High Hats, Swiss Cheese, and Fluorescent Lighting?

Jeff J. McCullough, Pacific Northwest National Laboratory
Kelly L. Gordon, Pacific Northwest National Laboratory

ABSTRACT

For the U.S. Department of Energy, the Pacific Northwest National Laboratory is conducting a technology procurement to encourage faster development and market acceptance of new residential recessed downlights that are airtight, rated for insulated ceilings, and hard-wired for compact fluorescent lamps (CFLs). This paper discusses the potential energy savings of new high-efficiency downlights, and the results of product testing to date.

Recessed downlights are the most popular residential lighting fixtures in the United States, with 21.7 million fixtures manufactured in 2000. An estimated 350 million are currently installed in American homes. Recessed "cans" are relatively inexpensive and provide an unobtrusive, directed source of light for kitchens, hallways, living rooms, outdoor soffits and other areas.

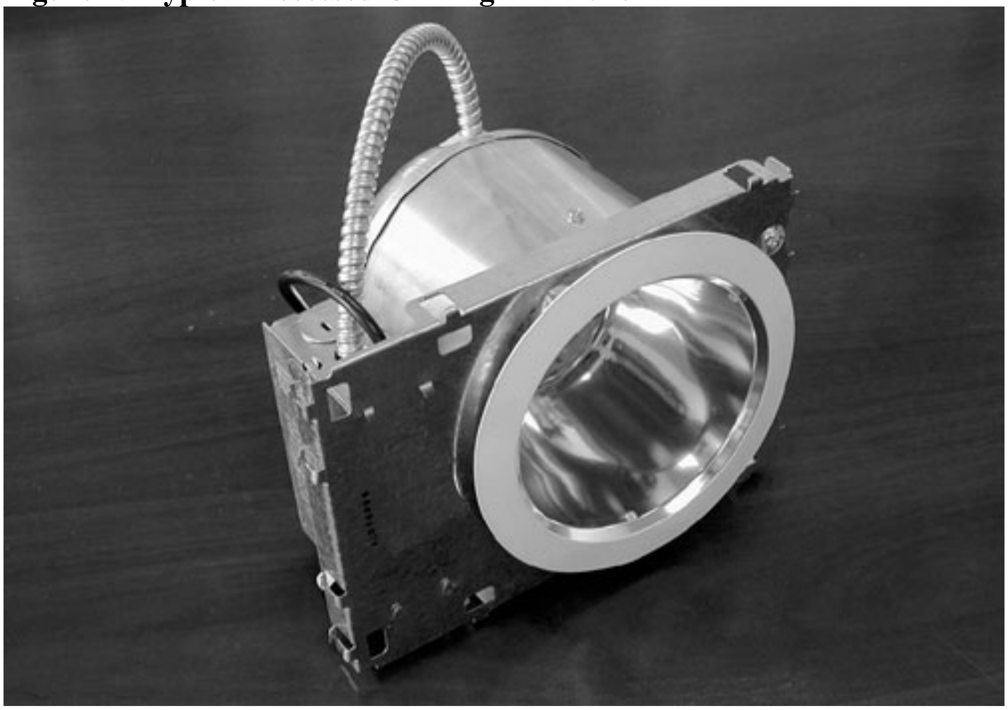
Recessed cans are energy intensive in three ways. First, virtually all recessed cans currently installed in the residential sector use incandescent light sources, typically reflector-type (R-)lamps drawing 65 to 150 watts. Second, heat from incandescent lamps adds to air-conditioning loads. Third, most installed recessed cans are not airtight, having holes in the fixture housing that allow conditioned air to escape from the living area into unconditioned spaces such as attics.

Addressing both lighting energy use and air leakage in recessed cans has proven challenging. Lighting energy efficiency is greatly improved by using CFLs. Air leakage can be addressed by using airtight fixtures and installation practices. But when CFLs are used in an airtight recessed can, heat generated by the lamp and ballast is trapped within the fixture. Excessive heat causes reduced light output and shortens the lifespan of the CFL. The procurement was designed to overcome these technical challenges and make new products available in the marketplace.

