compressed air systems account for 12% of total industrial electricity

consumption. Regional conservation potential studies have estimated that industrial compressed air systems waste 25% to 60% of the electricity they consume.

Leaks in the distribution system are the single greatest source of loss in compressed air systems. It has been estimated that 20% all energy consumption for air compressors is wasted due to leaks in the distribution pipes, valves, nozzles and other system connections. In individual plants, losses due to leaks may be as high as 50% of compressor system capacity.

Most compressed air systems consist of one or more compressors linked to distribution piping throughout a plant. Air for particular applications is drawn from the central distribution system by means of overhead pipes called "headers" and "sub headers." Air is drawn from the headers for particular end-uses by smaller pipes called "drops." These drops may lead directly to stationary piece of equipment or to hose connections. Flexible rubber hoses may be attached to the hose connections for the operation of portable hand tools and other equipment. Leaks may occur at any point in these distribution systems.

The following is a list of common leak areas:

- Hoses and disconnect plugs
- Cylinders and controls
- Pipe connections and valves
- Filters, seals, gaskets and O-rings
- Traps and liquid drains
- Abandoned equipment with air left on

Leaks may develop for a variety of reasons. Compressed air can be relatively hot, often exceeding 100°F in temperature. This heat can subject the distribution piping to expansion and contraction, which may loosen joints over time. Mechanical vibrations from operating machinery may also loosen piping joints. Wear on hoses and hose connections due to repeated use, fouling or malfunction of oil traps and liquid drains and deterioration of seals and filters may all result in leakage.

Leaks will vary in number and size. The system may not be able to maintain adequate pressure due to leaks. [Table 2-16] summarizes typical energy losses for compressed air leaks in a continuously operating 100 psig system, the most common pressure level used for general applications in industrial plants.

Table 2-16 Annual Energy Losses from Compressed Air Leaks

Hole Diameter	Wasted Air @ 100 psig (Ft^3/year)		Wasted Energy @ 100 psig (kWh/year)	
Hole Diameter	Sharp Hole	Rounded Hole	Sharp Hole	Rounded Hole
1/32″	553,000	808,000	1,500	2,200
1/16"	2,220,000	3,200,000	6,040	8,700
1/8"	8,800,000	12,900,000	24,240	35,540
1/4"	35,000,000	51,200,000	97,000	141,900
3/8"	79,000,000	115,500,000	218,500	319,460

Locating leaks in compressed air lines involves visual and acoustic inspection of the entire distribution system. Specialized leak detection equipment is available specifically for this purpose, usually in the form of a "gun" with a precise acoustic (or infrared) sensor connected to an amplifier and a pair of headphones. Such detectors can locate leaks from considerable distances, even in the presence of other ambient noise.

Measuring the rate of air loss through leaks is not necessary for repair; however, measurement of air loss through leaks is also useful as an indicator of piping system integrity for ongoing maintenance. A variety of leak measurement approaches are available, each with its own strengths and weaknesses in terms of cost, accuracy, ease of installation, and impact on the distribution system. A common technique requires the installation of a flow metering device at the main trunk of the distribution piping to measure the rate of air flow to the system. Such meters can be automatically and electronically monitored to provide continuous information on system air loads.

Leak repair techniques are dependent upon the type and location of leak. They may involve replacing cracked sections of pipe, replacing worn hoses, resoldering piping joints, or replacing faulty liquid drains.

<u>Energy Effects of Air Leaks</u> Energy savings are not directly proportional to the leakage reduction in a system, but depend on the part load efficiency of the air compression system. For example if system leakage was reduced from 50% of capacity to 10%, it would have the effect of unloading the compressor system 40%. If the system useful load were 50%, the system would see a demand drop from 100% to 60% load. An inefficient compressor system might reduce its kW from 100% to 85% of full load kW; a reduction of only 15% in kW for a 40% reduction in load. A compressor system with high part load efficiency might reduce its kW from 100% to 65%, a 35% reduction, over twice as much. Most sophisticated unloading schemes have different unloading techniques for high, medium and low demand, with varying efficiencies. The calculation of energy and demand savings from leak reduction is best done from monitored site specific data. PG&E suggests a 0.6 partial-loading rule of thumb to calculate energy demand savings.

The energy and demand savings from leak reduction will change with any change in plant load. The savings could go up or down. Since most systems rise in efficiency at higher loads, any increase in facility demand will raise system efficiency and lower the effective savings from leak reduction. Any decrease in facility demand would increase the effective savings. Without any other factor being considered these two effects would be estimated to cancel each other out over a diversified load. Economic activity such as a recession or economic boom might swing diversity strongly in one direction creating a net increase or decrease. However, over a full business cycle this also would cancel out. Therefore PEG expects no net change from changes in average plant load on the persistence of savings from leak reduction.

<u>Persistence of Leak Repair</u> The persistence of savings from leak repair is not known. Various estimates were found. PG&E, 1995, estimated that leak repair would persist for one year; this was increased to two years with flow metering to provide feedback to the operators. Nehme at SDG&E, 1997, estimates about a 5 year life expectancy before a facility returns to its pre-repair condition.

Measure Life: The persistence, or lifetime, of leak repair is a problematic issue. In the past, the savings achieved through improved operation and maintenance have been limited to a few years' duration. Experience with energy conservation programs of this nature indicates that staff turnover, work pressures and other factors cause a gradual deterioration of improved operating and maintenance practices.

No studies have been conducted to determine the rate at which compressed air leaks develop initially, nor of the rate at which they grow or recur after repair. Much is dependent upon customer commitments to ongoing maintenance after repair. Discussions with experts suggest that properly repaired leaks in balanced compressed air systems may not recur for a year or so in the absence of further maintenance. A good maintenance program can keep leaks down to an acceptable level indefinitely. However, providing one- time incentives, but not ongoing incentives for continued leak maintenance, probably will not by itself achieve long-term persistence.

To promote long-term persistence, the REO Program requires the installation of a flow meter. One of the reasons plants have trouble maintaining the energy efficiency of their compressed air systems is the lack of reliable gauges to monitor system performance. The installation of flow meters can address this problem, substantially improving measure persistence beyond the initial round of leak repairs. A flow meter allows operation and maintenance personnel to detect increased usage not related to connected loads and initiate appropriate action in response.

Conservatively, a 2 year measure life was used, only twice what might be expected without the flow meter. Given proper maintenance, leak repairs can reasonably continue for the life of the flow meter, which may approach 10 years or longer. (PG&E Advice Filing, 1995)

PEG concludes that relative technical degradation is possible through the generation and enlargement of air leaks.

