TASK 4.2

INVESTIGATE IDEAL LAMP LIGHT OUTPUT DIMMING RATIO REQUIRED FOR DIFFERENT TYPES OF APPLICATIONS

Introduction

The overall scope of this project funded by the US Department of Energy (DOE) is to recommend means of reducing barriers to the wide spread use of lighting controls for commercial/industrial (C/I) applications using fluorescent systems. It is important to note that this project is focused on load-shed applications and photoelectric dimming where energy savings and energy management are of central concern. The project does not address architectural dimming found in many conference rooms or residential applications where multiple visual functions requiring different light levels (e.g., audio-visual presentations, conferences) are required to meet occupant objectives. This particular task (4.2) is concerned with switch-dimming, step-dimming and continuous-dimming in spaces dominated by electric lighting. Switch-dimming is switching one or more lamps off within a luminaire; step-dimming is dropping power to all lamps within the luminaire. In every case, the discussion is limited to linear, T-8 fluorescent lighting systems operated with electronic ballasts. Although, consideration of daylight from windows and skylights is implicitly excluded from this task because, ideally, an occupant will not perceive reductions in light levels if a successful photoelectric dimming system is installed, the system performance discussion is applicable to photoelectric dimming as well.

Economic rationale

There are two, essentially distinct economic considerations with regard to the ideal dimming ratio. First, it must be acknowledged that lighting is introduced into C/I applications to meet human needs. It is assumed that dimming to lower light levels must not lead to a significant drop in human performance or satisfaction. Since occupant salaries and benefits dominate building economics, dimming must not have a measurable negative impact on their performance or their satisfaction. The first goal for this task is to develop a justification for dimming to lower light levels that does not significantly affect occupant performance and satisfaction. The following sections “Lighting to meet human needs” provides this justification. Second, given the first consideration, lighting system decisions will be driven by technical considerations that minimize system costs. There are many factors that affect life-cycle costs of a lighting system including, first costs, energy (kWh) costs, demand charges, load management benefits, lamp replacement costs, and disposal costs; these can be described as energy, capital and maintenance costs. As will be discussed in the section “Lighting system performance”, there are several strategies to minimize the life-cycle costs of lighting systems. These economic factors will be optimized differently for new construction, renovation, or retrofit. (Changes in legislation can also significantly affect lighting economics, but these are not addressed in this task.) The second goal for this task is to develop an economic justification for dimming (switch, step or continuous) from what we currently understand about linear T8 fluorescent system performance and costs.

Lighting to meet human needs

Prescribed illuminance levels are offered by sanctioning bodies such as the Illuminating Engineering Society of North America (IESNA) (Rea, 2000). It is formally acknowledged by the IESNA that a prescribed illuminance for nominally identical spaces will, in practice, vary. Naturally, photometric measurements show statistical variation and, moreover, humans are poor detectors of small changes in light levels, measured either in terms of subjective judgments of brightness or of objective measures of performance. Several recent studies by Kryszczuk (2001), Shikakura et al. (2001) and Akashi et al. (2002a, Appendix 2-A) found that people cannot reliably perceive reductions of up to 20% from the original illuminance level. A series of experiments by Rea and his colleagues (1986, 1987, 1991) show visual performance, defined in terms of speed and accuracy of processing visual information, does not vary by more than a few percent for most reading materials found in commercial spaces (Dillon et al., 1987). Since variations in visual performance are small for the range of illuminances presently recommended (300 to 1000 lx), task performance, which is dependent upon many non-visual factors, will vary even less (Boyce and Rea, 2001). Moreover, Rea et al. (1985) showed that people will perform compensatory behaviors (e.g., moving closer to the task) to ensure good performance while performing visual tasks. These studies indirectly support the IESNA position that variations of +/- 33% from the recommended illuminance can be considered as “the same” light level. Since these empirical data and the IESNA recommendations are consistent, it is reasonable to expect that occasional, modest dimming of the lights to lower levels to save energy or reduce electrical demand will be accepted by occupants and will not affect their performance.

The IESNA also acknowledges variations in the difficulty of visual tasks performed in spaces as well as variations in the visual needs of different individuals. Further, there will always be some statistical uncertainty in any behavioral measurement. This provides still greater potential opportunity for dimming while continuing to meet occupant visual needs. Nevertheless, it must be acknowledged that for every opportunity to reduce recommended light levels, and thereby reduce energy or manage load, there is a risk that these reductions can penalize certain individuals performing certain visual tasks. Without question a dimming strategy can only be satisfactorily realized if those individuals and visual tasks are considered. This point is entirely consistent with the IESNA recommendations that lighting specifiers should not apply general recommendations without understanding the visual requirements in a specific application.