Introduction

For the U.S. Department of Energy (DOE), the Pacific Northwest National Laboratory (PNNL) is conducting a technology procurement to encourage faster development and market acceptance of new models of energy-efficient recessed downlights (also known as "recessed cans" or "high hats") that are rated for insulated ceilings, airtight (the common abbreviation is ICAT, standing for "insulated ceiling, air tight."), and hard-wired for compact fluorescent lamps (CFLs). See Figure 1 below for a typical recessed can fixture. The goal of the procurement is to bring at least three new models of energy-efficient recessed cans to market and to sell 400,000 of the fixtures, within the first three years of program implementation. PNNL anticipates these fixtures will sell at a price of $25 to $50, including the CFL.

Figure 1. Typical Recessed Can Light Fixture



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 procurement. PNNL identifies an appliance category with good potential for improvement and issues a request for proposals (RFP) asking manufacturers to submit bids to produce models of the appliance or technology that meet the procurement's high performance and energy efficiency standards. PNNL lessens the risks manufacturers normally take with new product development by sponsoring consumer education efforts and promoting the new technology through large volume appliance retailers, utilities, and energy efficiency organizations. PNNL has used this approach successfully to promote market acceptance of several energy-efficient technologies for DOE (Ledbetter et al. 1999).

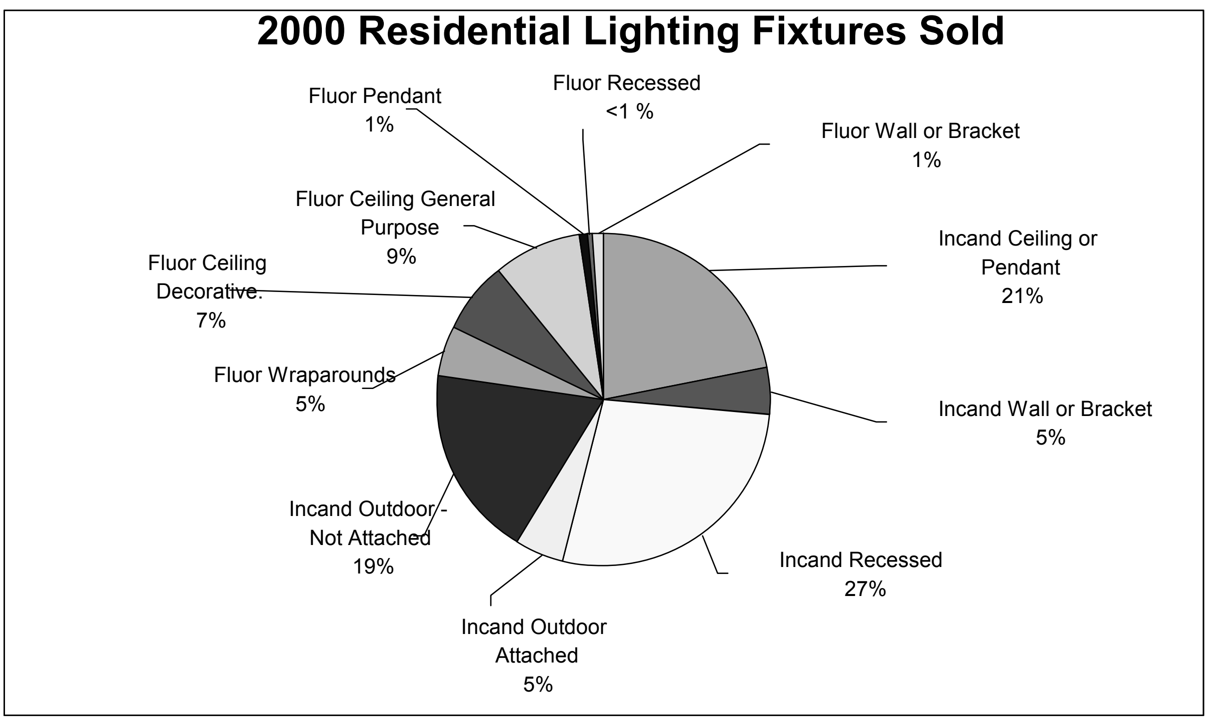
Residential recessed downlights were identified as a candidate for technology procurement in Summer 1999. In Fall 1999 PNNL began meeting with potential large volume buyers including builders, home centers, and government agencies to seek technical guidance and help with program design and to generate interest in the procurement. PNNL also met with lighting fixture manufacturers and suppliers, as well as electric utilities to solicit their guidance and knowledge and to inform them of the upcoming procurement. Based on market research, PNNL developed a set of specifications for high-efficiency, ICAT, hard-wired CFL recessed cans and prepared a RFP. The RFP was issued in November 2000. Due to relatively low response to the initial RFP and manufacturer requests for more time to respond, a second (Phase II) RFP was issued in August 2001. The RFP was sent directly to fixture manufacturers and made available through the program website at **www.pnl.gov/cfldownlights**. Lighting fixture manufacturers submitted a total of 18 prototypes. Seven proposed fixtures are now being tested in a laboratory setting and in the field. A more detailed discussion of fixture testing is provided below. Models that meet the program specifications will be promoted through the website, retail outlets, and program partners.