Drainage Drainage is needed to expel water and/or lubricants from the system. This is accomplished with open drains that continuously vent, or devices that control drainage. Open drainage can result in very high annual usage. Mechanical drainage devices reduce air usage but sometimes have faster drains and the resulting pressure drops can disrupt the system. Good drains can provide this function at almost no usage. Low air discharge drains need regular maintenance for proper operation. Without comprehensive maintenance, air usage for drainage is likely to increase from drain malfunction and bypass.

PEG concludes that relative technical degradation is possible through the lack of maintenance of liquid drains.

Minimizing Piping pressure loss The distribution piping needs to be properly sized in order to minimize transmission loses. Piping may be inadequately sized originally or the plant air usage may increase over time. Replacement of distribution piping is expensive. Adding storage at problematic points or moving one compressor in a multi-compressor operation to the point of need could alleviate the problem. Leak reduction to increase capacity should be investigated first before other measures because it provides savings in many ways.

Any solution to inadequate pipe sizing that is a structural change will likely have long persistence. Repiping is particularly permanent.

PEG concludes that adequate distribution piping sizing is a basic material change, and energy savings achieved are unlikely to experience relative technical degradation.

2.11.4. Conclusions

PEG concludes that energy savings from changes in the distribution and use of compressed air varying greatly in potential persistence. Energy savings from changes that involve substantial equipment alterations are more likely to be persistent than those from operational changes.

PEG concludes that relative technical degradation is possible through the generation and enlargement of air leaks.

PEG concludes that items under human control and that have a long history of wasteful practices are subject to degradation including: system pressure settings, regulator pressure settings, maintenance practices, and wasteful air use practices.

2.11.5. Calculation of Persistence

Calculation Methodology Quantitative information on the persistence of savings was not found. However, experts contacted uniformly agreed that persistence would be low without a comprehensive air management program. In larger systems it is not uncommon to add compressor power annually in order to keep pace with increasing waste.

Estimate of Persistence Without an AMP, the reduction of usage due to the utility programs was assumed to degrade at 15%/year for 5 years. The 25% remainder after five years was assumed to be due to substantial equipment changes and fairly permanent. TDF values are listed in Table 2-17.

Table 2-17 Compressed Air Distribution Systems — TDF

YEAR	TDF w/o AMP
1	1.00
2	0.85
3	0.70
4	0.55
5	0.40
6	0.25
7	0.25
8	0.25
9	0.25
10	0.25
11	0.25
12	0.25
13	0.25
14	0.25
15	0.25
16	0.25
17	0.25
18	0.25
19	0.25
20	0.25

2.12. Compact Fluorescent Lamps (CFL)

The measure baseline is standard incandescent commercial lighting (one 100 watt incandescent A-lamp) in down-lighting and wall sconces. The efficient measure is a fixture with two hard-wired 13 watt CFL lamps on the same operating schedule. The fixture has an integral magnetic or electronic ballast with replaceable 13 watt twin tube fluorescent lamps. Two 13 watt CFL provides the approximate lumen output of a standard 100 watt A-lamp.

Down-lights are a common lighting fixture in commercial settings. E Source, 1994, estimates that down-light fixtures account for 20% of the estimated 2.8 billion incandescent lighting sockets in the United States, or 560,000,000 units.

It is important to direct the light out of the luminaire and distribute it effectively. A straight CFL for incandescent replacement will usually not provide satisfactory light because the down-light reflector was optimized for a very different light source. To provide good illumination, a retrofit of a down-light must include a reflector retrofit. New hardwired CFL down-lights are optimized for the proper projection of the illumination.

2.12.1. CFL Typology

Compact fluorescent lamps come in three common types: integral, modular, and hard-wired.

An integral unit is a lamp, ballast, and base in a sealed assemblage that is discarded at end of life. The base fits a standard incandescent socket.

A modular unit consists of a lamp and a separate screw-in base-ballast. At end of lamp life, a new lamp can be installed. Lamps lives are typically 10,000 hours and ballast life 40-60,000 hours. The base fits a standard incandescent socket.

A hard-wired system consists of a fixture (including ballast, CFL socket, and reflector) provided with a changeable CFL lamp. A standard incandescent bulb cannot be installed in this fixture. At the end of lamp life, only another CFL lamp can be installed.

2.12.2. Savings Mechanism

Compact fluorescent lighting is more efficient than incandescent lighting. The small tube diameters make it economical to use the same highly efficient rare earth elements found in T8 lamps. (Audin 1994) The rare earth phosphors provide high efficiency and good color rendering.

The 13 watt twin-tube compact fluorescent light achieves 50 lumens per watt (lpw) with a magnetic ballast and 53 lumens per watt with an electronic ballast. Smaller CFLs generally are less efficient because the ballast losses are a higher percentage of the total draw, Table 2-18. A standard 100 watt incandescent A19 lamp achieves 16.8 lpw.

Table 2-18 CFL Efficiency

Twin-Tube CFL	System Efficiency (lumens/watt)	
	Magnetic Ballast	Electronic Ballast
5W	27	NA
7W	32	NA
9W	37	44
13W	50	53
18W	49	61
27W	63	67
40W	68	74

Source: (E Source 1994)

2.12.3. Operation

A fluorescent lamp produces light by discharging an electric arc through a tube filled with low pressure mercury vapor. The mercury vapor primarily produces ultra-violet radiation which is absorbed by a phosphor coating on the inside of the tube. The phosphors convert the 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, facilitating arc establishment. The lamp rapidly heats to operating temperature increasing 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. The ballast limits current to the lamp while providing the proper operating voltage. The end of lamp life is generally caused by depletion of emissive material from the cathodes. The efficiency of compact fluorescent lights is affected by temperature, position, time on, lamp life, and ballast characteristics.

2.12.4. Retention Issues

The efficient measure is a hardwired unit. This helps to avoid the major retention drawbacks of CFL screwbase replacements: poor lighting, theft, and ease of reversion to incandescent..

Poor light output can generate reversion to incandescents. New England Public Service Company found that "insufficient brightness" was the most common reason residential customers gave for reverting to incandescents from screwbase fluorescents. (NEPSCo 1993) Poor light output may result from insufficiently bright lamps or inefficient luminaries.

