Reflector CFLs: Friend or Foe?

J. J. McCullough and Linda Sandahl, Pacific Northwest National Laboratory

ABSTRACT

A project sponsored by the U.S. Department of Energy (DOE) and the Northwest Energy Efficiency Alliance (Alliance), and implemented by the Pacific Northwest National Laboratory (PNNL), aims to improve the performance of reflector type (R-lamp) compact fluorescent lamps (CFLs) and increase their availability in the Northwest and throughout the United States by means of a technology development and procurement strategy.

R-lamps are increasingly common in homes across the United States, used in recessed downlights, track lights, and surface-mounted flood light fixtures. An estimated 120 to 140 million R-lamps are sold each year, nearly all of them with incandescent light sources drawing from 65 to 100 watts of power per lamp.

The huge success of CFLs in the market over the last 5 to 10 years has led to a proliferation of compact fluorescent technology in lamps of many differing types and wattages. However, reflector CFLs have been slow to catch on. While the market transformation community has embraced reflector CFLs, there are serious concerns about their performance and longevity when used in recessed downlight fixtures installed in insulated ceilings, especially with airtight housings (ICAT). Ambient temperatures increase dramatically which directly impacts light output and significantly reduces lamp life. PNNL has developed prescriptive specifications and performance-based testing including both short-term testing to directly measure steady-state ballast component temperatures, as well as full lamp life testing at the temperatures experienced in ICAT housings. This paper describes project results to date.

Introduction

On behalf of the U.S. Department of Energy (DOE) and the Northwest Energy Efficiency Alliance (Alliance), the Pacific Northwest National Laboratory (PNNL) is conducting a technology procurement to stimulate development of a new generation of reflector compact fluorescent lamps (R-CFLs) for use in insulated ceiling-rated airtight housings (ICAT) that provide similar light levels to their incandescent counterparts and demonstrate compliance with ENERGY STAR® minimum specifications (Figure 1).

Since 1993, PNNL has assisted DOE's Emerging Technologies Program, and its predecessors, in its efforts to improve the energy efficiency of the U.S. buildings sector by encouraging the commercialization of energy-efficient appliances and equipment. One method PNNL has used to achieve faster market acceptance of new energy-efficient products is technology procurements. PNNL identifies an appliance category with good potential for energy-efficiency improvement and, with input from industry and its partners, defines product specifications. PNNL then issues a request for proposals asking manufacturers to submit bids to produce models of the appliance that meet the procurement's high performance and energy efficiency standards at the lowest possible price. PNNL, on behalf of DOE, works with potential large-volume buyers and supporters (i.e., utilities and market transformation groups) to promote the winning products. This approach lessens the risks manufacturers normally take with new product development by establishing initial product demand estimates, sponsoring consumer education efforts, and promoting the new technology through large-volume retailers, utilities, and energy efficiency organizations. PNNL has used this approach to successfully promote market acceptance of several energy-efficient technologies for DOE.

Figure 1. Incandescent and CFL R-lamps

R-CFLs were identified as a candidate for technology procurement in Fall 2000. In Spring 2001 PNNL began meeting with potential large-volume buyers including builders, home centers, and government agencies to seek technical guidance and help with program design and to generate interest in the procurement. PNNL also met with product manufacturers, manufacturer trade associations, and suppliers to solicit their guidance and knowledge and to inform them of the upcoming procurement.

PNNL identified several technical and market challenges to increased use of R-CFLs installed in ICAT housings:

- Mean overall length (MOL). Few R-CFLs fit in recessed can fixtures designed for incandescent R-lamps when the program started, although several smaller models are now available.
- Delivered light output. Total light output for R-CFLs was often significantly less than their incandescent counterparts, and R-CFLs installed in high ambient temperature environments generally produced lower light levels compared to CFLs installed in "open" fixtures at room temperature. This continues to be a challenge.
- Beam angle[1]. The beam angle of R-CFLs was generally much wider than that of incandescent R-lamps, and significant amounts of light could be lost in the recessed can fixture. The only category where R-CFLs compare to the beam angle of incandescent R-lamps is the very wide flood category, and R-CFLs should not be considered for spotlight applications.
- ENERGY STAR® compliance. Very few R-CFLs were ENERGY STAR compliant at the start of this program. At the time of this paper there were more products available, however, their compliance with the specification in high-heat environments was questionable.
- Longevity. Operating life was often much shorter than the manufacturer rated life when installed in insulated ceiling environments. This continues to be a challenge.
- Availability and affordability. Prices for R-CFLs, when one could find them, were high – often upwards of $15 per lamp. Prices have since come down below $12, which remains substantially higher than incandescent lamps (which cost about 3 to $5).