Why Recessed Cans are Important

Prevalence

Recessed downlights are the most popular residential lighting fixture in the United States and have become increasingly prevalent over the past five years. Some 21.7 million recessed can fixtures were manufactured in 2000, up from 17.5 million in 1999 (a 23 percent increase) (U.S. Census Bureau 2001). The California Baseline Study in 1997 found that recessed cans represented 7.8 percent of all residential lighting fixtures and 8.4 percent of lighting energy consumption in California (CEC 1999). Overall, recessed lighting fixtures, including cans, represent about 12 percent of installed residential lighting fixtures and 15 percent of total lighting energy use nationwide (Calwell 1999). Based on these numbers, PNNL estimates 350 million recessed can fixtures are currently installed in American homes, virtually all using incandescent light sources. In the year 2000, only 0.44 percent of recessed cans sold were hard-wired for CFLs (U.S. Census Bureau 2001) (see Figure 2.).

Figure 2. Recessed Downlights are the Most Popular Residential Lighting Fixtures in the United States

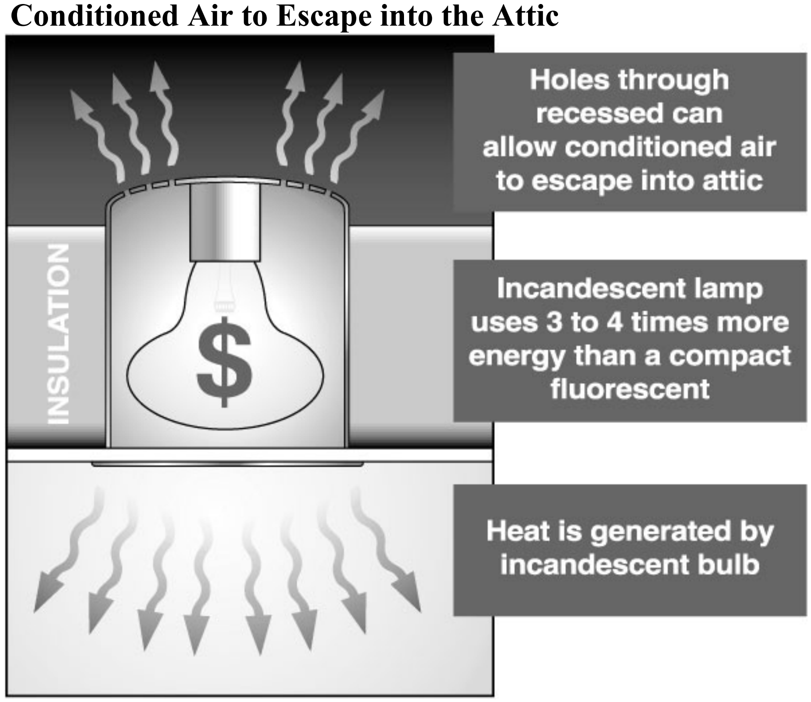


Recessed cans are relatively inexpensive compared to other types of installed residential lighting fixtures and provide an unobtrusive, directed source of light for kitchens, bathrooms, hallways, living rooms, and other areas. A basic incandescent ICAT recessed can is available at The Home Depot for $10 to $15, not including trim kit or lamp. A baffle or reflector trim kit[1] adds $5 to $20 to the cost and an incandescent reflector lamp adds another $5 for a total of $20 to $40 for an incandescent ICAT can. At least two of the fixtures proposed in the Recessed Downlights Technology Procurement have wholesale prices in the same range as ICAT incandescent cans (including the CFL). Prices of the other proposed fixtures are 25 percent to 125 percent more than those of standard incandescent ICAT cans.

Energy Intensity

Recessed cans are energy intensive in three ways (see Figure 3). First, virtually all currently installed recessed cans use incandescent light sources, typically reflector-type lamps drawing 65 to 150 watts. Second, heat from incandescent lamps adds to air-conditioning loads. Third, most installed recessed cans are not airtight, so they allow conditioned air to escape from the living area into unconditioned spaces such as attics.

Figure 3. Recessed Cans are Energy Intensive in Three Ways: Using Inefficient Incandescent Lamps, Adding Heat to Air Conditioned Spaces in Summer, and Allowing Conditioned Air to Escape into the Attic



[1] A baffle is added to reduce glare; reflectors are added to enhance light output; and trim is added for decorative reasons.

Potential to Save Energy in Recessed Cans