Manufacturers may overstate CFL light output. The National Lighting Product Information Program tested 13 watt CFL lamps under ANSI standard conditions on a reference ballast and found light output 8-16% less than manufacturers specifications. (Davis et al. 1994) This will be exacerbated when the CFLs light output declines with age. Down-light luminaire efficiency varies considerably. The Lighting Research Center found luminaire efficiencies from 37-85%. (LRC 1995)

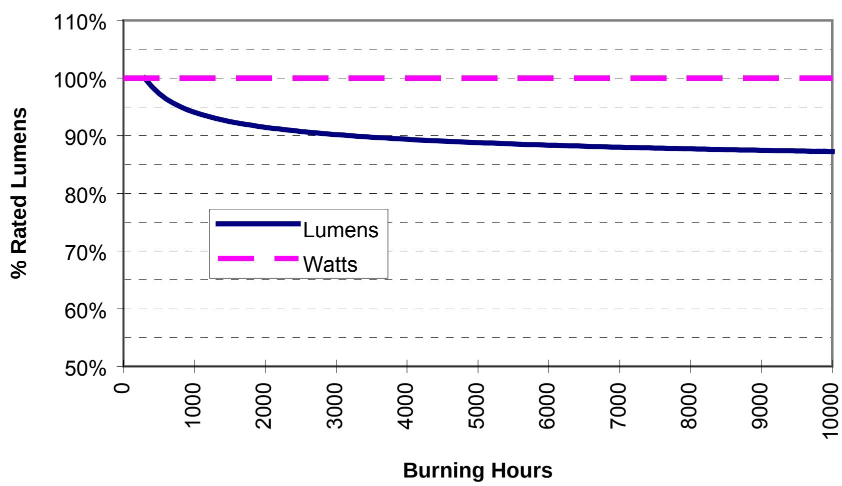
New CFL down-lights have reflectors specifically designed for a CFL, only the lamp can be stolen, and conversion to incandescent would require the entire fixture to be replaced. Replacement hardwiring kits usually include an reflector optimized for a CFL and the socket only fits a CFL.

> **PEG concludes that reversion to incandescent is unlikely unless a retrofit results in poor light quality.**

2.12.5. Degradation

Hardwired CFL Light Output and Watt Draw The effective light from a fluorescent system is affected by lamp lumen depreciation, ballast interactions (represented by the ballast factor), losses in the fixture, and dirt buildup on the fixture and room surfaces. The illumination depends on these factors as well as re-lamping strategies and maintenance practices.

The lamp lumen output decreases as the phosphor coating deteriorates and, to a lesser extent, from end darkening (due to emissions from the electrodes). Typical lamp lumen depreciation rates range from about 10 to 20 percent and are primarily a function of phosphor composition and current loading, Figure 2-16 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.



Source Osram Sylvania

Figure 2-16 Typical Lumen Depreciation Curve

The energy consumption of a ballast/lamp system is a function of 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 it is expected that the system will draw the rated wattage over its expected life.. While the exact wattage will vary somewhat between applications, it should remain constant over time.

Analysis

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.

> **PEG concludes that compact fluorescent watt draw is not likely to vary over the normal life of the ballast or lamp. As fluorescent lamps ages, the lumen output decreases while the power watt draw remains constant.**

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 lamp wall temperature (MLWT), 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, Figure 2-17. Most fixtures maintain lamp wall temperatures above 100ºF and the actual lumen output and power draw are generally less than the nominal rated values (by 5%-15% in many applications).

Down-lights can trap heat and increase the MLWT resulting in reduced light output and lower watt draw. The Lighting Research Center tested CFL down-lights for thermal performance. Vented and unvented down-lights increased fixture temperatures above ambient by 20.2°F (11.2°C) and 40.0°F (22.2°C) respectively. (LRC 1995) The 19.8°F additional increase in the unvented fixture is estimated to decrease the lumen output 10-15%. (Davis et al. 1994)

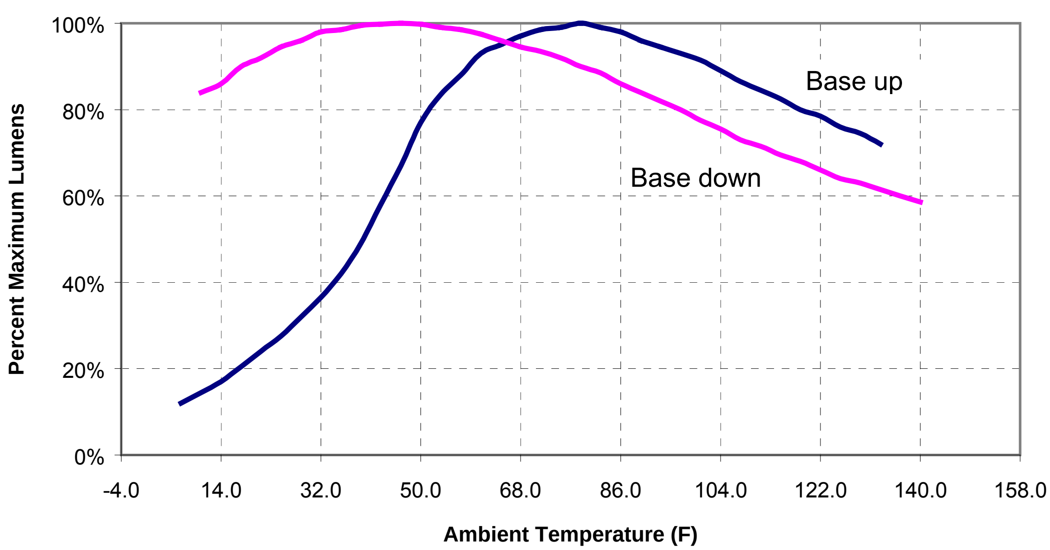
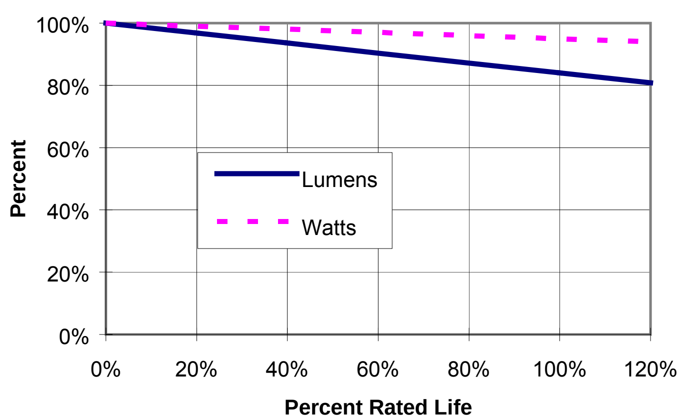


Figure 2-17 Temperature Effects on Lumen Output

If temperatures changed systematically over the life of a fixture/lamp/ballast combination, then energy savings from the measure could 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 were are covered in 2.12.4.4. 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. However, these changes are small in the overall heat balance of the fixture. A downlight with two 13 watt compact fluorescent lamps and an energy efficient magnetic ballast generates about 34 watts of heat and 9 watts of light. At a typical downlight luminaire efficiency of 60%, about 7 watts of light exit the fixture. (LRC 1995) 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 3°F (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.