PNNL developed a set of specifications for R-CFLs for use in ICAT recessed downlight fixtures and prepared a request for proposals. The proposal was sent to lamp manufacturers and made available through the program website **www.pnl.gov/r-lamps**.

Five manufacturers representing 12 R-CFL models submitted bids by the November 22, 2002, deadline. PNNL evaluated the products against the evaluation criteria, which included short-term thermal tests in a simulated ICAT environment. Eight R-CFL models submitted by three manufacturers were selected to move into long-term testing, which will be completed by September 2004. A more detailed discussion of lamp testing is included in the section of this paper discussing results of product testing to date. Models that meet the program specifications will be promoted through the website, retail outlets, and program partners.

Size of the Market

The U.S. Census Bureau Current Industrial Report (CIR) program provides monthly, quarterly, and annual measures of industrial activity. These surveys measure manufacturing activity in important commodity areas including electronic components and consumer goods. Unfortunately, the CIR for electric lamps was discontinued in 1994 and obtaining current market data is difficult. However, in 1994 manufacturers reported approximately 130 million R-lamps manufactured (U.S. Census Bureau 1995). Given the popularity of these products, it is reasonable to assume that annual production has increased. Recessed lighting fixtures, including downlights, represent about 12 percent of installed residential lighting fixtures and 15 percent of total lighting energy use nationwide (Calwell et al. 1999).

[1] The total angular spread of light cone intercepting the 50%-of-maximum intensity.

Potential to Save Energy

An example of the energy savings that would result from changing a standard 65- watt EPACT incandescent R-lamp to a 16-watt R-CFL is provided in Table 1. In addition to the lighting energy savings there is also a reduction in the lamp's heat output, which contributes to the space cooling requirements.

Table 1. R-CFLs – Lighting Energy Savings

	Incandescent R-lamp	R-CFL	Savings
Avg. lamp wattage	65	16	49
kWh consumption per year	95	23	72
Avg. electricity cost per year	$8.27	$2.00	$6.27
*Energy costs are based on a rate of $0.0871 per kWh, the 2003 national average residential retail electricity price cited by EIA Monthly Energy Review, May 2004.			

This example is for a single lamp, operated four hours per day for one year. Most homes have multiple recessed downlights so the savings would be multiplied.

Effects of High Temperature Operation

CFLs installed in "enclosed" fixtures or ICAT recessed fixtures are subjected to sustained elevated temperatures for which they are not designed. Elevated temperature operation has three profound negative impacts on CFL performance: reduced light output, reduced lamp life and color shift. The specifications developed for this project address light output and lamp life. PNNL decided not to address color shift in this project because of the complexity and expense of addressing the issue, and because there was no indication that lamp users were significantly concerned with the issue.

Reduced Light Output

CFL light output is, among other things, a function of the vapor pressure inside the lamp. Fluorescent lamps contain a larger amount of liquid mercury than will become vaporized at any one time. Excess liquid mercury condenses at the coolest locations ("cold spot(s)") on the lamp walls and vapor pressure depends upon the temperature of the cold spot(s). Lamp design, ambient temperature, drafts, etc., all affect the cold spot. A lamp that is too hot (or too cold) will see a light output reduction on the order of 10% to 20% due to too much or too little mercury being available for the discharge. A general rule of thumb for light loss is 1% for every 1.1°C (2°F) increase in ambient temperature above 38°C (100°F). To combat the problem, some manufacturers have resorted to using mercury amalgams (an alloy of mercury and other metals). The amalgam stabilizes and controls vapor pressure inside the lamp by absorbing or releasing the available mercury. Lamps with amalgam provide more than 90% of their rated light output over a wider range of ambient temperatures. The one negative impact of amalgam technology is that lamps take longer to come up to full brightness, although they still meet the ENERGY STAR criteria of maximum three-minute run-up time.

