# TASKS 4.3, 4.4, 4.5
# INVESTIGATION OF THE EFFECTS OF DIMMING ON FLUORESCENT LAMP LIFE

## Introduction

The overall objective of this project is to identify and seek to reduce the barriers to wide acceptance and use of energy-saving daylighting, electric lighting, and control technologies, including occupancy sensors, photosensors, dimming electronic ballasts, and whole building integrated control systems. The following are detailed descriptions of the scope of work from tasks 4.3, 4.4, and 4.5:

- **Task 4.3** – Investigate critical performance factors, such as optimal electrode voltage vs. percent rated current required maintaining electrode hot spot temperature. The focus will be on popular 32 Watt, T8 lamps, and on the performance of rapid start dimming ballasts.
- **Task 4.4** – Investigate impact on lamp life of starting lamps when dimmed, i.e., at lower than rated current. This is related to lamps starting under dimmed conditions.
- **Task 4.5** – Investigate the allowable dimming range that can be achieved without additional electrode heating voltage. This will enable lower cost, instant start, dimming ballasts for load shedding, lumen maintenance, etc. This task requires investigation of instant start, dimming ballasts for load-shedding applications.

Overall, these three tasks require the LRC to investigate the interaction between dimming ballasts and fluorescent lamps, and to identify the impacts of dimming on fluorescent lamp life. This knowledge will be used to help reduce the barriers to widespread use of electronic dimming ballasts.

The first section reviews research on the topic of fluorescent lamp failure mechanism, electrode characteristics, ballast operation and starting on lamp life. This section provides necessary background information on fluorescent lamps, ballasts, and their interactions. The sections that follow relate directly to specific tasks as follows:

The section, ***Optimum electrode heating as a function of the discharge current***, provides a direct answer to Task 4.3, detailing how dimming affects fluorescent lamp life and how to reserve dimmed lamp life by supplying optimum electrode heating.

The section, ***Impact on lamp life of starting lamps when dimmed***, focuses on task 4.4, providing theoretical analysis and laboratory testing on how starting lamps when dimmed may reduce lamp life.

The section, ***Allowable dimming range without additional electrode heating***, investigates the allowable dimming range that can be achieved without additional electrode heating voltage. These results are a direct answer to task 4.5.

***Appendix-4.3 - A*** presents a market analysis for load-shedding ballasts, which is needed in task 4.5 in order to decide the allowable dimming range in such applications.

## Fluorescent Lamp Life

### Lamp failure mechanism

The failure of fluorescent lamps is caused mainly by the loss of the electron emissive coating of the lamp electrodes (den Hoek, 2002, Verderber, 1985, Waymouth, 1971). Under certain circumstances, such as high frequency operation and frequent starting on instant start ballasts (“cold ignition”), fracture of the tungsten coil is also observed, which causes the lamp to fail (Haverlag, 2002). Electrode temperature directly affects the evaporation and erosion of the emitting material and thus the lamp life. A very high electrode temperature (greater than 1000 ºC) will reduce lamp life due to evaporation of the emitting material, and a low electrode temperature (less than 700 ºC) will reduce lamp life due to erosion of the emitting material by sputtering (Ji, 1998).

With the introduction of low-mercury content lamps it is possible that lamp life, when over 20,000 hours, might also be influenced by a reduction of available mercury within the lamp. Since there is a strong movement in the industry to limit the mercury content of fluorescent lamps, some new lamp designs are manufactured with near the minimum amount of mercury needed for an efficient mercury discharge. Over time, free mercury in the lamp bonds to other materials within the lamp envelope, especially the sputtered and/or evaporated electrode material that gets deposited over the inside lamp walls (*personal conversation with lamp manufacturer representative*). For lamps with excess mercury added, mercury absorption is not an operational problem because the lamp electrodes limit life before the excess available mercury is removed. However, lamps with marginal amounts of mercury dosing, combined with severely sputtered and/or evaporated electrodes may show different end-of-life behavior.

## Electrodes for fluorescent lamps

### Electrode characteristics

Fluorescent lamps operated on alternating current have two identical electrodes that serve alternately as the anode and the cathode. The electrode at the negative end of the tube (the cathode) and its associated discharge region (the negative glow) serve the function of injecting the necessary electron current into the discharge column. The positive electrode (the anode), on other hand, must extract electrons from the discharge column at the other lamp end. The sketch in **Figure 1** (Waymouth, 1971) identifies the main discharge regions and electric potentials for a fluorescent lamp.

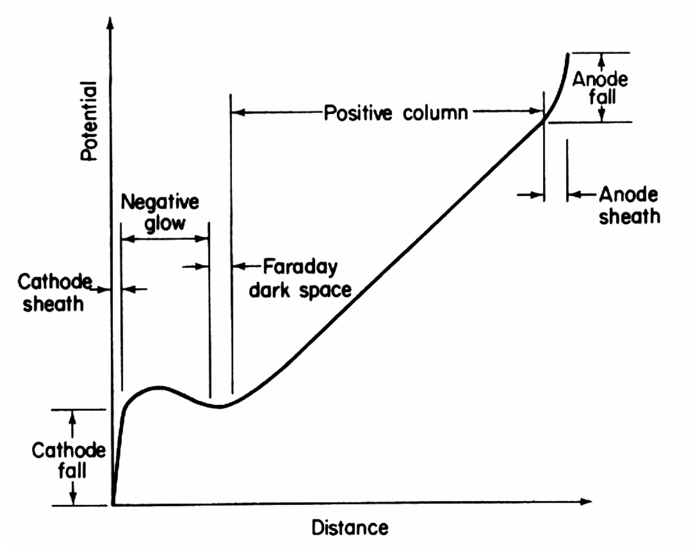


*Figure 1. Sketch identifying the main discharge regions and potentials across them (Waymouth, 1971)*

Fluorescent lamps used for general lighting applications are known as hot cathode lamps. These are different than cold cathode lamps used for “neon” signs and other special applications. Hot cathode lamps produce light much more efficiently than cold cathode lamps. Hot cathode operation is what is generally referred to as fluorescent lighting. Therefore, this discussion will consider only hot cathode lamps.

Electrode temperature is an important factor that affects lamp operation and life. The majority of the electrons emitted by the cathode result from the process of thermionic emission, whereby thermally excited electrons have enough energy to free themselves from the material. The work function is a property of a material that determines the energy needed for an electron to escape the material. Fluorescent lamp electrode filaments are coated with an emission mix, made from calcium (Ca), barium (Ba), and strontium (Sr) oxides, that has a very low work function, ranging from 0.9 to 1.1 eV, compared to that of the bare tungsten filament whose work function would be about 4.5 eV. For coated filaments, temperatures of about 900 °C are high enough to create thermionic emission of electrons sufficient for the discharge current. Without the emissive coating, thermionic emission is insufficient for the discharge current, which, if maintained, would lead to the destruction of the electrode and lamp failure.

The emissive coating on the electrodes is removed by two processes: evaporation and sputtering. Evaporation is the continual, temperature dependent removal of material into the low pressure atmosphere inside the lamp envelope. The removed material is deposited on nearby cooler surfaces, such as the lamp wall, that results in lamp end-darkening. Sputtering is the removal of material by the impact of positively charged ions accelerated toward the cathode. Sputtered material also gets re-deposited on nearby surfaces, including the electrode.