> **PEG concludes that fixture temperatures should be nearly constant over time for a given set of equipment characteristics and operating conditions. Compact fluorescent watt draw is not likely to vary due to changes in temperature with age.**

Incandescent Lumen Depreciation and Wattage Reduction The lumen output of an incandescent lamp depreciates during the life of the bulb. This happens because the tungsten filament slowly evaporates. As it evaporates, the filament diameter becomes smaller and resistance increases. At a higher resistance the lamp uses fewer watts, operates at a lower temperature, and produces less light. The evaporated tungsten condenses onto the bulb wall further reducing the lumen output of the bulb. Over its rated life an incandescent lamp depreciates about 16% in lumen output and uses about 5% less wattage, see Figure 2-18.



Source: Osram Sylvania

Figure 2-18 Incandescent Efficiency and Watt Draw

The lumen depreciation and watt draw reduction are linear with time. The diversified base power draw is a combination of incandescents in various stages of their life-span. The diversified power draw will remain constant as they burn out and are replaced.

> **PEG concludes that no change in power usage is likely in measure baseline on a diversified basis.**

Ballasts The primary functions of a fluorescent lamp ballast are to provide the voltage needed to start the lamp, 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. Most CFLs employ magnetic ballast, though electronic ballasts are becoming more popular. (Audin 1994) Most downlight manufacturers offer an electronic ballast as an option. (LRC 1995)

Analysis

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 cut parasitic 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 efficiency). 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% while lamp efficiency 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 have 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, total harmonic distortions of less than 10%, and a current crest factor 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).

Mechanisms of ballast failure are listed in Table 2-19. No common failure mode should result in increased wattage for very long. (Wolf 1997)

Table 2.19 CFL & Ballast Failure Modes

CFL & Ballast Failure Modes	Effect of Failure
Open filament in normal PF model	Cuts out ballast, no watt draw
Open filament in high PF model	Small current across the capacitor, very low watt draw
Magnetic ballast, shorted coil	Higher power draw, lamp would glow brightly and lamp would burn out rapidly
Preheat cutout failure, capacitor	Higher power, Filament would glow, no arc
Normal end of life	Ballast overheats. Thermal protection cause end of life cycling: heat up, cut-out, cool down.

Electronic ballast input wattage does not change as the lamp ages. An electronic ballast has a shut off for protection at end of lamp life. (Ng 1997)

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:

1) 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 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.

2) 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.

3) 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).

> **PEG concludes that compact fluorescent watt draw is not likely to vary due to ballast degradation.**

2.12.6. Conclusions

Overall, the investigation found no evidence to suggest that energy savings from hardwired compact fluorescent down-lights may degrade over time. The technology is believed to be quite stable.

During the lamp life the lumen output decreases, however, the watt draw remains constant. Individual incandescent lamp watt draw decreases by about 5% over its rated life; but the reduction is linear, and on a diversified basis the wattage is constant. Therefore, the CFL's energy savings remain constant.

> **PEG concludes that the energy savings from hardwired compact fluorescent down-lights are unlikely to degrade over time relative to the baseline incandescent down-lights.**

2.12.7. Estimate of Persistence

A TDF of one (1) is estimated for all years based on the conclusion that the energy use of both the efficienct and baseline measures are stable over time.

3. RESEARCH PLANS FOR ASSESSING RELATIVE TECHNICAL DEGRADATION

3.1. Overview of Research and Study Needs

Section 3 contains research plans for assessing relative technical degradation. The research plans are designed to balance the need to develop reliable answers in a reasonable time frame without effort exceeding the worth of the answers.

The plans focus on assessing the particular technical degradation mechanisms which were identified during the engineering analysis. By identifying the key performance factors and sources of uncertainty, the analysis allowed these plans to focus on just one or two critical factors. 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 nature of these projects and the uncertainty in the variances of the data.

In *Persistence 1*, two measures were found liable to experience relative degradation. This study found five. In *Persistence 2* there was a number of measures subject to previously unstudied human factors.

3.2. ASD — Injection Molding Machines

This research plan was developed to assess the potential impact of relative technical degradation of adjustable speed drives on injection molding machines. A detailed assessment of potential technical degradation mechanisms for this technology is provided in section 2.4 of this report. This plan is based on the conclusion that relative degradation may occur due to decreased operator attention or competence after the first year. CADMAC protocols do not require performance studies of industrial process end uses. This study plan was developed as a contingency.

3.2.1. Technology Description and Review of Degradation Issues

The baseline measure is an injection molding machine with a continuously operating hydraulic pump. Capacity control is provided with a hydraulic bypass valve. The efficient measure is the same injection molding machine retrofitted with an adjustable speed drive. The bypass remains in place but bypassing is minimized by adjusting the ASD.

The likelihood of energy savings degradation is increased because of several factors:

1) each production run will have unique settings for optimum energy efficiency.

2) each new operator will need additional training.

3) the original control system and bypass remain in place.

4) no adverse production problems result from a return to standard operations.

The ASD control settings must be different for each mold and resin. For savings to persist the control settings must be optimized for each specific production run. The difficulty of setting the controls properly is greater in shops with a wider variety of manufactured parts. Some ASD controllers have a memory feature that simplifies setup if the same part is produced more than once.

As operating personnel change or attention lapses control setting optimization and energy savings may degrade. Operators are accustomed to tuning machine operation by adjusting the hydraulic valves. ASDs are not commonplace in the industry. Each new operator will need to be specially trained until they are comfortable with adjusting VSD settings or they are likely to revert to standard practice.

The bypass is still necessary and must remain in place. Reversion to continuous high speed operation is simple.

Resetting controls to standard operation may be particularly problematic in IMMs because variable operation is not critical to the process. The most important production parameters are speed and quality. Neither of these suffer from continuous full speed pump operation. The only inducement for proper settings is energy savings.

3.2.2. Research Questions

The ASD and pump are fairly impervious to degradation of energy savings as mechanical/electrical devices. Degradation potential is expected in control settings. Electrical use will be influenced by the requirements of the piece in production and the control system optimization. Therefore, measurements of electrical usage alone might not accurately portray energy savings. A better parameter is a non-optimization ratio (NOR) — the electrical use divided by the minimum potential energy use for a fully optimized application. A NOR of one is maximum energy savings, a NOR of two means twice as much energy use as optimized production.

The research question is: Does the NOR change over time and if so, what is relationship between NOR and time?

3.2.3. Proposed Approach

<u>Study Methods</u> In order to obtain estimates of persistence, the non-optimization ratio needs to be measured at two or more times. An immediate estimate of degradation can be obtained by remeasuring ASDs installed and tested in the past. Several organizations, including EPRI's Adjustable-Speed Drive Demonstration Office, have installed and optimized ASDs on IMMs. Installations were often 4-6 years ago, and remeasurement will yield long-term results.