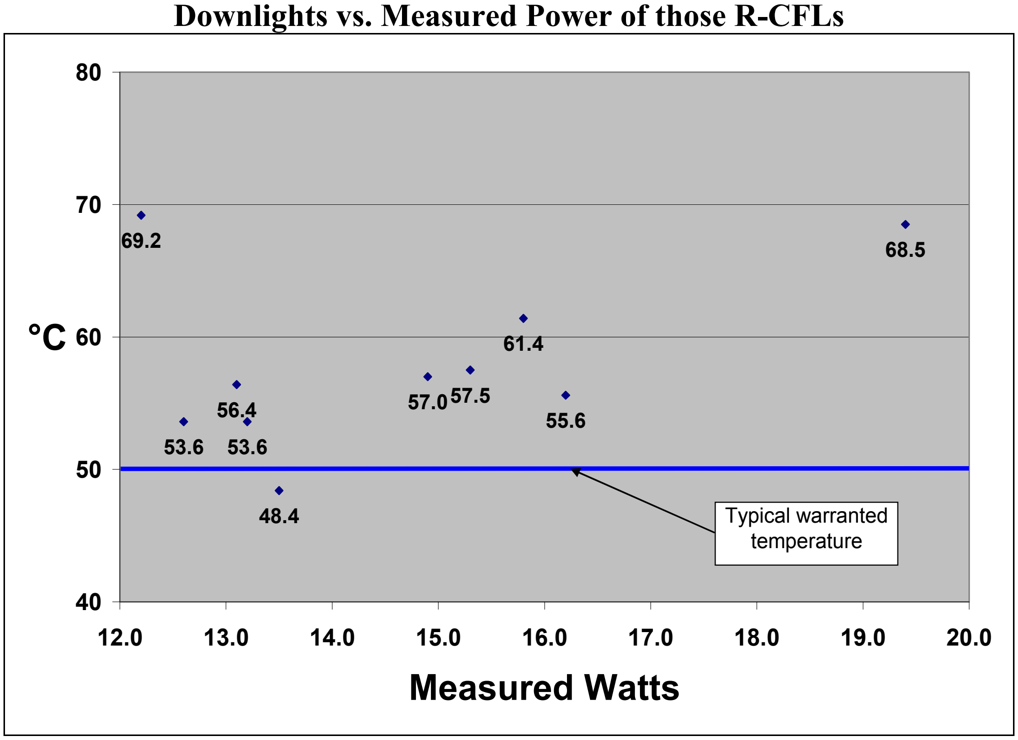
Reduced Lamp Life

Typical CFL products are designed to operate at ambient temperatures of approximately 30 to 40°C (86 to 104°F). This not only maximizes the light output but provides the highest efficacy. When temperatures exceed the optimal range, the electrical properties of the lamp change, which in turn causes the ballast to operate outside its design parameters, allowing more than the rated current flow through the lamp. Long-term operation at higher-than-rated current shortens the life of the lamp.

Another cause of high ambient temperature operation (and reduced lamp life) unique to integral (or screw-based) CFLs is the fact that the ballast components are in close proximity to the heat-generating lamp cathodes. The problem is further exacerbated in ICAT or enclosed applications. Ballast components are exposed to temperatures that approach and/or exceed the temperature ratings of the individual components. The ballast is only as good as its "weakest link" and a single component failure can be catastrophic. CFL manufacturers identified electrolytic capacitors as the component most susceptible to heat and premature failure. These components, as used in integral CFLs, are typically rated for a maximum operating temperature of 85 or 105°C.

R-CFL manufacturers typically warranty their products for an ambient temperature of 50°C and at least 6,000 hours of rated life[2] (an ENERGY STAR requirement). Figure 2 shows the results of 10 current model R-CFLs tested by PNNL in a simulated ICAT environment. It can clearly be seen that most operated above the manufacturers' maximum operating temperature guidelines.

Figure 2. Measured Ambient Temperatures Adjacent to R-CFLs in ICAT Recessed Downlights vs. Measured Power of those R-CFLs



[2] The point at which 50% of a large sample of lamps are still in operation

High Failure Rates

While product return data is not widely available, one retailer promoting energy- efficient lighting and other energy conservation products indicates that the overall returns for R-CFLs are higher than for any other CFL product type, with premature product failure the most prevalent reason for customer returns. Energy Federation Incorporated (EFI) indicates that the "returns to sales" ratio for R-CFLs is over four times higher than for bare glass CFLs (Steele 2002). Size and fit issues account for some reflector returns as well. Return rates are higher for R-40 reflectors than for R-30 reflectors (about 5% vs. 3%), which would most likely be attributable to a size/fit problem. Thermal related stress is probably the single most common cause of compact fluorescent lighting product failures for both lamps and fixtures.