Operating life, therefore, is limited by evaporation and sputtering of electrode coating. If the electrode temperature is too high, lamp life is reduced by evaporation of the emissive coating. While a low electrode temperature will reduce the evaporation of the emissive coating, it may increase lamp electrode sputtering. Sputtering increases at low electrode temperatures because alternate processes take the place of thermionic emission for generating the supply of electrons for the discharge. These processes require a drop in electric potential adjacent to the electrode, which is responsible for accelerating ions, which impact the electrode. This drop in electric potential is called cathode fall voltage. Near end of life, when the emission mix is depleted from the electrode filament, the work function of the electrode material increases up to about 4.5 eV, that of bare tungsten. To sustain the discharge, the sharp drop in electric potential at the cathode increases dramatically to aid in extracting electrons. Large increases in cathode fall voltage result in either catastrophic sputtering of the electrode, or the ballast failing to sustain or initiate the discharge due to the higher overall lamp voltage.

## Cathode fall voltage

Cathode fall voltage is a fundamental property of the discharge and always indicates the electrode sputtering level (Hammer, 1995). Cathode fall voltage is the drop in electric potential from the cathode to the end of the cathode sheath region; a distance of about 0.1 mm. The cathode fall voltage accelerates the electrons emitted from the electrode toward the lamp arc stream and enables ion generation when these accelerated electrons collide with the mercury and argon atoms in the gas atmosphere of the lamp. Once produced, these ions are accelerated by the cathode fall voltage and strike the cathode. The ion bombardment heats the cathode surface, raising the electrode temperature and increasing the emission of electrons. High cathode fall voltage will cause ions to strike the cathode so forcefully that a great deal of emissive coating sputtering occurs. Alternately, low cathode fall voltage indicates an abundance of free electrons from which the rate of thermionic emission is high. This implies that the electrode is operating at an excessively high temperature with a high electrode-evaporation rate that eventually will shorten lamp life.

Theoretically, the thermionic emitting properties of the electrode can be used to indicate cathode fall voltage and the resulting degree of sputtering during lamp operation. The cathode at its operating temperature with no external electric field has a certain thermionic emission of electrons, called zero-field thermionic emission. A higher zero-field thermionic emission, implies little or no sputtering. Several researchers developed different methods to measure the zero-field thermionic emission and electrode temperature, while other researchers developed models to predict these values (Waymouth, 1971, Soules et al 1989, Watanabe 1995). However, these researchers never related their measurement to real lamp-life data. Thus, it is still not clear how these properties relate to fluorescent lamp life. Research on cathode fall voltage has progressed beyond measurement and models to relate the cathode fall voltage data to lamp life (Hammer 1989 and 1995, Misono 1992, Watanabe 1993).

**Figure 2** shows the postulated lamp-life relationship with cathode fall voltage. **Figure 3** shows Misono's data on the relation between cathode fall voltage and lamp life for experimental lamps. At 60 Hz operation, the acceptable range of peak cathode fall voltage is approximately 11.0 to

14.5 V. However under high frequency operation (>20 kHz), this range will be as low as 7 to 10V (Hammer 1989).

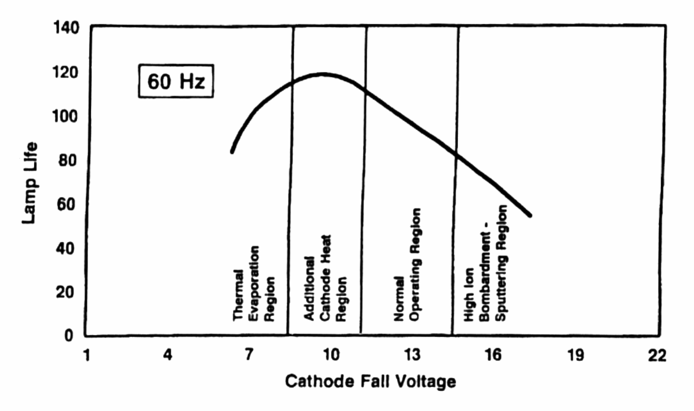


***Figure* 2.** *Postulated lamp life (%) vs. cathode fall voltage (V) at 60 Hz (Hammer, 1995)*

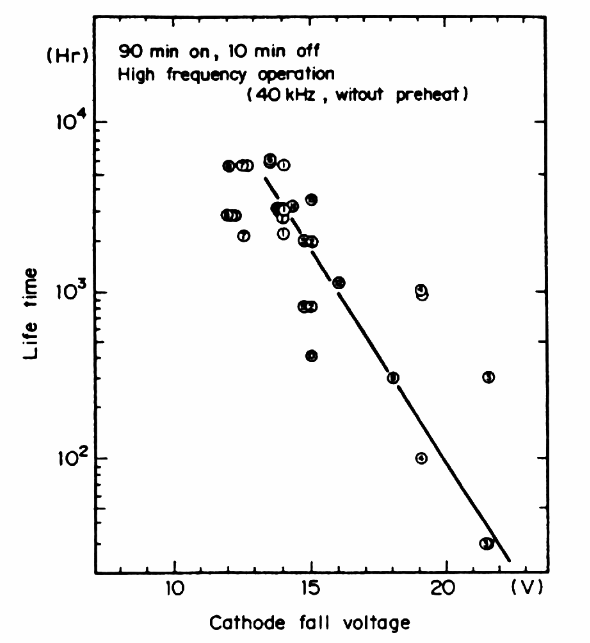


***Figure* 3.** *Relationship between lamp life and cathode fall voltage (Misono, 1992)*

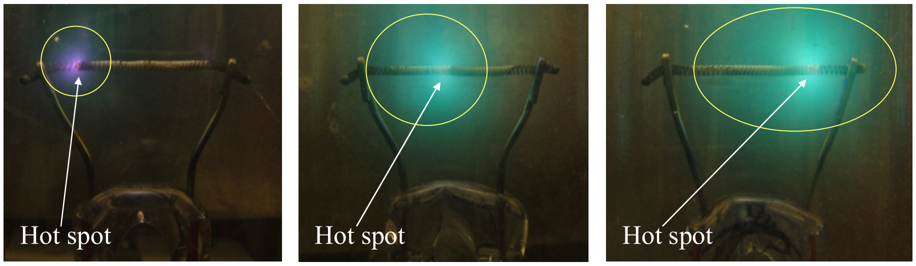
## Electrode thermal model

In alternating current (ac) operation, when no separate heating of the cathode is provided, most of the cathode heating arises from electron bombardment during the half-cycle when the electrode is acting as anode (Lowry, 1951). Some additional heating results from ion bombardment during the half-cycle when the electrode is acting as cathode and from the resistive losses (loss = $I^2R$) in the tungsten wire core caused by the discharge current flowing in through the leads and out through the cathode surface. In these cases, the cathode heat developed is related to the arc current being drawn.

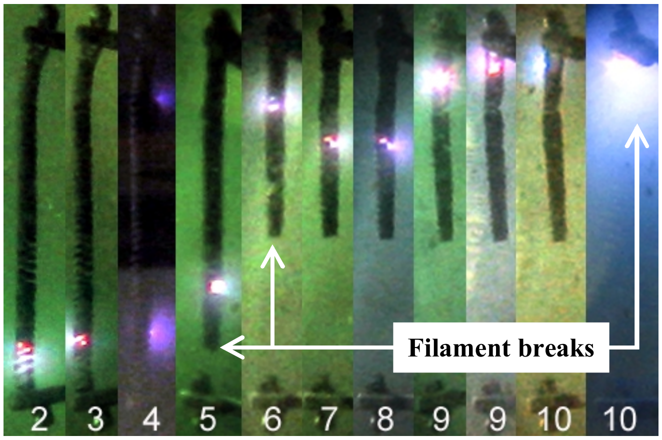
For both low frequency lamp operation (60 Hz) and high frequency operation (> 20 kHz) most of the cathode heating comes from the anode cycle because the energy dissipated (lost) at the anode is much larger than that lost at the cathode. According to Watanabe (1993), for 50 Hz operation, anode cycle loss is about 6 times the cathode cycle loss. For 43 kHz operation, anode cycle losses decrease due to the lack of the anode fall voltage, however, the anode loss from the work function of the electrode material is still about one and a half times larger than the cathode fall loss.