A longer term method involves multiple measurements over time (a longitudinal study). This method would produce an estimate over several years.

Proctor Engineering Group suggests a phased approach. Existing, older sites would be measured first. If the variation in NOR is sufficiently small, a reasonably accurate estimate of degradation could be generated. If there is high variability in NOR the data would have to be expanded through measurements over time.(potentially at additional locations)

<u>Data Collection and Site Visits</u> Both the initial selection of sites by EPRI and others and subsequent site selection are likely to display self selection bias. Those facilities that are most conscientious about ASD

training and energy savings might be interested in having researchers measure their efficiency. An additional confounder could be changes in operator behavior because they are being studied (a version of the Hawthorne Effect). Both of these should be addressed in the study.

Two methods of determining NOR will be used. In the first, energy use per part is measured as found. Then the production cycle is optimized for least energy use and remeasured. The ratio of these two measurements yields the NOR. This method is suboptimal since it may take considerable time to optimize the machine reducing production. The second method of measuring NOR is to monitor hydraulic oil bypass. Optimized settings minimize oil bypass. If the second phase of this research is needed, this method will be used. This method will reduce the Hawthorne Effect confounder as the operator becomes less conscious of the bypass monitoring system.

Data Analysis, Engineering Model and Results Analysis of changes in the non-optimization ratio over time will provide the basis for an estimate of the savings persistence.

3.2.4. Task List and Estimated Budget

Table 3-1 lists the key research tasks for phase 1, retesting previously optimized installations.

Table 3-1 ASD — Injection Molding Machines Research Project
Phase 1 Task List and Budget

	Budget	
Task	Low	High
Planning and Administration	8,000	12,000
Site Identification and Qualification	2,000	6,000
Data Capture	12,000	25,000
Data Analysis	4,000	6,000
Reporting	6,000	9,000
Total	**32,000**	**58,000**

3.3. Daylighting Controls

This research plan was developed to assess the potential impact of relative technical degradation of automatic daylighting controls on dimmable fluorescent lighting systems. A detailed assessment of potential technical degradation mechanisms for this technology is provided in section 2.6 of this report. This plan is based on the conclusion that relative degradation may occur due to control system malfunction and system bypass.

3.3.1. Technology Description and Review of Degradation Issues

The baseline technology is standard manually operated fluorescent lighting in an office building. The efficient measure is the office building retrofitted with photosensors controlling dimmable fluorescent lighting.

PEG has identified human interaction as the most likely degradation mechanism. Human interactions include system bypass (where the system is rendered inoperable and the lights returned to manual operation) and maladjustment where the controls are reset such that little or no savings occur. Human interactions can either improve or degrade the system performance from the first year savings.

Daylighting savings can experience mechanical degradation of the control system and degradation due to human intervention. A review of the literature indicates that initial commissioning problems are the primary reasons for failure to achieve projected savings. The same literature review indicates that human interaction is the primary post-installation degradation mechanism. A careful and thorough commissioning usually resolves initial installation problems, but comprehensive commissioning appears to occur in only a minority of installations. After installation system degradation via bypass results from attempts to eliminate operational defects.

3.3.2. Research Questions

The standard control is usually continuous operation during occupied hours. A manual control system produces stable energy use.

Existing data on savings degradation of daylighting systems points to bypass/disconnection as the primary mode of savings loss. Secondarily, dimmable ballasts are not standardized and the dimming characteristics of a replacement may be different from the original causing loss of savings or bypass (100% loss of savings). Less than optimum dimming is a much smaller effect than bypass and no study is recommended for the less than optimum dimming factor.

The research question is: What is the average, time sensitive effect on energy savings of bypass and disconnection?

3.3.3. Proposed Approach

Daylighting controls represent 7.5% of SCE's commercial sector resource value under Persistence Phase 2. No other utility has resource value associated with daylighting controls. The study would be conducted on a representative sample of SCE's daylighting control projects. Research is proposed for dimmable systems only because they are subject to a higher degree of degradation and are the defined efficient condition.

Field tests of dimmable lighting circuits would be completed at 20 different buildings with circuits aged two years or more. The anticipated degradation is catastrophic (the lamps change from being controlled to full brightness). If the proportion of control failures in the second year is the 24% projected in the analysis a sample of 20 buildings should detect the degradation (within 15.7% at a 95% confidence, one-tailed)

Study Methods The response of the dimmable circuit to an increase in light at the sensor would be tested. The circuit would be determined to be in operation or not. The proportion of inoperable systems and their age would be used to estimate the degradation curve of this measure.

3.3.4. Task List and Estimated Budget

Table 3-2 lists the key research tasks and provides low and high budget estimates for each.

Table 3-2 Daylighting Research Project - Task List and Budget

Task	Budget	
	Low	High
Planning and Administration	5,000	12,000
Site Identification and Qualification	6,000	12,000
Site Visits	25,000	50,000
Data Analysis	10,000	14,000
Reporting	6,000	8,000
Total	**52,000**	**96,000**

3.4.

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3.5. Variable Air Volume HVAC Systems

This research plan was developed to assess the potential impact of relative technical degradation of variable air volume systems in new commercial construction. A detailed assessment of potential technical degradation mechanisms for this technology is provided in Section 2.8 of this report. This plan was developed based on the conclusion that existing data was inconclusive.

3.5.1. Technology Description and Review of Degradation Issues

The baseline technology is constant air volume HVAC system (CAV) in new commercial construction. The efficient measure is a variable air volume HVAC system (VAV) in the same building.

Both CAV and VAV systems are expected to have increased energy use in years subsequent to the first because of accumulating sensor errors, equipment failures, and human interventions. .

VAV systems are likely to experience higher degradation relative to constant air volume systems due to greater system complexity, more interactive effects among building system components, and a larger number of failure mechanisms. On the other hand, constant air volume systems experience greater degradation due to comparable temperature measurement error. Which factor will predominate could not be determined. Rate and degree of degradation for both the CAV and VAV will be highly dependent on the quality of initial commissioning and the quality of operations and maintenance procedures.

3.5.2. Research Questions

There are two primary research questions. What is the relationship between VAV system efficiency and time? What is the relationship between CAV system efficiency and time?

3.5.3. Proposed Approach

HVAC energy consumption represents about 45% of total office building energy use. (Diamond 1992) Energy can be lost in three areas: production, distribution, and demand. The CAV or VAV system is the distribution system. Chillers and boilers are primary production equipment. If chiller or boiler efficiency was to degrade significantly, the energy use might dramatically increase even thought the CAV or VAV distribution system performed well. The setting of the space temperature controls can also significantly affect energy use independent of the distribution system efficiency.