Addressing both lighting energy use and air leakage in recessed cans has proven challenging. Replacing the incandescent bulbs with CFLs would greatly improve the lighting energy efficiency. Air leakage can be addressed by making fixtures airtight. But when CFLs are used in an airtight recessed can, heat generated by the lamp and ballast is trapped within the fixture. Excessive heat causes the CFL to have reduced light output (10-20 percent) and a shorter lifespan. Improved fixture designs incorporating hard-wired CFLs hold the potential to address the thermal issues while providing a permanent, efficient light source.

Lighting Energy Savings

An example of the energy savings that would result from the change in light source alone is provided in Table 1.

Table 1. CFL Recessed Cans – Lighting Energy and Cost Savings

	CFL Can	**Incandescent Can**	**Savings**
Average. Lamp Wattage	28W	100W	72W
kWh Consumption/ Year	41kWh	146kWh	105kWh
Average. Electricity Cost/ Year*	$3.47	$12.38	$8.91
*Based on a rate of $0.0848 per kWh, the 2001 national average residential retail electricity price (EIA Dec. 2001. Savings do not include heating/cooling savings.			

The example in Table 1 is for a single fixture using a single lamp, and operated for an average of four hours per day. Most homes that contain recessed downlights have at least six fixtures.

Heating, Ventilation and Air Conditioning (HVAC) Energy Savings

HVAC energy savings potential comes from two sources: the reduced cooling requirements due to the use of cooler operating fluorescent lamps and ballasts and the reduced heating and cooling requirements by virtue of airtight fixture housings.

Quantifying air leakage through recessed downlights is difficult due to the many variables involved: wind driven forces, differences in fixture designs, installation technique, climate, lamp type and wattage, insulation material, hours of operation, HVAC system characteristics, etc. However, in general, the magnitude of the "stack effect"[2] is a function of the lamp wattage (Bennett and Perez-Blanco 1994). Air leakage through recessed cans fitted with incandescent lamps can be 3-5 times the passive air leakage (where passive refers to simple openings in the building envelope). Compact fluorescent lamps generate up to 75

[2] The "stack effect" occurs within non-airtight recessed cans when there is a temperature difference between the space below the fixture and the space above the fixture. Because of the temperature difference, the air inside the fixture is either more or less dense than the air outside, causing accelerated airflows through the housing.

percent less heat compared to incandescent lamps of equivalent light output, thus decreasing the temperature differential and the rate of air leakage.

The typical non-ICAT recessed downlight has approximately 1.6 in.^{2} [4.06 cm^2] of effective leakage area (ASHRAE 2001). The National Electric Code (NEC) requires that insulation not be installed within three (3) inches [7.62 cm] of non-ICAT downlights to prevent heat entrapment and to allow the free circulation of air. The typical method to maintain clearance is to place sheet metal shields around the fixtures, which creates a kind of "chimney" through which air flows from the conditioned space to the unconditioned attic.