The main electrode heat loss mechanisms are conduction to adjacent elements, electron emission cooling, radiation cooling, and convection cooling of the electrode surface. The reduced demand on the electrode to supply electrons resulting from dimming the lamp can reduce the heat loss from electron emission cooling. However, this reduction of heat loss cannot completely compensate for the reduction of electrode heating due to dimming.

The inherent bombardment type of cathode heating that occurs on the lamp electrodes ordinarily results in what is known as “hot spot” operation. Since points on the cathode will vary in potential depending on their distance from the lead wire supplying power, and since it is a practical impossibility to maintain all areas of the cathode surface at exactly the same electron emitting efficiency, the discharge tends to localize at the most efficient emitting areas and also at areas nearest the lowest electric potential. The result is that this type of cathode does not operate at a uniform temperature throughout its length. A “hot spot” develops, which comes to a temperature and area equilibrium depending on the arc current being passed. During lamp life, emission mix material leaves the electrode by evaporation. Due to the relatively high temperature of the “hot spot,” the emission mix evaporates more in that location. This results in the hot spot moving like a candle flame from one end of the electrode to the other. When all of the emission mix material is consumed, the lamp will quickly extinguish. Soules (1989) has presented an excellent simulation of this process. Investigations at the LRC support this “candle flame” movement of the hot spot occurring over the life of lamps operated on instant-start ballasts (See **Figure 4**).



**64 mA** **121 mA** **180 mA**



**Days of operation @ 30 mA**

***Figure 4.*** *Movement of Hot Spot for Instant Start Fluorescent Lamp under Dimmed Condition*

## Electrode heating under 60 Hz and high frequency operations

When a fluorescent lamp operates on alternating current, the electrode alternately operates as both cathode and anode. During the anode cycle, since the anode does not emit ions, a negative space charge builds up in front of the electrode and an anode fall voltage is formed, analogous to cathode fall voltage. Under 60 Hz operation, the anode fall voltage averages approximately 5 V and is marked by oscillations in voltage about this level (Waymouth, 1971). Electrons accelerated by this anode fall are collected by the anode and contribute a significant fraction of the energy to heat the emitter coil. Since no ions exist in front of the electrode during the anode cycle at 60 Hz operation, the anode current flows uniformly into the electrode. Thus, the electrode is heated rather uniformly during the anode cycle.

When a fluorescent lamp is operated at high frequency (> 20 kHz), the electrons and ions formed in front of the electrode during its cathode cycle are hardly removed during the following anode cycle because of the short length of time of the half-cycle period. The anode can draw electrons from the free electrons remaining from the period in which the electrode was a cathode. As a consequence, the anode fall voltage vanishes and the anode cycle loss decreases due to the lack of the anode fall voltage. The average electrode temperature therefore is lower under high-frequency operation than under low-frequency operation due to the drop in the anode cycle loss. However, the electrode hot-spot temperature under high-frequency operation may be still higher than the electrode temperature under low-frequency operation. This is supported by the fact that the cathode fall voltage under high frequency operation is lower than that under 60 Hz operations (Hammer, 1995). Watanabe (1993) explained this peculiar sounding phenomenon as follows:

> Ion space charges are formed in front of the cathode spot position during the cathode cycle. When the polarity is changed, the ion space charges are quickly neutralized by the electrons from the positive column, and the electric field vanishes. Then, mercury ions in front of the cathode-spot position diminish mainly through the diffusion process during the anode cycle…Therefore mercury ions randomly travel a distance of 240 $\mu$m during the anode cycle. Since this distance is comparable to the size of the cathode spot, it is reasonably concluded that the ion space charges in front of the cathode-spot position are virtually not removed during the anode cycle.

Due to the ion space charge in front of the cathode spot, the anode cycle loss is concentrated at one particular spot on the electrode in the case of high frequency operation. Thus, the cathode-spot is efficiently heated during the anode cycle under high frequency operation. In contrast, uniform heating by the anode cycle loss under low frequency operation is less effective for increasing the cathode-spot temperature. In this case, high frequency operation will not only increase the lamp efficacy due to the elimination of anode fall voltage, but also may enhance lamp life due to the effective heating of the cathode spot (Watanabe, 1993).

## Ballast operating effects on fluorescent lamp life

There are three operating parameters that may affect fluorescent lamp life: lamp current crest factor (CCF), supplemental electrode heating voltage, and lamp operating current. The ballast that operates the lamp mainly determines these three parameters.

Lamp current crest factor is the ratio of peak lamp current to the root mean square lamp current. A higher CCF indicates a distorted wave shape with the potential for high peak current, which can damage the lamp electrode and reduce lamp life. Fortunately, most electronic ballasts have satisfactory CCF of less than 1.7, which is regarded as an acceptable limit by ANSI ballast performance standards. However, this limit is based on 60 Hz operation, therefore applying it to high frequency operation is questionable. Perhaps higher CCF values are acceptable for high frequency operation due to the more efficient heating of the electrodes under high frequency operation.

Supplemental lamp electrode voltage is the voltage across the electrode filament at each lamp end that is supplied by certain ballast types to heat the electrodes during lamp operation. For

Instant start and modified rapid start ballasts, this voltage is 0 V (non-existent), but some electronic rapid start ballasts, and most magnetic rapid start ballasts continue to provide about 3.5 V across the electrodes during lamp operation. Although this increases the active power of the system, it can diminish or possibly avoid the sputtering of the electrode emissive material that occurs if the electrode temperature drops below 700 ºC. The electrode temperature will likely drop to below 700 ºC when the lamp is dimmed.

Lamp operating current is the current flowing through the lamp during operation. The Ballast factor (BF) is the ratio of the luminous flux emitted by a lamp operated on a given ballast to the flux emitted by the same lamp when operated on a reference ballast. These two parameters are directly related in that reducing the lamp operating current reduces the light output of the lamp and therefore reduces the BF. ANSI sets maximum limits on lamp operating current to minimize the evaporation of the electrode emissive coating and minimum limits to avoid electrode sputtering. ANSI does not address the issue of dimming the light output of lamps. Lamp voltage increases slightly as lamp current is decreased, making the direct relationship between lamp current and light output deviate slightly from being directly proportional.

## Starting effects on fluorescent lamp life

There are four main methods to start fluorescent lamps: preheat start (or switch-start), rapid start (includes modified rapid start), programmed start, and instant start.

In a preheat start system, a starter switch diverts lamp current across the filaments at the lamp ends to preheat the lamp electrode for several seconds. Then, when the starter's switch opens, the ballast provides approximately 200 to 300 V across the lamp to strike the arc. This method is obsolete in the U.S. and is rarely used in commercial and industrial lighting systems.

Rapid-start ballasts include an electrode heating circuit that provides a low filament heating voltage (about 3.5 V) to obtain an electrode temperature ranging from about 700 to 1000 ºC within a one- or two-second starting-period while at the same time applying a starting voltage of 200 to 300 V to the lamp. Most rapid-start ballasts continue to supply the electrode heating voltage even after the lamp has started, which results in power efficiency losses of about 1.5 to 3 watts per lamp. There is also a ballast type that uses a rapid start starting method, called cathode disconnect (or modified rapid start), that removes the supplemental heating after the lamp has started.