Because whole building data captures production, distribution, and demand in a single measurement it is inadequate to analyze the performance of the HVAC distribution system alone. An ideal dataset for analysis would include both VAV and CAV buildings and monitored distribution efficiency for 20 years. That approach is too expensive to be considered. The proposed approach would track the deviations in critical control points over a longitudinal field study. The results of this field study would be used in simulation models to estimate the energy consumption effects of the control point changes.

Study Methods Energy use would be modeled using field measured valves for sensor error and control setting bias. The two models would be otherwise identical new office buildings — one with a CAV and one with a VAV distribution system. Critical control points would be monitored in a sample of buildings to find the frequency and degree of error. A simulation model would be used to predict the change in energy consumption resulting from field measured errors. The resultant energy consumption would be simulated over twenty years and the relative technical degradation modeled. Alternative system models informed by the field control point data could easily be run to assess the sensitivity of the results to model assumptions.

Research Methodology The recommended method to measure sensor calibration and control setting degradation is a longitudinal study of a select group of six buildings with CAV or VAV systems. Critical components within CAV and VAV air distribution systems that impact heating and cooling energy consumption, such as supply air sensor variability and bias, would be measured in field studies. A data acquisition system (DA) would be installed in the HVAC system independent of the HVAC controls. Calibrated and sensitive control point sensors on the DA system would record data side by side with building sensors. Instrumentation would initially be in place for two years. At that time, the need for additional data would be assessed.

3.5.4. Task List and Estimated Budget

Table 3-4 lists the key research tasks and provides low and high budget estimates for each.

Table 3-4 VAV Research Project - Task List and Budget

	Budget	
Task	Low	High
Planning And Administration	5,000	12,000
Site Identification And Qualification	6,000	12,000
DA Lease and Installation	24,000	50,000
Monitoring and Data Quality Assurance	25,000	50,000
Computer Simulation Modeling and Analysis	30,000	45,000
Reporting	10,000	20,000
Total	**100,000**	**189,000**

3.6. Energy Management Systems

This research plan was developed to assess the potential impact of relative technical degradation of energy management systems. A detailed assessment of potential technical degradation mechanisms for this technology is provided in Section 2.9 of this report. This plan was developed based on the conclusion that degradation may occur due to accumulating sensor error and human interventions.

3.6.1. Technology Description and Review of Degradation Issues

The baseline technology is standard manual control of an HVAC system including manually set thermostats and on/off controls. The efficient measure is an energy management system to control the same HVAC functions.

By definition, manual control systems are assumed to produce stable energy use. If building operator personnel change, the building's energy use is very likely to change — either better or worse. On a diversified basis, these changes are expected to balance and the weather corrected diversified load should remain constant.

If a sensor was initially reading correctly and settings were initially proper, sensor changes and settings adjustments could either increase or decrease the temperature in the controlled zone. If the average daily temperature in the zone is increased there is a degradation of savings from the potential. If the average daily temperature is decreased from the optimum, there are usually complaints from occupants and the temperature is adjusted. For this reason, most changes would result in increased or unchanged energy consumption. While an optimized EMS has primarily degradation potential, the literature strongly notes that most EMSs are not upon acceptance. (Petze 1996) Therefore, a significant potential exists for operation and maintenance personnel to both degrade or improve system performance.

In a longitudinal study of energy use from 28 buildings from BPA's Energy Edge Program, Diamond (1992) found that the two buildings with EMSs suffered significant reductions in energy savings in years subsequent to the first year. This initial period of degradation agrees with Tanaka and Miyasaka (1994) who found in eight buildings in Japan an initial period of low reliability which gradually entered a period of stability.

3.6.2. Research Questions

The primary research question is: What is the relationship between EMS controlled HVAC system energy usage and time from installation?

PEG has identified two areas where degradation is likely to occur: control point accuracy and human interactions. The sensor/transducer is the primary source of most data inaccuracies. All sensors are subject to drift and need periodic recalibration. Without recalibration the system is likely to respond non-optimally to changing conditions. Human interactions can either improve or degrade the system performance.

3.6.3. Proposed Approach

An EMS controls the building's HVAC equipment. Changes in the EMS and the settings will directly impact space conditioning energy use as measured at the meter. The most appropriate study is a historical analysis of space conditioning energy use for the first year and subsequent years. The billing data needs to be analyzed for weather dependence and normalized for weather and significant changes in building use. The buildings in this study should be selected so that the only space conditioning modification is the EMS system.

<u>Study Methods</u> PEG will select an initial sample of 25 buildings where EMSs were installed as part of utility conservation programs.

<u>Data Collection and Site Visits</u> An initial phone interview with operational personal will determine if major changes have occurred which would compromise the integrity of the historical data. Events such as major change of tenancy could significantly impact energy use. Major changes to the HVAC itself would also make historical data non-comparable before and after the change. Experience with other analysis of this type suggests a 60-70% drop-out rate due to data quality issues.

Historical monthly utility records will be collected for buildings that appear to offer an uninterrupted period of comparable data pre/post EMS installation. Each site will be visited at least once to verify EMS operation.

<u>Data Analysis and Results</u> A variety of analysis methods would be applied to the monthly data to estimate the change in energy consumption over time.

3.6.4. Task List and Estimated Budget

Table 3-5 lists the key research tasks and provides low and high budget estimates for each.

Table 3-5 Energy Management System Research Project - Task List and Budget

Task	Budget	
	Low	High
Planning and Administration	6,000	10,000
Site Identification and Qualification	12,000	18,000
Data Collection and Site Visits	25,000	40,000
Data Analysis	25,000	25,000
Reporting	8,000	10,000
Total	**76,000**	**103,000**

3.7. Compressors and Compressed Air Distribution Systems

This research plan was developed to assess the potential relative technical degradation of efficient compressors and efficient compressed air distribution systems. Efficient compressors would be studied together with air distribution systems because the degradation mechanism is due to the compressors influence on the distribution system. Detailed assessments of potential technical degradation mechanisms for these technologies are provided in Sections 2.10 & 2.11 of this report. This plan is based on the conclusion that relative degradation may occur due to reintroduction of standard inefficient practices, increased leakage, and equipment disrepair. CADMAC protocols do not require performance studies of industrial process end uses. This study plan was developed as a contingency.

Existing information on degradation of compressed air systems is almost universally anecdotal.

3.7.1. Technology Description and Review of Degradation Issues

Two measures would be studied, air compressors and compressed air distribution systems. For the air compressor measure, the baseline technology is an existing lubricant flooded rotary screw compressor. The efficient measure is a new higher efficiency compressor. Savings degradation could result from increased air horsepower increasing air wastage in the distribution system.