Results of Product Testing to Date

R-CFLs provided by manufacturers in response to PNNL's competitive solicitation were evaluated to determine if they met the minimum requirements detailed in the technical specifications and then were performance tested in a laboratory apparatus. Products first had to be ENERGY STAR certified or be eligible for ENERGY STAR certification and then were required to meet additional criteria aimed at addressing the performance issues identified above:

- specification of the maximum warranted operating temperature
- minimum 125ºC rated electrolytic capacitor(s)
- minimum electrolytic capacitor rated life of 5000 hours
- maximum overall length (R-30 = 5.6"/R-40 = 6.6")
- minimum luminous flux of 500 lumens (initial)
- maximum beam angle of 120º

If the lamp met the minimum requirements, it was forwarded to the Luminaire Testing Laboratory, Inc. (LTL, an independent luminaire testing laboratory located in Allentown, Pennsylvania) where it was subjected to two different laboratory tests: the "Short-Term Test" and, if successful, the "Elevated Temperature Life Test." The objectives of the short-term laboratory test were as follows:

- Determine the "thermal factor" corresponding to the reduction in delivered luminous flux by virtue of operation in the simulated insulated ceiling environment.
- Measure steady state ambient temperatures at a minimum of four elevations within the recessed downlight housing.
- Directly measure electrolytic capacitor(s) temperature(s) at steady state operating conditions.

The objectives of the elevated temperature life test were:

- Perform elevated temperature life testing on a minimum sample size of 10 units per model.
- Measure degradation of light intensity over time.

A total of 12 models representing 5 manufacturers were submitted in response to the request for proposals. One model was deemed "non-responsive" for failing to meet ENERGY STAR and PNNL requirements. The remaining 11 products were moved into short-term testing for thermal evaluation. Based upon short-term testing results, a further three were removed from consideration for not delivering the advertised wattage and rated light output. Therefore eight models entered elevated temperature life testing.

Short-Term Test

The short-term test consisted of operating the R-CFL in a simulated insulated ceiling environment at full power for a minimum of six hours, while taking temperature measurements at several locations. Manufacturers provided one sample of each model, that had been modified by the manufacturer with an "access port" to accommodate direct measurement of the electrolytic capacitor(s). Thermocouples where attached to the end of the capacitor via the access port. The short-term test was conducted using a thermal testing apparatus capable of the following:

- Maintain ambient temperature surrounding the apparatus at 25°C ±1°C (77°F ±2°F).
- Containment of loose-fill cellulose insulation to a minimum depth of 12".
- Fitted with an easily removable, tight closing lid gasketed for air tightness.
- Support the luminaire at a distance of 36" above the illuminance measurement plane.
- Automatically sample and record the ambient temperatures surrounding the lamp for a duration of six hours.
- Automatically sample and record the electrolytic capacitor(s) temperature for a minimum duration of six hours.
- Equipped with a photo sensing array consisting of a minimum of five illuminance meters located 36" below the thermal testing apparatus. One meter located directly below the center of the luminaire. The remaining four meters oriented 12" from the center meter and at 90° intervals from the center meter.

Short-term test procedure. The short-term test procedure has two-steps. The first step is to establish a baseline spot light intensity measurement, measured three feet directly beneath the lighting fixture. The second step is to simulate the insulated ceiling environment by adding insulation around the fixture. The light intensity beneath the fixture measured from pre- and post-insulation conditions determined the thermal factor, expressed as a percentage. The short-term test procedure follows:

1. Install the lamp in the apparatus within an ICAT recessed downlight housing, such that the end of the lamp intersects the plane of the aperture.
2. Apply power to the lamp. Record power readings.
3. Allow the system to reach steady-state illuminance.
4. Record photometer measurements.
5. Remove power from the fixture.
6. Immerse the luminaire in 12" (measured from the base of the apparatus) with loose fill cellulose insulation.
7. With the lid closed, apply power to the luminaire.

8. Begin automatic temperature recording.
9. At six hours of operation, record photometer measurements. Record power readings.
10. Test completed.

The data collected in the short-term test were used to further evaluate the products against the PNNL performance criteria. The thermal factor was applied to the manufacturer rated light output (measured at 25°C) to verify the product met the minimum requirement of 500 delivered lumens requirement in an insulated ceiling environment. The highest recorded ambient lamp temperature was compared to the manufacturer certified maximum warranted operating temperature. The measured temperature of the electrolytic capacitor(s) was compared to the temperature rating of the capacitor manufacturer. Eight products that successfully completed the short-term test were moved into elevated temperature life testing.