Programmed start, being recently introduced to the market, is defined in ANSI 2002 standards as follows:

> Those systems in which the sequence for starting hot-cathode electric discharge lamps is as follow: (1) the lamp cathodes are initially preheated to a temperature sufficient for adequate electron emission and without establishing local ionization across the cathodes; (2) this cathode heating is accomplished by supplying the required energy from a voltage or current source in the ballast itself, while during the preheated period the voltage across the lamp is kept below a level to initiate a glow discharge; (3) after the preheating period the voltage across the lamp is increased to a sufficient level to initiate the arc breakdown

discharge; and (4) cathode heating may be reduced or removed after the lamp is in full conduction.

Supplying the correct amount of supplemental heating is critical for the above starting methods. If the electrode heating voltage is too high, the overall temperature of the electrode may exceed 1000 ºC, thus reducing lamp life due to a high electrode coating evaporation rate, especially if the supplemental electrode heating is not removed after the lamp starts. If the electrode heating voltage is too low, the temperature of the electrode may be too low for sufficient thermionic emission, thus reducing lamp life due to excessive coating loss through sputtering. The electrode **Rh/Rc** ratio is often used to measure whether or not the electrode is heated to an appropriate temperature during starting. **Rc** is the cold lamp electrode resistance at room temperature (25 ºC). **Rh** is the hot lamp electrode resistance at the end of the preheat period but just before the glow to arc transition. Ji (Ji, 1998) illustrated that **Rh/Rc** ratio correlates well with rapid start fluorescent lamp life (See **Figure 5**). A higher **Rh/Rc** ratio enables more starts.

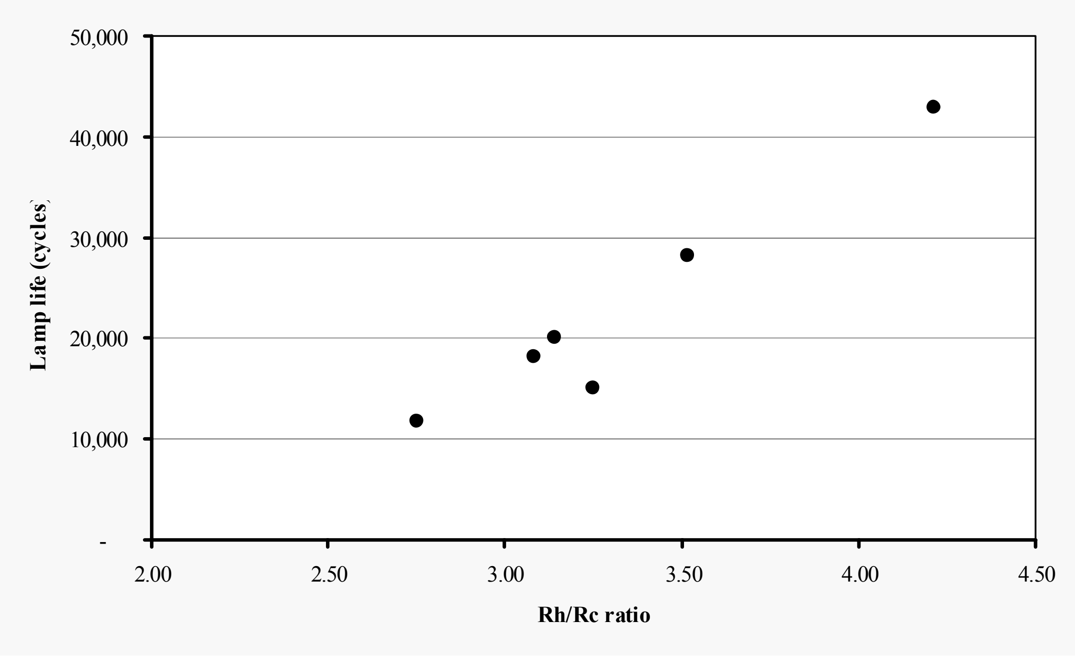


***Figure* 5. *Rh/Rc* *ratio vs. lamp life (Ji, 1998)***

Instant start ballasts supply a high initial voltage (over 400 V for 4-foot lamps) to strike the arc and start the lamp. The high voltage is required to initiate the discharge between the unheated electrodes. Since no supplemental heating is provided to the electrodes either before or during lamp operation, instant start ballast systems are more efficient than rapid start systems.

According to the U.S. Census Bureau (2001), 85% of the electronic ballasts sales for fluorescent lighting systems are instant start. This is despite the fact that rated life claims for lamps operated on instant start ballasts are less than that for rapid start operation. However, rated life may not take into account operation at high frequency which provides better self-heating of the electrodes and the longer cycle times found in many applications (on for 8 to 10 hours at a time compared to the three-hours-per-start cycle for rating purposes). Recent life test results show that high frequency electronic instant start systems have nearly the same lamp life as rapid start systems (Ji, 1998). The widespread market acceptance of instant start electronic ballasts can be attributed to the benefits of the instant start method, including higher efficiency (5% higher than rapid start), faster starting and lower initial costs (3 - 9%).

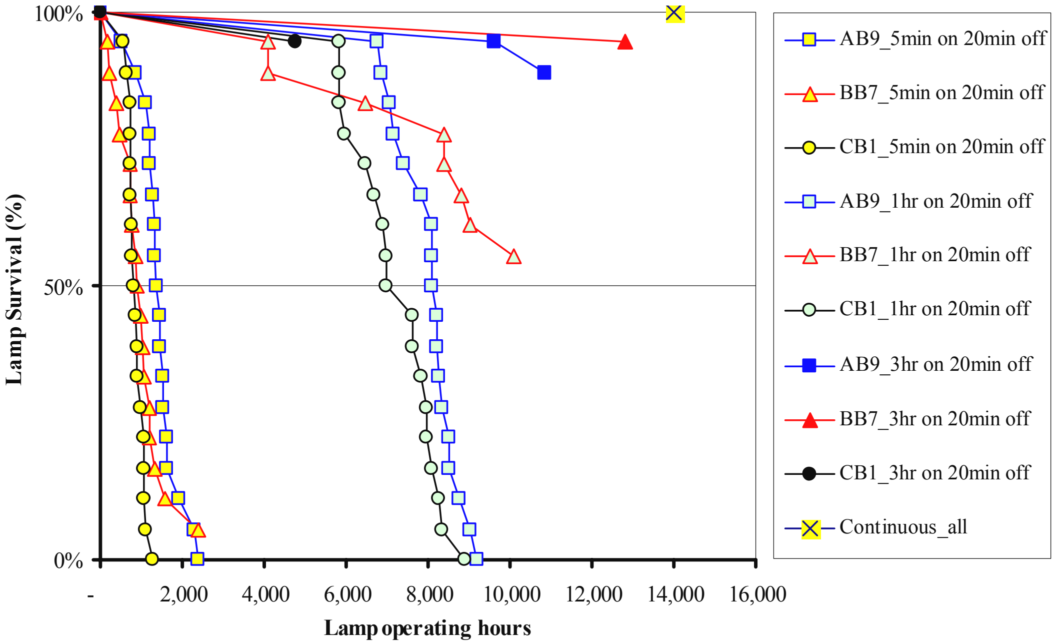


***Figure* 6.** *Instant start fluorescent lamp life at different operating cycles*

As previously stated, the operating life of fluorescent lamps is determined in most cases by the rate of the electrode emitter depletion. There are two different contributions to this process: depletion during steady–state operation and depletion due to starting. Damage to the cathode from the starting process is generally more serious than steady-state operation. Waymouth (1971) found that starting could reduce the life of the fluorescent cathode by a factor of about 2 to 3. **Figure 6** shows the Lighting Research Center (LRC) life test results for T8 lamps operated on high frequency instant start electronic ballasts at different operating cycles. The lamps used in the study were manufactured by GE, Philips and OSI. The difference in life is more than a factor of four comparing the 5-minute-on per-start to the 1-hour-on per-start. It is important to note that frequent switching of lamps operated on instant start ballasts shortens life significantly, yet the market still chooses instant-start ballasts over other ballast types by a large margin. This demonstrates that lamp-life is just one of many factors considered when choosing a particular technology. Consumers apparently accept the damaging effects of starting using instant-start ballasts because they gain energy savings and lower initial costs.