For the second, the baseline technology is a standard compressed air distribution system. The persistence study found that the baseline uses approximately 37% of the compressed air appropriately. The rest of the air is wasted by air leakage and wasteful practices. The efficient measure is the same system with major leaks and wasteful practices corrected. With this system it is estimated that 75% of the compressed air is used appropriately. The persistence of savings is expected to vary by waste/solution category. Energy savings from functional changes in distribution equipment are likely to degrade slowly. Energy savings from operational changes and leak reduction could degrade more quickly.

Experts agree that air wastage cannot be eliminated, but that it can be maintained at an acceptably low rate by a comprehensive and vigorous air management program (AMP). Current industrial culture does not support such programs. Three pieces of equipment are generally necessary to implement an AMP: an expander, flow meter, and ultrasonic leak detector. While their presence does not ensure a good air management program, their lack generally ensures its absence. Often additional compressor power is substituted for air management. This temporarily fixes the symptom, but ultimately results in more air wastage and exacerbated supply problems. Without an AMP, wastage rates for operational items are generally expected to return to or exceed pre-program levels.

Insufficient air at plant end uses causes unacceptable problems in production and quality. The lack of air is often considered a supply problem rather than an air management problem. In that case a new higher capacity compressor is often installed. The new compressor might be considered "high efficiency" and large enough to handle the load. Energy savings would be expected because of the increased efficiency. However much of the increased efficiency is just increased capacity at the same input horsepower and kW. Since the new unit can provide more air and the system had demanded more air, the pressure in the distribution lines increases. Debris in the piping enlarges the leaks by abrasion. As the leaks get bigger, air flows increase accelerating the process. When the pressure is increased by adding compressor power, the velocity of the air leaks increase which further accelerates abrasion and leak enlargement. Finally, the leakage increases until it absorbs the extra capacity, and the system operates as poorly as it did before.

Leaks reduce available point of use pressure and cause insufficient supply. If the plant has an effective air management program, the problem will be identified and repaired. The supply pressure problem would thus be corrected with no addition to the connected load.

The final goal is electrical demand and usage reduction. Compressor operating characteristics determine the relationship between air and electrical usage. If compressor operation is unmanaged, reductions in air usage may result in little if any reduced electrical usage. An AMP manages compressor operation such that reduced air usage results in corresponding reduced electrical use.

3.7.2. Research Questions

Compressed air systems involve a complex interaction between compressors, the distribution system, production end uses, and human factors. The main objective of conservation efforts is to reduce electrical usage and demand. The two primary factors expected to influence energy usage are the efficiency measure applied and whether the air distribution system is actively managed.

The primary research question is: What is the relationship between kWh, air horsepower demand, and time in service?

3.7.3. Proposed Approach

The proposed approach would measure electrical consumption, air horsepower, and air leakage horsepower.

Field monitoring would capture the full complexity of the compressed air system operation. Only the complex environment of real plant conditions will provide a measure of the various interacting factors. However, this complexity can be captured in two straightforward, robust measurements — the electrical usage and compressed air delivery.

<u>Electrical and air energy usage</u> can be readily measured at the compressor. Electrical and air energy usage will be monitored at five to ten sites that represent five classes:

1) Supply-side conservation without air management

2) Supply-side conservation with air management

3) Demand-side conservation without subsequent air management

4) Demand-side conservation with subsequent air management

5) No program involvement

Monitoring costs can be reduced by combining this effort with other work in progress (such as the PG&E air compressor program). The number and location of sites will be based on potential synergy with utility programs.

Measurement of air leakage rates Air leakage is the single largest waste category. Periodic air leakage rate measurements are part of an air management program. Obtaining and analyzing this data would provide useful information on leak generation and enlargement rates.

Engineering Model and Results The TDFs will be estimated based on engineering analysis of the field data combined with estimated population characteristics. Measured air usage data will provide estimates of the effect of adding compressor power, air wastage reduction programs, and any differentials due to the presence of an effective air management program.

3.7.4. Task List and Estimated Budget

Table 3-6 lists the key research tasks and provides low and high budget estimates for each. There is considerable uncertainty in field testing related costs because the degree to which the research can be combined with pre-existing program participation is not known.

Table 3-6 Compressed Air Systems Research Project - Task List and Budget

	Budget	
Task	Low	High
Planning and Administration	6,000	15,000
Site Identification and Qualification	6,000	12,000
DA Lease and Installation	25,000	55,000
Monitoring and Data Quality Assurance	25,000	50,000
Acquisition of existing data on monitored leakage rates	5,000	7,500
Data Analysis	15,000	25,000
Reporting	9,000	15,000
Total	**91,000**	**179,500**

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APPENDIX A

SUMMARY OF TECHNICAL DEGRADATION FACTORS

Table A-1 Persistence 2 Summary of TDFs

Section #	2.1	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12
YEAR	LED exit	ASD Pump	ASD IMM	Wall Floor Insul	Day Lighting	Ag Pump	VAV	EMS	Cmpr w/o AMP	CADist w/o AMP	CFL Downlite
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	1.00	1.00	0.98	1.00	0.76	1.00	1.00	0.80	0.69	0.85	1.00
3	1.00	1.00	0.91	1.00	0.66	1.00	1.00	0.60	0.48	0.70	1.00
4	1.00	1.00	0.74	1.00	0.58	1.00	1.00	0.40	0.33	0.55	1.00
5	1.00	1.00	0.57	1.00	0.51	1.00	1.00	0.20	0.23	0.40	1.00
6	1.00	1.00	0.50	1.00	0.46	1.00	1.00	0.10	0.15	0.25	1.00
7	1.00	1.00	0.48	1.00	0.41	1.00	1.00	0.10	0.10	0.25	1.00
8	1.00	1.00	0.47	1.00	0.37	1.00	1.00	0.10	0.07	0.25	1.00
9	1.00	1.00	0.47	1.00	0.34	1.00	1.00	0.10	0.05	0.25	1.00
10	1.00	1.00	0.47	1.00	0.31	1.00	1.00	0.10	0.03	0.25	1.00
11	1.00	1.00	0.47	1.00	0.29	1.00	1.00	0.10	0.02	0.25	1.00
12	1.00	1.00	0.47	1.00	0.27	1.00	1.00	0.10	0.01	0.25	1.00
13	1.00	1.00	0.47	1.00	0.26	1.00	1.00	0.10	0.01	0.25	1.00
14	1.00	1.00	0.47	1.00	0.24	1.00	1.00	0.10	0.01	0.25	1.00
15	1.00	1.00	0.47	1.00	0.23	1.00	1.00	0.10	0.00	0.25	1.00
16	1.00	1.00	0.47	1.00	0.23	1.00	1.00	0.10	0.00	0.25	1.00
17	1.00	1.00	0.47	1.00	0.22	1.00	1.00	0.10	0.00	0.25	1.00
18	1.00	1.00	0.47	1.00	0.21	1.00	1.00	0.10	0.00	0.25	1.00
19	1.00	1.00	0.47	1.00	0.21	1.00	1.00	0.10	0.00	0.25	1.00
20	1.00	1.00	0.47	1.00	0.20	1.00	1.00	0.10	0.00	0.25	1.00

APPENDIX B

SUMMARIES OF FINDINGS AND RECOMMENDATIONS

B.1 LED Exit Sign

PEG concludes that savings from LED Exit signs are unlikely to show relative technical degradation over time.