Elevated Temperature Life Testing

The elevated-temperature life testing procedure is identical to (IESNA 1991a) LM-65-91 except that the ambient temperatures are maintained at 60°C ±5°C (140°F ±9°F), versus the 25°C ±10°C (77°F ±18°F) prescribed in LM-65-91, to simulate the in-situ environment. Elevated-temperature life testing is being conducted using a testing apparatus (Figure 3) described as follows:

- Capable of testing a minimum of 100 lamps.
- Maintains ambient temperature in the plane of the lamps at 60°C ±5°C.
- Automatically cycles power to all testing luminaries at a rate of 3 hours "ON" followed by 20 minutes "OFF" for a period of 6000 hours of lamp run-time.
- Automatically senses and records the catastrophic failure of each lamp within a resolution of one hour.
- Automatically records the ambient temperature in the plane of the lamps at a minimum of four locations.
- Prevents radiant heat exposure from adjacent lamps.

A total of eight R-CFLs passed the short-term test and were moved into the ETLT. Ten samples of each model began testing on September 17, 2003. These tests will be completed in mid-June 2004 (for products rated at 6,000 hours) and mid-September 2004 (for products rated at 8,000 hours). Successful completion of elevated-temperature life testing will satisfy the performance testing phase of the evaluation process, at which time models that successfully complete the testing will be made public and product promotion will begin.

Preliminary Elevated Temperature Life Testing Results

As of the end of May 1, 2004, which represents approximately 5000 hours of testing, six of the eight R-CFL models were dropped from consideration due to premature failure in elevated-temperature life testing (a model is determined to have failed if more than 5 of the 10 samples tested for that model had failed). Two R-CFL models submitted by one of the manufacturers continue to perform very well, with only one sample lamp failure between the two models. Table 2 provides an overview of long-term testing performance as of May 1, 2004.