In contrast, an ICAT recessed downlight meeting the "airtight" requirement has a maximum effective leakage area of only 0.084 in.^{2} [0.21 cm^2] (ASTM 1991). This decrease in air leakage directly impacts the consumer. For example, an ICAT recessed downlight installed in Phoenix, AZ saves a homeowner approximately $1.56 per year in cooling costs just by having the fixture installed in the building envelope (8.22¢/kWh, electric air conditioning, coefficient of performance (COP) of 2.0). The same fixture installed in Minneapolis, MN saves $3.57 per year in heating costs (based on natural gas at 66.9¢/therm, and annual fuel utilization efficiency (AFUE) of the furnace of 0.80). These savings are above and beyond the electricity savings from using more efficient light sources.

Airtight recessed cans are required under the 1995 Model Energy Code. (BOCA 1995) Approximately 60 percent of states have adopted the 1995 MEC in their state energy codes. While enforcement practices vary across states, a majority of states now have the airtight requirement in their energy codes.

Technology Procurement and the Role of Program Partners

Technology procurement is an interactive method of pulling new energy-efficient technologies and products into the marketplace. By working closely with potential buyers, technology procurement greatly increases the likelihood that products brought to market will be well received by buyers. By organizing large volume buyers for new products, technology procurement reduces the risks to manufacturers of new product introduction, and allows them to introduce products at more competitive prices.

PNNL successfully used the technology procurement approach to bring 17 new models of sub-compact fluorescent lamps (sub-CFLs) to the market between 1998 and 2001. During this three-year period, the program sold 3.3 million of the screw-based, energy-efficient sub-CFLs and brought costs down from $10 or $20 per bulb to under $5 per bulb (Ledbetter 2001). PNNL and DOE have also used the technology procurement approach to introduce super-efficient refrigerators, high-performance clothes washers, and high-efficiency photocopiers to the marketplace. In addition to recessed downlights, PNNL and DOE are currently engaged in technology procurements introducing high-efficiency commercial rooftop air conditioners and screw-in CFL reflector lamps.

Technology Procurement Process

DOE has developed a standardized but flexible technology procurement process that generally includes the following steps:

- organizing selected large volume buyers and market influencers (such as utilities, government agencies, and national accounts);
- developing technical specifications for new products in cooperation with buyers, and then reviewing them with potential manufacturers;
- issuing a competitive solicitation to potential suppliers requesting bids for new products meeting the specifications;
- selecting one or more winning products from among these bids and entering into basic ordering agreements with winning suppliers that specify the terms and prices under which volume buyers can purchase new products directly from the manufacturer or supplier; and
- marketing and promoting the new products through web sites, news releases, publications, and presentations featuring participating suppliers and retailers.

Recessed Downlights Technology Procurement Partners

While sharing many similarities with the other procurement efforts, the Recessed Downlights Technology Procurement is characterized by particularly strong partnerships with market transformation organizations and utilities across the United States. Ten organizations have formally joined the DOE program as partners and made direct financial or in-kind contributions to support the costs of product testing and promotion. These organizations are:

- Consortium for Energy Efficiency (CEE)
- Long Island Power Authority (LIPA)
- National Grid USA
- Natural Resources Defense Council (NRDC)
- Northeast Energy Efficiency Partnerships (NEEP)
- Northwest Energy Efficiency Alliance (NEEA)
- NSTAR Electric
- Sacramento Municipal Utility District (SMUD)
- United Illuminating (UI)
- Wisconsin Energy Conservation Corporation (WECC), representing Wisconsin Focus on Energy (WFOE)

These partnerships provide a basis for field-testing and promoting new products being developed under the program. Each of the partners provides links to local homebuilders and is active in ENERGY STAR® programs in its region. NEEA's ENERGY STAR® Residential New Construction Lighting Program is a good example of a partner program that is synergistic with the Recessed Downlight Technology Procurement.