## Optimum electrode heating as a function of the discharge current (task 4.3)

Fluorescent lamp electrodes are designed to operate at a temperature high enough to support thermionic emission of electrons when they are operated near the rated discharge current. Dimming a fluorescent lamp by reducing the lamp current will reduce the cathode hot spot temperature. The consequence will be an increase in cathode fall voltage that is sufficient to increase the electrode temperature again by increasing the energy of the ions reaching the electrode. This may result in a higher electrode sputtering rate and lead to an early lamp failure. At the same time, however, the reduced discharge current requires less electron emission from the cathode. This reduced requirement somewhat offsets the lack of cathode heating, but because cathode electron emission is highly non-linear with electrode temperature, cathode fall voltage still rises upon dimming. At lamp discharge currents in the range of a few percent of the rated current value, lamp life may drop down to values of only a few days.

In order to avoid these negative effects on lamp life when dimming, there is the possibility of applying supplemental electrode heating current, which goes through the electrode filament and heats it by resistance heating to the temperature that is necessary for thermionic emission. Obviously, the lower the dimming level at which the lamp is operated, the higher the supplemental electrode heating current required. However, the electrode heating current should not be too high. The guiding principles are:

a. Too little heat reduces lamp life due to sputtering.
b. Too much heat reduces lamp life due to a high rate of the emission-mix evaporation.

Following these arguments, an optimum supplemental electrode heating current (or electrode voltage) exists for lamp dimming as a function of the discharge current and must be maintained in order to keep lamp life within a reasonable range. Various approaches for the determination of this optimization are possible through the following measurements:

a. Lamp life at various levels of the discharge current and different values for the electrode heating current
b. Electrode temperature (overall hot spot location) at different discharge and supplemental heating currents
c. Evaporation of barium from the electrode at different discharge and supplemental heating currents
d. Cathode-fall voltage measurements at different settings of discharge and heating currents made by the following techniques:
    1. Langmuir probe

2. Capacitive coupling
3. Measuring the lamp operating voltage

The first method yields the most reliable results as it is a direct measure of life and can match conditions as closely as possible to the situation the lamp user would experience. Unfortunately, results from such measurements will only be available after two to three years of testing with much effort and at great expense.

Hilscher (2002), from OSRAM GmbH, found a way of acquiring cathode-fall voltage of a fluorescent lamp operated at different discharge and electrode heating current values by measuring the lamp operating voltage. The lamps used in the experiment were 32 W, triple tube compact fluorescent (OSRAM DULUX T/E 32W), operated on 25 kHz electronic ballasts. **Figure 7** shows the maximum observed cathode fall voltage, **Ucf** (i.e. the cathode fall voltage that corresponds to a minimum or no supplemental heating current) as a function of the discharge current. This clearly indicates that the cathode fall voltage increases exponentially with the reduction of lamp discharge current.

The measured values of the cathode fall voltage were used to determine minimum, target, and maximum values for the cathode-heating current. In practice it is difficult to isolate supplemental cathode heating current from lamp current, since the same wires that attach to the lamp carry both currents at the same time. An approximate value that represents the effect of the heating current is calculated as the sum of the squares (SOS) of the current in each lamp-end lead wire. These so called SOS values, given in terms of lamp current, are used as design guides for proper supplemental electrode heating. For the triple tube, 32W compact fluorescent lamp, Hilscher (2002) obtained:

$$SOS_{min} = 0.518 - 0.544*Id \ \text{(A)}$$

$$SOS_{target} = 0.163 - 0.255*Id \ \text{(A)}$$

$$SOS_{max} = 0.181 + 0.267*Id \ \text{(A)}$$

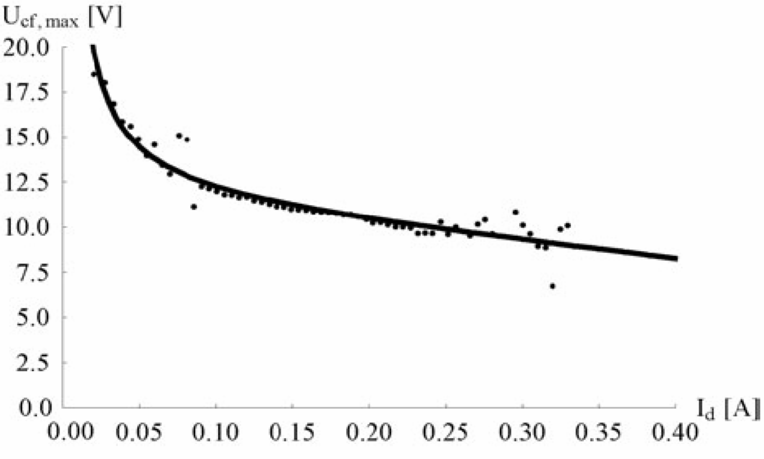


***Figure 7.*** *Maximum cathode fall voltage (Ucf) as a function of lamp discharge current (Id) (Hilscher, 2002)*

Tetri (2000) conducted a life test on dimming T8 fluorescent lamps operated on dimming ballasts that provided cathode heating. Tetri found that when the lamps were operated at static dim levels of 1%, 5% or 15% luminous flux, or dimmed dynamically up and down according to daylight illuminance levels, the lamp would reach the nominal lamp life and lumen maintenance factor. Thus, Tetri concluded that dimming with proper cathode heating would not impact fluorescent lamp life. Examination of the life data from this experiment reveals a trend of decreasing lamp life for higher output levels that was not discussed by the authors. This hints at the possibility that the shortest life might be at an intermediate dim level. A probable reason for this is that at the lowest dim levels of 1% and 5%, very little current is demanded from the electrodes, so precise heating is not critical. As the current increases for higher levels of light output, heating becomes more critical, but the lamp current is still insufficient for self-heating of the electrodes.

## Impact on lamp life of starting lamps when dimmed
(task 4.4)

During the instant start and rapid start starting processes, the lamp undergoes a transition from cold cathode glow discharge to hot cathode discharge. The cold cathode glow discharge is formed when the cathode is capable of emitting electrons only by ion-impact-induced secondary electron emission. Even though the discharge might be self-sustaining, the current near the cathode is carried mainly by positive ions. As a result, each electron that leaves the cathode must cause the production of many ions at a point near the cathode. For this to occur, a very high cathode-fall-voltage must exist–often several hundred volts.