Lumen depreciation determines the service life of the LED. Many manufacturers' claims are misleading or inaccurate. Retention studies are recommended to determine the actual life for the measure.

Retention Study The service life of LED exit signs is rated by manufacturers between 20-500 years. The rate of lumen degradation is largely controlled by the design because it is related to the current density. New LED types have not been in service long enough to obtain service life data except from accelerated testing. After some period of time, sign brightness will fall below a safe level and the sign will cease to be operable.

Participating utilities estimate the useful life of LED exit sign as follows:

- PG&E 16.0 years
- SDG&E 12.0 years
- SCE 15.0 years

PEG recommends a study to determine the average service of installed units.

A single survey of buildings could be conducted. If chosen from different program years, the LED exit sign ages would vary between the buildings. The building survey would determine if the program exit sign were still in service.

Several aspects of the definition of "in-service" would need to be clarified. If the original sign is present and glowing but too dimly and should be replaced for safety reason, is it still in-service? If the original LED exit sign was replaced with a newer LED exit sign, is that still in service?

B.2 ASD General

PEG concludes that increases in energy consumption due to technical degradation of an ASD are unlikely.

PEG concludes that 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 technical degradation studies on specific measures.

Technical Degradation Study Sensor and control setting changes, including system bypass, may significantly affect the persistence of ASD savings. Since most systems were designed and successfully operated with constant speed, the system will operate with the ASD turned off. If the operator is insufficiently familiar with the ASD control or unusual problems develop after the ASD installation, there may be a tendency to suspect or blame the ASD for performance problems. It could then be bypassed as an attempt to solve the problem. Even if the problem is later discovered to have a different cause, the ASD may not be returned to operation. The operation of closed loop pumps may be particularly prone to sensor or control setting changes. If the changes result in less flow, delivery problems would result and the operation would be corrected. If changes result in higher flow rates, no problems might be detected so corrective action might not occur.

On-the-other-hand, some operator might gain experience with the ASD's interaction with their system and be able to fine-tune the system over time. This would result in a gradual increase of energy savings over time.

The potential for degradation would be dependent on site characteristics. Operations where flow rates are not visible and/or higher flow rate cause no operational problems would be more susceptible to this effect than others.

B.3. Adjustable Speed Drives — Waste Water Pumps

PEG concludes that when operated by an ASD pump efficiency will be maintained over a longer period than the baseline application. A pump driven by an ASD controlled motor is likely to experience negative relative technical degradation due to decreased pump wear.

While sensor and control setting changes and system bypass may significantly affect the persistence of ASD savings, the application to waste water pumping is relatively unsusceptible to such problems and no degradation of savings is expected.

PEG Recommendation No technical degradation is expected on ASD applications to waste water pumping. No further studies are recommended.

B.4. ASD — Injection Molding Machine

PEG concludes that ASD control settings during mold setup may affect the persistence of ASD savings on injection molding machines if the level of operator attention or competence drops after the first year savings are measured. This should be investigated through measure technical degradation studies.

PEG Recommendation Operator control and sensor feedback of injection molding machines may degrade towards less energy savings. Energy savings degradation could occur without negative impact on production rates or quality, the most important production parameters. A study of technical degradation is recommended.

B.5. Wall and Floor Insulation

PEG concludes that savings from wall and floor insulation are unlikely to show any measurable amount relative technical degradation after the first year.

PEG Recommendation PEG does not recommend additional studies on wall and floor insulation

B.6. Daylighting Controls

PEG concludes that the energy savings from dimmable daylighting systems are likely to degrade over time due primarily due to control problems resulting in system bypass.

PEG concludes that the achievement and persistence of energy savings from daylighting systems are likely to be highly variable between different installation due to commissioning factors and human factors.

PEG concludes that switched and stepped daylighting systems are have few degradation mechanisms and are less subject to degradation than dimmable systems.

PEG Recommendation Control problems and system bypass may lead to energy savings degradation. A study of technical degradation is recommended.

B.7. Agricultural Pumps

PEG concludes that abrasive qualities of well water significantly degrade the efficiency of agricultural pumps over time.

PEG concludes that the efficiency versus service life curve for agricultural pumps was not fully characterized in pre-existing sources. PEG's own analysis of a utility pump test database indicates negative relative degradation.

PEG Recommendation An estimate of technical degradation was derived. No further studies are recommended.

B.8. VAV on HVAC

PEG concludes that both CAV and VAV systems are likely to experience degradation over time. Competing factors favor greater persistence in each system type Relative degradation rates are unknown.

PEG Recommendation Both CAV and VAV system are likely to experience increased energy use over time. Data on relative degradation is inconclusive. A study of technical degradation is recommended.

B.9. EMS

PEG concludes that performance studies indicate significant potential for positive or negative relative degradation of energy savings from energy management systems. Difficult to quantify human factors appear to be the main determinant of performance.

PEG Recommendation Filed studies indicate significant changes in energy use over time but the dataset is too limited to derive a reliable estimate of persistence of savings. A study of technical degradation is recommended.

B.10. Air Compressors

PEG concludes that relative technical degradation between existing air compressors and replacement air compressors is unlikely. However, energy savings degradation may result if new air compressors increase losses in the distribution system and end uses.

PEG Recommendation Compressor initiated increases in air wastage may lead to energy savings degradation. A study of technical degradation is recommended.

B.11. Compressed Air Distribution Systems

PEG concludes that energy savings from changes in the distribution and use of compressed air varying greatly in potential persistence. Persistence of energy savings may be significantly affected by maintenance practices

PEG Recommendation Quantitative information on which to base estimates of persistence is lacking. A study of technical degradation is recommended.

B.12. CFL

PEG concludes that there is no increase in power usage expected during the life of the CFL. PEG concludes that there is no change in power usage expected in measure baseline on a diversified basis. PEG concludes that savings from CFLs are unlikely to show relative technical degradation over time.

PEG Recommendation Retention issues are expected to be minimal for hard-wired units. PEG does not recommend additional studies on hard-wired compact fluorescent downlights.