NEEA's program promotes the use of ENERGY STAR® lighting fixtures in new homes in Oregon, Washington, Idaho, and Montana. A team of lighting designers and energy efficiency experts is developing lighting design templates that builders can use to construct new homes with energy-efficient lighting. A website will provide various design layouts for kitchens, bathrooms and other rooms for specific houses. Information on types of products specified in the templates will also be provided, along with links to suppliers. Because recessed cans feature so prominently in new construction, NEEA is looking to DOE's procurement as a source of high-efficiency recessed cans to promote through the web-based design templates. PNNL serves on the advisory committee for NEEA's initiative and coordinates closely with the design team.

Results of Product Testing to Date

Recessed can fixtures proposed by manufacturers in Phases I and II of PNNL's competitive solicitation have been tested in several ways to evaluate their performance. Fixtures were first assessed against the minimum requirements detailed in the technical specifications developed by PNNL with input from partners and lighting experts. These specifications address characteristics including the minimum and maximum fixture dimensions, air tightness, lamp base, type of reflector, electrical connections, power characteristics, listings and user protections, and product labeling. If the fixture met the minimum requirements, it was forwarded to the Luminaire Testing Laboratory (LTL, a private luminaire testing facility located in Allentown, Pennsylvania) for two different laboratory tests, called the Short-Term Test and the Long-Term Test. The objectives of the laboratory tests were the following:

- Determine a "thermal factor" corresponding to the reduction in delivered luminous flux by virtue of operation in a simulated insulated ceiling environment.
- Verify steady state ballast case temperature listed by manufacturer when operated in a simulated insulated ceiling environment.
- Measure steady state lamp base temperature when operated in a simulated insulated ceiling environment.
- Measure steady state ambient air temperature surrounding the CFL(s) when operated in a simulated insulated ceiling environment.
- Determine product longevity and lumen maintenance under long-term cyclic operation when operated in a simulated insulated ceiling environment.

Short-Term Test

The Short-Term Test consisted of operating the fixture in a simulated insulated ceiling at full power for 12 hours, while taking temperature measurements at several locations. The Short-Term Test was conducted using a thermal testing apparatus capable of the following:

- Maintains ambient temperature surrounding the apparatus to 77°F ±2°F [25°C ±1°C].
- Contains loose-fill cellulose insulation to a minimum depth of 12 in. [30.48 cm].

- Is fitted with an easily removable, tight closing lid gasketed for air tightness.
- Supports the luminaire at a distance of 36 in. [91.44 cm] above the illuminance measurement plane.
- Automatically samples and records the *ballast case temperature* in a minimum of two locations for a duration of 12 hours. Prior to performing the test, the hottest points of the ballast are identified and thermal sensing probes are attached in these locations. Sampling is conducted at a minimum interval of 1 minute for the first hour and a maximum interval of 5 minutes for the remaining 11 hours.
- Automatically samples and records the *ambient temperature surrounding the lamp* for a duration of 12 hours. A temperature sensor is installed at the midpoint between the centroid of the lamp and the reflector in a direction perpendicular to the lamp. The thermal sensor is protected from direct/indirect radiant heat. Sampling is conducted at a minimum interval of 1 minute for the first hour and a maximum interval of 5 minutes for the remaining 11 hours.
- Automatically samples and records the *lamp base temperature* in a minimum of two locations, specified by the lamp manufacturer, for a duration of 12 hours. Sampling is conducted at a minimum interval of 1 minute for the first hour and a maximum interval of 5 minutes for the remaining 11 hours.
- Automatic sampling equipment synchronizes all temperature measurement devices.
- Is equipped with an array consisting of a minimum of five (5) illuminance meters located 36 in. [91.44 cm] below the thermal testing apparatus. One meter is located directly below the center of the luminaire. The remaining four meters are oriented 12 in. [30.48 cm] from the center meter, at 90° intervals. Distances are measured from center to center of the meters.