In the case of hot cathode discharge, the current at the cathode is carried mainly by thermionically-emitted electrons; positive ions are needed only to neutralize electron space charge and provide a modest electron-accelerating field at the cathode surface. The necessary ion production is much less than one ion per electron. The cathode fall voltage is therefore very small, typically on the order of the ionization potential of the atoms of the gas (5 to 10 V). **Figure 8** illustrates the potential versus distance for cold cathode and hot cathode discharges operated at the same current in similar tubes at the same gas pressure (60 Hz) (Waymouth, 1971). The positive column potential drop, $\mathbf{V_p}$, and anode fall, $\mathbf{V_A}$, are the same, but cathode fall voltage, and therefore total potential, are substantially greater for the cold cathode discharge.

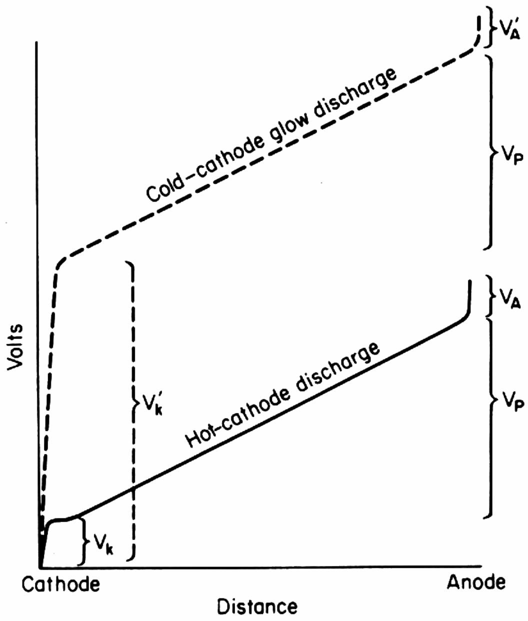


***Figure* 8.** *Potential versus distance for cold cathode and hot cathode discharges (60 Hz operation)*

In the usual range of glow discharge conditions encountered in the process of lamp starting, the cathode fall voltage increases with rising current (Brown, 1959). This helps the transition from cold to hot cathode discharge by increasing the energy input to the cathode from the discharge. The positive ions reaching the cold cathode strike it with kinetic energies equal to the charge times the accelerating potential, which can be as high as the full cathode fall voltage. Most of this energy goes into heating the cathode, which increases the cathode temperature. The higher the cathode fall voltage and the ion current, the faster the cathode is heated to thermionic emitting temperature and the sooner the discharge is converted to a hot-cathode discharge.

When starting the lamp with an instant-start ballast at its rated lamp current, a sufficiently high potential is applied to the lamp to ionize the gas and to reach full operating current without a temporary pause in the glow state. The discharge current and lamp light output reach their normal operating values typically well before the 100 ms time limit measured after the application of the open-circuit voltage as defined by ANSI. The instantaneous energy input to the cathode during the transient glow-discharge-like condition that persists while current is increasing to normal operating current is very high. The rate of change of cathode surface temperature has been described as “almost of explosive violence” (Waymouth, 1971). As a result, during lamp starting, simple blasting off of chunks of cathode material by the drastic temperature rise will reduce the amount of coating remaining and would be expected to reduce lamp life. It is not known whether this potentially explosive heating reduces lamp life in practice, however. Most fluorescent lamp electrodes are designed with a coiled-coil or triple coil structure to help restrain the emission material so the lamp can last its rated life (typically 20,000 hours at 3 hours per start for T8 lamps) with no problem.

In the case of starting lamps when dimmed, i.e. at lower than rated current, the transition from cold-cathode glow discharge to hot-cathode discharge will most likely be extended due to the decrease of lamp current and the corresponding decrease in heating power available to the electrode. Although this may alleviate somewhat the violent cathode damage due to the explosive temperature rise, overall it is much more damaging on the cathodes because of the potential for a relatively extended period of glow discharge ion bombardment (sputtering). In the extreme case, when the lamp is dimmed to levels below about 20%, the current in the steady-state glow discharge is too low to heat the cathode to a sufficient temperature to convert it to the hot cathode mode. The discharge will “hang up” in the glow state. The high-energy ion bombardment in the glow discharge knocks away surface atoms and erodes the cathode to the point of destruction in a short time. Waymouth (1971) explained this sputtering damage during glow discharge at starting as follows:

> Under glow-discharge conditions, with cathode fall voltages of 200 V or so, sputtering rates of 0.1 atom removed per incident ion would be quite typical. Besides, sputtering also damages the thermionic emission of the surface (even without significant material removal) in two ways. First, since the cathode is cold, atoms are sputtered away, bounced back on the cathode surface by the gas, and re-deposited helter-skelter instead of in an orderly way. Destruction of the ordered surface of the crystal must be expected to increase the work function and thus reduce thermionic emission. Second, tungsten atoms sputtered from the surface of exposed tungsten are deposited on the surface of the oxide almost as readily as on the tungsten, “plating” the oxide with a metallic covering and increasing its work function. The resulting reduction of accelerating field emission of the cathode means that the cathode fall voltage in the discharge must be higher to increase the ion current; the increased power input to the cathode increases its temperature to bring the electron emission up to the required level. The increased cathode fall voltage, ion current, and temperature persist for ten minutes to an hour after the damage, until the effects of the damage have been ‘annealed out’.

**Figure 9** illustrates the relationship between lamp current and starting time for one Sylvania OCTRON FO32/735 T8 lamp operated by a high-frequency electronic ballast. It clearly indicates that start time increases exponentially with the reduction of lamp current.

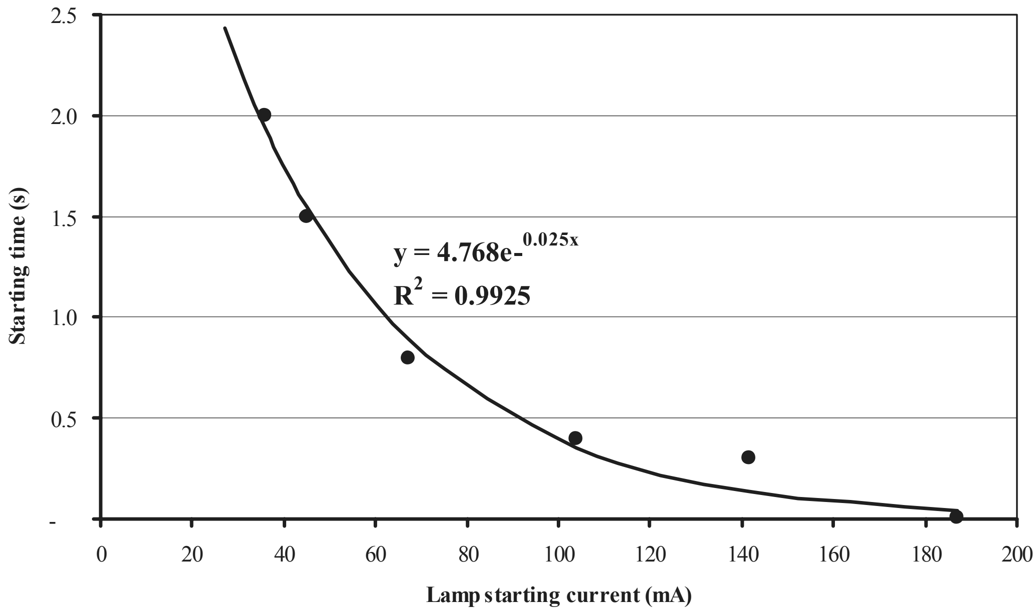


*Figure* **9.** *Relationship between lamp starting current (mA) and starting time (s)*

Also, it is observed after each start that the cathode operates for a significant time at a higher temperature than it does under continuous-burning conditions. This period of increased temperature greatly increases the evaporation rate of cathode coating material, and consequently the overall loss rate of coating material, leading to shortened lamp life.