It is also important to realize that people are not rigid with regard to their preferences for changes in light level, even when the magnitude of those changes is reliably perceived. For example, most people find very dim lighting in high-end restaurants acceptable but, for nominally identical visual requirements, prefer much higher illuminance levels in cafeterias or lunchrooms. In a simulated commercial space, Akashi et al. (2002b, Appendix 2-B) showed that 80% of the people in his study would accept dimming to 62% of the original light level (a 38% reduction, from 500 lx to 310 lx). It is also clear that certain biases can be introduced into subjective judgments for one type of application, even in the same building space. For example, occupants will set illuminances in residential dining rooms to different levels depending upon the situation. Illuminance levels while feeding the family in the dining room will be typically higher than those while entertaining guests. In a simulated commercial space, Akashi et al. (2002b) showed that 80% of the subjects in his study were willing to accept dimming to 46% of the original light level (a 54% reduction, from 500 lx to 230 lx) under conditions where they felt they were helping their employer financially and helping the environment, both locally and globally.

As argued at the end of this task report, the evidence suggests that occasional dimming by 33% will be readily acceptable to occupants and, if the purposes for dimming were explained well, occupants would also accept dimming by 50%.

Lighting system performance

Lighting system economics are judged on several performance characteristics that can be characterized as energy, capital, and maintenance costs. Ideally, lighting systems will be chosen based upon a life cycle cost analysis that minimizes energy, capital and maintenance costs over the life of the system while maintaining lighting design objectives. Before the wide spread introduction of T-8, electronic ballast lighting systems in the 1990s, lamp-ballast system performance was fairly well understood and consistent among the various T-12 lamp and magnetic ballast manufacturers. This consistency provided good predictions of the life cycle costs of fluorescent lighting systems. Today, however, the characteristics of different T-8 lamps and electronic ballasts have become so idiosyncratic that it is difficult to predict lamp life, one of the most important performance parameters for estimating life cycle costs. This difficulty is significantly exacerbated when one considers dimming fluorescent lighting systems.

As with the older T-12, magnetic ballast systems, the life of modern T-8, electronic ballast systems will still be governed by how the ballast controls heat to the lamp electrodes during starting and during operation. Specifically, the failure of fluorescent lamps is caused mainly by the loss of electron emissive coating of the lamp electrodes, either by sputtering or by evaporation (Verderber, 1985; Waymouth, 1971). (Although under certain circumstances, such as high frequency operation and frequent starting on instant start ballast ("cold ignition"), fracture of the tungsten coil is also observed which cause the lamp fail (Haverlag, 2002)). Very high electrode temperature (greater than 1000 ^{o}C) will reduce lamp life due to evaporation of the emitting material, and a low electrode temperature (less than 700 ^{o}C) will reduce lamp life due to erosion of the emitting material by sputtering (Davis and Ji, 1998). The precise optimization of temperature within this range is presently unknown as well as spatial-temporal effects of dimming electrodes, and this uncertainty is likely the reason for the idiosyncratic performance of different lamp and ballast combinations.

Modern high frequency ballasts for fluorescent lighting systems have improved efficiency significantly, and recent advances in ballast control of lamp starting has demonstrably improved lamp life by reducing sputtering. Some improvements in lamp filament design have also occurred, but the electrical optimization of fluorescent lamps for extended life has changed little since the 4-foot T-12 design was established in the 1930s (Waymouth, 1971). For the most part, ballast and lamp developments have occurred separately, each taking advantage of the new technology as it became available. These parallel developments by different manufacturers have added to the complexity and uncertainty in lamp-ballast performance, specifically lamp life. Moreover, little is known outside the lamp manufacturers about lamp life during dimming.

Dimming Methods

There are two approaches to dimming lamps within a building space, dimming all the lamps by a fixed amount or switching off some of the lamps. Although there is still much to learn about how lamp-ballast system combinations affect lamp life, much more is known about the impact of switching on lamp life than about the effects dimming on lamp life.

It is well established that on-off switching of fluorescent lamps will reduce lamp life (O'Rourke and Figueiro, 2000; Carriere and Rea, 1988). Sputtering is the primary failure mechanism associated with starting, and, except for very special cases, lamp life will be shorter the more frequently the system is switched on and off. Broadly, there are two ways to switch a lamp, with or without application of heat to the electrodes before starting. In general, heating the electrode before starting will reduce sputtering and thereby increase lamp life.