Figure 3. Drawing of the Elevated Temperature Life Testing Apparatus

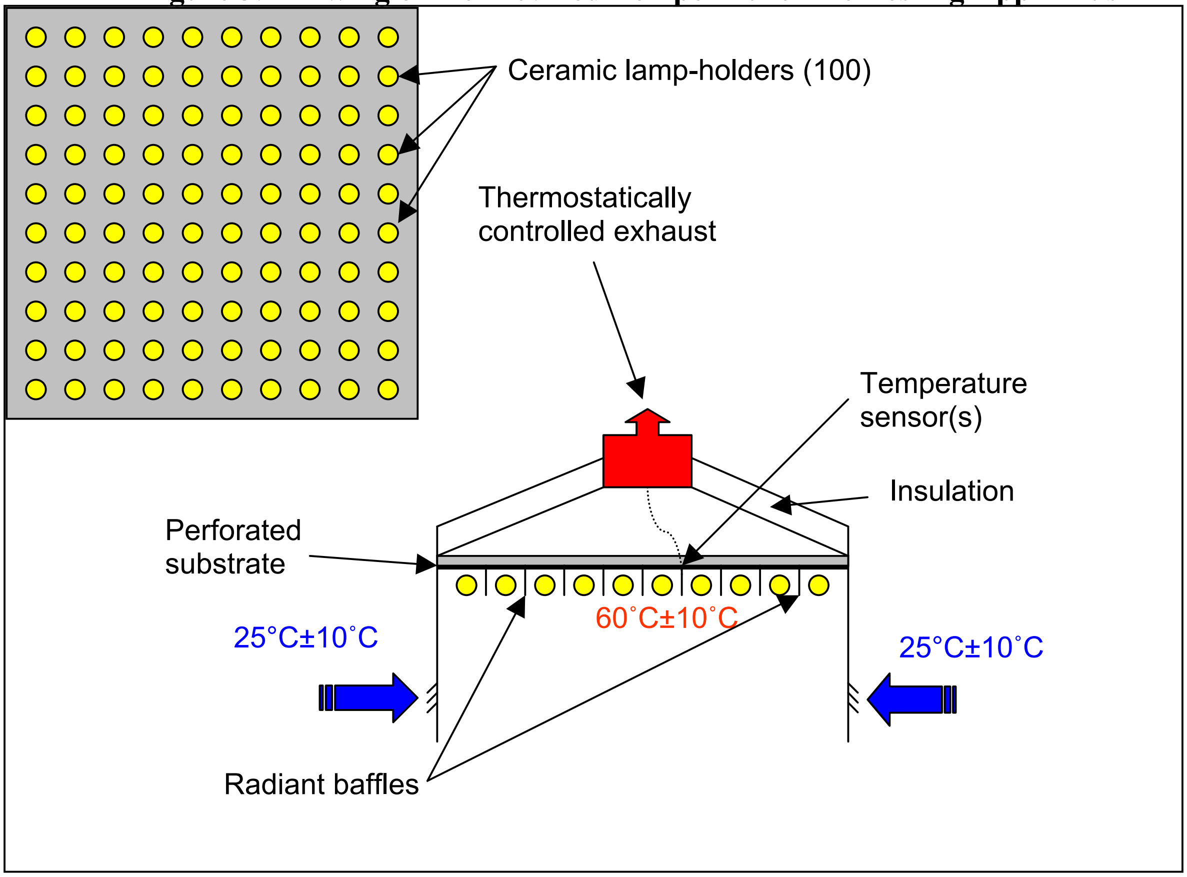


Table 2. Elevated-Temperature Life Testing Status as of May 1, 2004

Manufacturer ID	Model ID	# Failed (of 10)	Calculated "rated life" (hours)
A	4A	10	2376
A	4B	9	1075
A	5A	7	3466
B	8A	8	4520
B	9A	10	2595
B	10A	10	2793
C	11A	1	TBD
C	7A	0	TBD

Failure Mode Analysis

PNNL subcontracted with a ballast expert to conduct postmortem evaluation upon the failed lamps to determine the mode of failure and identify opportunities for improvement. A total of 52 lamps were provided to the expert. Below are the results of what was found:

- Lamps had one or two “blackened” lamp ends.
- 1 lamp had a small pinhole next to one of the cathodes.
- 11 ballasts had burned resistors.
- 2 ballasts had burned thermistors.
- 4 ballasts had ruptured capacitors.
- 1 ballast had a burned electrical trace on the circuit board.
- 1 lamp had become disconnected from the ballast. When the lamp was re-connected, the unit operated correctly.
- The electrolytic capacitors showed no discoloration or other visible evidence of damage due to high temperature.

In nearly all cases the lamp failed first which in turn damaged the electronic components. Integral CFLs intended for “single-use” do not employ end-of-lamp-life sensing circuitry as is typically found in remote “hard-wired” ballasts intended for multiple lamp life replacements. The circuitry prevents the ballast from continually attempting to start the lamp; without this circuitry, the lamp cathodes can overheat or cause excessive voltage leading to damaged components. The information learned from the ballast expert is contrary to the industry-held belief that elevated operating temperatures lead to the premature failure of electronic components (specifically the electrolytic capacitor). However, it must be pointed out that the products tested only represent three manufacturers and a very small portion of currently available products.

The primary recommendation of the ballast consultant is to increase the filter capacitance to sufficiently to reduce the lamp current crest factor[3] is reduced to a value of 1.7 or less. A lamp current crest factor of 1.7 is generally accepted by the lamp industry as sufficient to prevent premature failure of the lamp. Values greater than 1.7 can cause excessive emissive material to be displaced from the lamp cathodes leading to reduced lamp life.

Conclusions

Next Steps

Elevated temperature life testing will be completed in September 2004 at which time PNNL will announce the winning manufacturers. Successful manufacturers will be offered a basic ordering agreement, which is the mechanism by which products will be offered to buyers who purchase minimum quantities. The agreement establishes fixed prices for various tiers of quantity and usually has a duration of one year with clauses allowing for extensions.

Phase II

PNNL intends to conduct a second phase aimed at bringing more products into the marketplace. Based on the lessons learned from Phase I, PNNL is considering modifying the prescriptive requirement of 125°C electrolytic capacitors to a more performance-based specification requiring products to successfully operate at elevated temperatures. In addition to elevated-temperature life testing at 60°C, we are also considering concurrent life testing at 25°C using models from the same manufacturer batch. This approach will provide a direct comparison

[3] The ratio of the peak lamp current to the root mean squared (rms), or average lamp current

of lamp performance at elevated versus standard temperatures and address the inconsistencies between an industry-perceived problem of component failure and the results we have seen in elevated-temperature life testing. Phase II is anticipated to be launched in Fall 2004.

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