Technically, it is possible to apply supplemental electrode heating current to heat the electrode before starting lamps when dimmed. This is similar to the situation of rapid start or programmed start fluorescent lamp. However, this is at the expense of efficiency, and/or initial cost. The possibility also exists that the intended supplemental electrode heating current is not effectively applied in all cases. LRC researchers found that in actual applications, connections and excessively long, tightly bundled wire leads reduce the amount of heating that actually takes place. On at least one LRC project this condition seriously reduced lamp life when traditional dimming ballasts that employ supplemental electrode heating were used (LRC, to be published).

Therefore, starting lamps when dimmed, i.e., at lower than rated current, is not recommended. To ensure long life, especially when supplemental electrode heating is not applied (e.g., instant start), a procedure of starting the lamp at its nominal full output level and then dimming it down to the desired light levels is necessary. Starting at full power will minimize the damaging effects of starting. This is advisable whether supplemental electrode heating is applied as part of the starting sequence, but most critical without supplemental electrode heating.

## Allowable dimming range without additional electrode heating
(task 4.5)

In ac operation, when no separate heating of the cathode is provided, most of the cathode heating arises from electron bombardment during the half-cycle when the electrode is acting as anode. Some additional heating results from ion bombardment and from the resistance losses (loss = $I^2R$) in the tungsten wire core caused by the discharge current flowing in through the leads and out through the cathode surface. In these cases, the cathode heat developed is positively related to the arc current being drawn. The main heat loss comes from the conduction to adjacent elements, the electron emission cooling, radiation cooling, and convection cooling of the electrode surface. Although dimming can reduce the electrode heat loss from the reduction of electron emission cooling, this reduction of heat loss does not compensate completely for the reduction of electrode heating.

Obviously, a certain amount of variation in lamp current is entirely permissible and results in no unfavorable performance. This is demonstrated by the fact that ballasts with ballast factors ranging from 1.3 to 0.77 are widely used and appear to maintain lamp life acceptably. Nevertheless, any cathode operates best at some definite value of lamp current. A cathode that is properly designed for best operation at 225 mA, for example, will run too hot at 400 mA and entirely too cold at 75 mA. If such a cathode is operated at too high a current and temperature, results may include excessive vaporization of barium, discoloration in the form of anode spots, and reduced lamp life. If the cathode is operated at too low of a current, too high of a percentage of the total emission must be obtained by ion bombardment, field emission, or some mechanism other than thermionic emission. This method of operation is conducive to an excessive cathode-fall voltage, greatly increased cathode sputtering by ion bombardment, and in extreme cases, very short life.

It has also been found that sputtering under continuous operating conditions is small under fairly wide variations of lamp current. Wehner (Stuart and Wehner, 1962) found that at a cathode fall voltage less than 20 V, the electrode sputter field is quite small, about $10^{-6}$ atoms removed per incident ion. Also there is little cathode temperature dependence in the sputtering yield (Stuart and Wehner, 1962). A great deal of the electrode heating energy comes from the collection of electrons in the anode half-cycle, and due to thermal inertia, the electrode does not cool down between its half-cycle of cathode duty. During operation, evaporation normally occurs at about a factor of 20 times greater than the rate of removal by sputtering. Therefore, sputtering can be ignored entirely in comparison with evaporation as a cause of coating loss under continuous burning conditions at nominal lamp currents. A lamp should be able to preserve a reasonable life within fairly wide variations of lamp current if it is started at its full rated current, and then dimmed down to the desired light level after it has reached its full light output. Now the question is: how much dimming is allowable for such reasonable lamp life?

In order to answer this question regarding the effect of lamp current on high frequency instant start fluorescent lamp life, a life test was designed at the Lighting Research Center. The life test included a total of 80 lamps at eight different lamp current conditions: ten lamps at each lamp current. All lamps were operated on 120 V ballasts for one lamp. The lamp current conditions selected were 180 mA, 121 mA, 64 mA, 49 mA, 41 mA, 30 mA, 24 mA, and 21 mA.

All ballasts were operated at 120 V, were from the same manufacturer, and had the same model number. The ballasts were rated to operate one lamp at 180 mA, which corresponds to a ballast factor of about 0.9, taking into account high frequency lamp operation. In order to achieve the different, reduced, lamp currents required by the life test design, a high voltage ceramic capacitor was placed in series with the lamp. The value of the capacitor, along with the specific ballast characteristics (e.g., operating frequency, output circuit details) determined the lamp current for each capacitor-ballast system. All of the capacitor-ballast systems were tested with a T8 fluorescent lamp to ensure that they operated the lamp closely to the selected lamp current.

In order to avoid the adverse effect of starting lamps under dim mode, the capacitors were connected in series with the lamp through a shorting device to bypass the capacitor during starting. After the lamps started, the shorting devices were manually removed, thereby dimming the lamps.

Calibrated capacitor-ballast systems were installed on two metallic racks that served as the support structure for holding the lamps. Each rack had eight levels, one level for each lamp current condition. One rack held six ballast-capacitor-lamp systems (48 lamps total). The other held four systems (32 lamps total). **Figure 10** illustrates one such life test rack. Both racks were powered by a regulated 120 V power supply.

***Figure 10.*** *Instant start fluorescent lamp life test rack*

The life test was started with the capacitors shorted, thus all systems were started at their nominal lamp current. After 30 minutes of operation, the capacitor-shorting devices were removed, dimming the test lamps to their intended lamp currents. At this point, measurements of the lamp operating time began. Hours of operation for each lamp were accumulated until the lamp failed. A lamp was considered failed when it had no visible light output to the experimenter's bare eye. The average lamp life was defined as the number of hours at which 50% of the test lamps at a given operating current failed.

As of November 6th, 2002, the lamps had accumulated 93 days of operation (2139 hours). By this date, all lamps operated at 49 mA and below had reached their median life (50% had failed). At the other extreme, all lamps operated at or above 121 mA were still operating. For the group at 64 mA operating current, only one lamp had failed by this date. **Figure 11** summarizes the results for the dimming testing of instant start fluorescent systems. The results show that dimming to about one third of rated current (121 mA), a T8 fluorescent lamp operated with an instant start circuit still keeps a reasonable long life (more than 2139 hours with no failures).

Using current electricity pricing practices and load shed programs, LRC researchers found that load shed-related dimming of 100 hours per year would capture most of the economic benefit (see Appendix 4.3 - A). If the damage to the electrodes during dimmed operation is simply cumulative, meaning that no effects that accelerate the damage caused by dimming are occurring, then 2000 hours of dimmed operation is sufficient for load shedding applications. For example, a 20,000-hour lamp life corresponds to about 5.5 years of operation at 10 hours per day. If load shed dimming amounts to 100 hours per year, then 550 hours of dimmed operation is required. This dimmed operation would be expected to reduce the life of the lamp by about 25% (550/2100), equivalent to a 15,000 hour life. A more exact calculation, taking into account the reduced dimmed operation time due to the reduced life yields a life reduction of only 19%, corresponding to a life of 16,200 hours.