Instant start systems apply a high voltage across the lamp electrodes to start the lamp. These "cold starts" have been shown to increase sputtering of emissive coating on the electrodes which leads to shorten lamp life compared to continuous operation. Rapid start and program start systems apply heat to the electrodes prior to starting to minimize sputtering. Although the distinction between instant start and rapid start systems was useful for older T-12, magnetic ballast systems, this distinction is less clear today with T-8 electronic ballast systems. Empirical evidence has shown that lamp life is not significantly different for rapid start and instant start electronic ballast systems (Davis and Ji, 1998). The reason appears to be that although there is a distinction in how rapid start and instant start systems, as separate groups, actually start the lamps, there is little, if any, impact on lamp life. Although there is no formal definition for program start, commercially available systems called program start, in fact, control electrode heating prior to starting and significantly increase lamp life (Davis and Ji, 1998).

Switch-dimming can occur external to the ballast utilizing separate electrical circuits or with multiple-lamp ballast. Switch-dimming can be accomplished with tandem wiring ballasts of adjacent fixtures or with ballasts that control multiple lamps within a fixture. Separate electrical circuits, one of which could receive a signal to shed load, could supply these ballasts. This option is independent of the ballast, and any ballast type could be used, but this approach may be a better solution for new construction or a major renovation because rewiring an existing installation would not be cost effective. It is also possible to switch lamps independently of each other with multiple-lamp ballasts. Turning off one lamp in a two-lamp, three-lamp, or four-lamp ballast results in 50%, 33%, or 25% dimming, respectively. Lamp life will, of course, depend on the frequency of switching, but it will also depend upon the particular lamp-ballast combination used, and although the relationship between switching and lamp life is better understood than the impact of step- or continuous-dimming on lamp life, there is still great uncertainty in predicting lamp life and, thus, life cycle costs.

The impact of continuous- and step-dimming on lamp life is less well known, as previously mentioned. However, the principles affecting lamp life remain the same. Namely, electrode heating is the key issue to consider during lamp operation in the dim mode. Filament temperatures below approximately 700°C will be associated with sputtering of the filament emissive coating, whereas temperatures above 1000°C will be associated with evaporation of the emissive coating. Between these two temperatures, the spatial-temporal effects of dimming are not well understood.

Rapid start and program start ballasts are currently the only ballasts used for dimming. These ballasts add heat to the electrodes while operating, as well as for starting, to minimize sputtering and extend lamp life. Dimming ballasts account for about 1% of the fluorescent ballast market, presumably because of their relatively high cost. An instant start ballast sells for between $8.00 and $15.00, while a dimming program start ballast, the most expensive type, may cost well over $50.00. These ballasts also use more energy at full light output than an instant start ballast because of electrode heating and the additional dimming interface circuitry, they may save energy relative to fixed-level systems if they are dimmed to at least 15% of full light output.

Instant start ballasts make up 80% of the market of electronic ballasts sold today. This ballast design is the simplest and the cheapest, which is why it is also the most prevalent. Instant start ballasts do not provide heat to the filaments while starting or operating the lamps when dimmed. The lower filament temperatures of instant start systems are believed to cause greater sputtering of emissive coating from the lamp electrodes, which leads to shorter lamp life.

This logic would preclude the development of instant start dimming ballasts and, indeed, an instant start dimming ballast cannot be found in the specification market. Consider, however, that ballast factor simply describes the fixed level of dimming offered by the instant start system. Since manufactured ballasts with different ballast factors have the same rated life, it should be possible to actively dim instant start ballasts within the range of currently manufactured ballast factors.

Ballast factor (BF) is the ratio of the light output of a lamp or lamps operated by a specific ballast to the light output of the same lamp(s) operated by a reference ballast. BF can range from 0.73 to 1.50 (Lighting Research Center, 2000). Thus, the range of “fixed” dimming currently offered by instant start systems is 73% (0.73/1.00) or 49% (0.73/1.50), depending upon the ballast used as the reference. Again, however, there appears to be a wide range of continuous- or step-dimming instant start systems that are possible, but active dimming with these systems has not been explored. Naturally, the big advantage of instant start dimming is the relatively low cost of the ballast. If it could be shown that lamp life was not significantly affected by continuous- or step-dimming of instant start systems, then the life cycle cost of dimming would be significantly reduced, due to the low initial costs and high efficacy over the life of the system.