One interesting point worth mentioning is that impact of dimming on instant start fluorescent lamp life is quite analogous to frequent switching effects on life. **Figure 12** is a re-plot of Figure 4, which shows the Lighting Research Center (LRC) life test results for T8 lamps operated on high frequency instant start electronic ballasts at different operating cycles. Frequent switching of lamps operated on instant start ballasts significantly shortens life, yet the market still chooses instant-start ballasts (85% shipment in 2001) over other ballast types by a large margin. This demonstrates that lamp-life is just one of the many factors considered when choosing a particular technology. Consumers apparently accept the damaging effects of starting using instant-start ballasts because they gain the energy savings and lower initial costs. Based on the above calculation, dimming 100 hours per year to 67% rated current levels is expected to reduce overall life by less than 20% (20,000 hour life reduced to 16,000 hours). Considering the energy savings, it should be reasonable for consumers to accept low cost instant start load shedding ballasts (about $9 cost increment on the standard instant start ballast) that enable the user to dim the lamp to 67% rated current level.

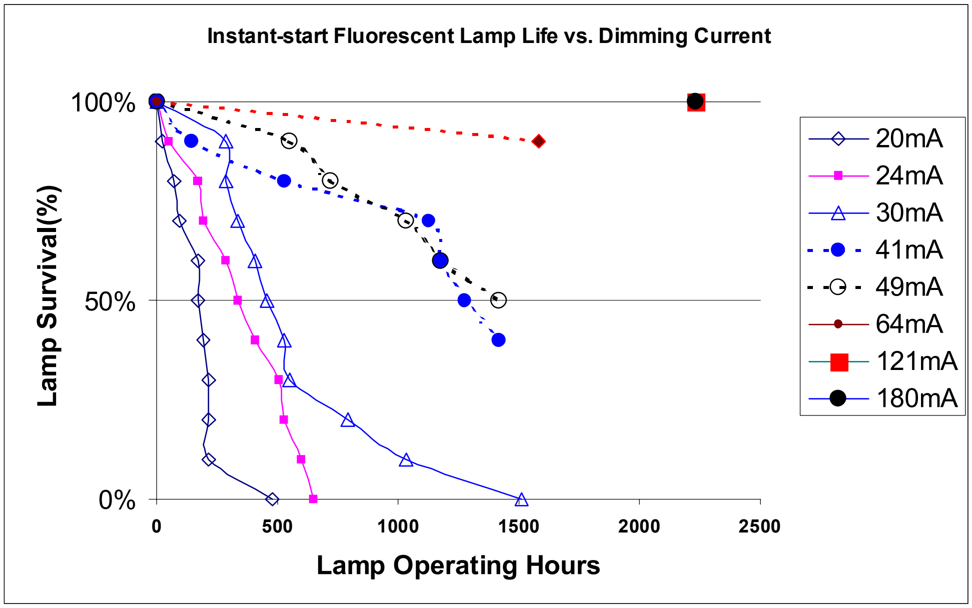


*Figure 11.* *Instant start fluorescent lamp life vs. dimming current*

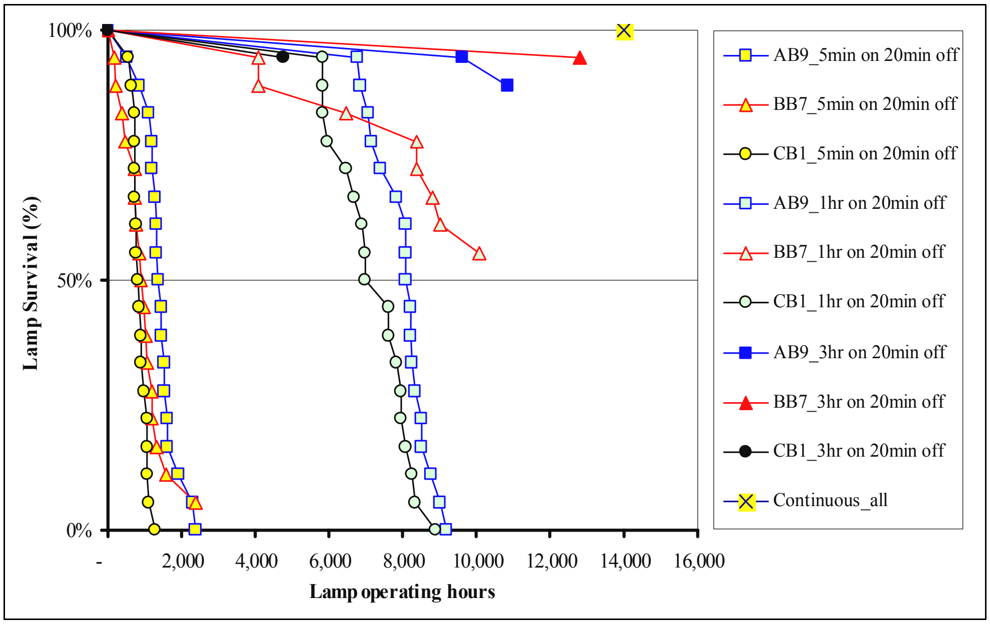


*Figure 12.* *Re-plot of Instant start fluorescent lamp life at different operating cycles*

# REFERENCES

ANSI C82.11 Consolidated-2002, ANSI standard for lamp ballast-High frequency fluorescent lamp ballasts –supplements*, American National Standard Lighting Group, NEMA*

Brown, S.C. *Basic data of plasma physics* (Cambridge, MA: M.I.T. Press, 1959)

Hammer, E.E. "Comparative starting operating characteristics of typical F40 systems." *Journal of the Illuminating Engineering Society* 18, no. 1 (1989): 63-69.

Hammer, E.E. "Cathode fall voltage relationship with fluorescent lamps." *Journal of the Illuminating Engineering Society* 24, no. 1 (1995): 116-122.

Hilscher, A. "Determination of the cathode fall voltage in fluorescent lamps by measurement of the operating voltage." *Journal of Physics D: Applied Physics* 35, (2002): 1707-1715.

Lowry, E.F. "Thermionic Cathodes for Fluorescent Lamps and Their Behavior." *Illuminating Engineering* 46 (1951): 288-294.

Misono, K. "Cathode fall voltage of low-current fluorescent lamps." *Journal of the Illuminating Engineering Society* 20, no. 2 (1991): 108-115.

Lighting Research Center "Integrated skylight luminaire." *Field Test Delta* 1, no. 1 (to be published).

Davis, RG., Ji, Y. "Fluorescent lamp-ballast systems." ESEERCO Final Report 94-40, part 1, 1998. Troy NY, Lighting Research Center.

Soules, T.F., Ingold, J.H., Bhattacharya, A.K., Springer, R.H. "Thermal model of the fluorescent lamp electrode." *Journal of the Illuminating Engineering Society* 18, no. 2 (1989): 81-92.

Stuart, R.V., Wehner, G.K. "Sputtering at Very Low Bombarding Energies." *Journal of Applied Physics* 33, no. 7 (1962): 2345-2352.

Tetri, E., "Daylight linked dimming: effect on fluorescent lamp performance." *Lighting Research and Technology* 34, no.1 (2000): 3-10.

US Census Bureau, "Fluorescent lamp ballasts: 2001." *Current Industrial Reports* MQ335C (01)-5, (July 2001).

Watanabe, Y., Murayama, S. "Cathode fall characteristics of fluorescent lamps under high-frequency operation." *Japanese Journal of Applied Physics* 32, Pt. 1, no. 8 (1993)

Watanabe, Y. "Dependency of cathode temperature on operation frequencies in fluorescent lamps." *Journal of the Illuminating Engineering Society* 24, no. 1 (1995): 48-57.

Waymouth, J.F. *Electric discharge lamps* (Cambridge, MA and London, England: M.I.T. Press, 1971).