As mentioned several times, there remains uncertainty about the performance of switching modern electronic lamp-ballast systems. Dimming systems are even less well understood and there are no standards to guide the manufacturers or the specifiers to ensure satisfactory system performance. It is beyond the scope of this section to describe the physics of electrode heating, but it can be emphasized that reducing filament heat during dimming is a distinctly non-linear process, exacerbated by variations in manufacturing. So called “deep dimming” without heating the electrodes certainly adds complexity to the issue of dimming, but it appears that dimming by 33% or, perhaps, even 50% may have no measurable impact on lamp life, for short periods of time (less than 100 hours/year).

The optimum dimming ratio

The optimum dimming ratio will be driven by maximizing lighting system performance while minimizing negative impacts on occupants within the building space. Human factors research suggests that occupants have difficulty in detecting dimming of 20% from recommended levels of illuminance, and that the majority (80%) of people will readily accept dimming of 33%. Moreover, under some conditions the majority (80%) will accept dimming of 50% (Akashi et al., 2002a and 2002b). As noted several times, there are some uncertainties about lighting system performance with electronic ballast systems not found with the older, obsolete magnetic ballast systems. Without question more research is needed to understand lamp-ballast interactions before a precise optimum dimming ratio can be deduced. Nevertheless, it is useful to develop some interim recommendations that could lead to more widespread use of technologies that should improve life cycle cost of fluorescent dimming systems through lighting controls.

Perhaps the most obvious approach is to utilize existing program start systems that maintain electrode heating during dimming. The major strength of this approach is that these systems ensure customers will achieve rated lamp life. They can also serve as a platform for “deep dimming” for maximizing photoelectric and user-controlled dimming, as well as any other control strategy. The largest barrier to this approach is that these systems are expensive to purchase, and they are slightly more expensive to operate because they have slightly higher energy expenditures due to lamp electrode heating. Since clear economic benefits of photoelectric dimming and of user-controlled dimming have yet to be established, this strategy will probably continue to capture only a few percent of the market.

A more cost effective strategy is switch-dimming, either with different circuits or with ballasts that switch out certain lamps. This approach reduces initial cost considerably but does not allow for added functionality achieved by the program start dimming system. If added functionality is not required, or expected, a switch-dimming approach appears to be a very logical line of development. It should be noted, again, that the effect of switching on lamp life is better understood, but there is still some uncertainty in the performance of electronic ballast and lamp systems and more research should be undertaken. There is also some uncertainty to this approach regarding user acceptance. One objection to switch-dimming and to step-dimming is that occupants have been shown to be dissatisfied with sudden transitions in light output (Boyce, 1984). Another objection might be that occupants do not like to see luminaires with deactivated lamps. Nevertheless, as shown by Akashi (2002b), it may be possible to adjust occupant expectations such that switch-dimming can be acceptable under some circumstances, but this has yet to be shown.

Another approach to dimming that has not been properly explored is continuous- or step-dimming of instant start systems. The largest appeal to this approach is that these systems are the least expensive. Strategies for new construction and retrofit would seem to be cost effective if it was established that modest dimming to no more than 50% of maximum light output for less than 100 hours/year did not significantly affect lamp life. Preliminary evidence from our laboratory suggests that operating lamps in a dimmed mode (90 mA, or a ballast factor of 0.44) is in fact possible for periods of time longer than 100 hours/year. Certainly, commercially available ballasts with a ballast factor of 0.73 are warranted at rated lamp life, so operating them at 27% dimmed mode (BF of 1.00) appears to be readily achieved without significantly affecting lamp life.

Whatever approach is taken, it would be useful to standardize on dimming levels. We recommend that the industry standardize on 33% and 50% dimming. Both the lighting system performance data and the human factors data suggest that that these values will have minimum negative impacts on lighting system performance and on occupant satisfaction and performance. The major advantage of this standard would be to accommodate switch-dimming of two, three and four lamp systems as well as both instant start and program start dimming systems, utilizing either continuous- or step-dimming.[3] Naturally, the cost of dimming will vary depending upon the lamp-ballast system, but every approach can be accommodated by this standard. The marketplace will determine which system will ultimately be more attractive.

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[3] It must be noted, however, that dimming light levels is only equal to dimming power for switch-dimming and for continuous- or step-dimming without electrode heating (i.e., instant start systems). For the same reduction in power using electrode heating (i.e., rapid start or program start), the light levels will always be relatively lower than they will be for instant start systems.

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