Fixtures were determined to have passed the Short-Term Test if they met the following two criteria:

- The fixture produced at least 900 net lumens. The net lumens are determined by multiplying the rated fixture lumens, as documented by results of the IESNA LM-41-98 test provided by the manufacturer, (IES 1998) by a thermal factor to account for the effect of increased heat build-up caused by operation in an insulated ceiling. The thermal factor is the ratio of the average lumens produced by the fixture before it is immersed in insulation to the average lumens produced by the fixture after immersion in insulation.
- Recorded ballast case temperatures did not exceed the ballast's warranted temperature (the temperature the manufacturer listed as the maximum).

In Phase I of the RFP process, four (4) fixtures were proposed. Two were determined not to meet the minimum requirements identified in the specifications. The remaining two fixtures initially failed the Short-Term Test. In both cases, the fixture manufacturer modified the fixture and repeated the Short-Term Test with success. In Phase II, 18 fixtures were proposed. Two fixtures were eliminated immediately because they did not meet the minimum requirements of the specifications. A total of 13 fixtures were subjected to the Short-Term

Test. (Three fixtures were not tested because they were essentially identical to fixtures that were tested). Six of the 13 fixtures failed the Short-Term Test because their ballast case temperatures exceeded rated levels and/or they failed to produce a minimum of 900 net lumens.

Long-Term Test

A total of nine (9) fixtures (two from Phase I and seven from Phase II) ultimately passed the Short-Term Test. These fixtures were then subjected to the Long-Term Test. This test is identical to IESNA LM-65-91 (IES 1991) but is carried out in a simulated insulated ceiling environment. The Long-Term Test was conducted using a testing apparatus described as follows:

- Maintains ambient temperature surrounding the apparatus to 75°F ± 5°F [25°C ±3°C].
- Contains loose-fill cellulose insulation to a minimum depth of 12 in. [30.48 cm].
- Supports the luminaire at a distance of 36 in. [91.44 cm] above the illuminance measurement plane.
- Automatically cycles power to all testing luminaires at a rate of 3 hours "on" followed by 20 minutes "off" for a period of 12 months.
- Automatically senses and records thermal/catastrophic failure of the lamp and/or ballast.

Success in the Long-Term Test requires that fixtures continue operating and maintain at least 80 percent of their initial net lumens upon reaching 40 percent of rated lamp life. The specifications require a minimum rated lamp life of 10,000 hours, so fixtures must maintain a lumen level of at least 80 percent after they have burned for 4,000 hours. Under the testing regime described above, 4,000 hours of lamp operation is reached after about six months of long-term testing.

One of the Phase I products failed in the Long-Term Test because its lumen output dropped below 80 percent of initial lumens before 40 percent of elapsed lamp life. This was a product that used a 40-watt, "2C", double "circline" lamp. Other fixtures being tested have not yet completed 4,000 hours of testing. However, all of the others use quad or triple tube lamps containing amalgam, and are thus expected to exhibit better lumen maintenance than the non-amalgam circline lamp. All fixtures currently being tested are non-dimming.

Field Testing

The next required performance test is field-testing in model or occupied new homes. Fixtures that successfully complete six months of long-term cyclic testing are eligible for field-testing. PNNL is carrying out two types of field tests during 2002 and 2003:

- Fully instrumented tests in which PNNL will install on each fixture a set of thermocouples located on the ballast and wired to a central data logger. In addition to temperature data, PNNL will monitor the fixture's operating hours by installing current transformers in appropriate locations. These data will allow subsequent calculation of energy savings and local peak power reduction. Data will be periodically downloaded from the loggers for evaluation by PNNL.

- Non-instrumented tests in which fixtures will be installed in model or occupied new homes.

In both types of field tests, the fixtures will be evaluated according to the following two criteria, based on information collected from builders, visitors and occupants:

1. Ease of installation compared to a standard incandescent ICAT recessed can and
2. Functional operation of the fixture as a suitable replacement for an incandescent ICAT can for the duration of the field test.

PNNL will also collect feedback from homebuilders, partner utilities, visitors, and occupants on the following qualitative factors:

- quality of light produced by the fixture
- perceived fixture glare
- light levels
- overall appearance of the fixtures, including the trim ring, reflector, and light source.

Conclusions

As product testing is completed, fixtures that have met the requirements of the program will be promoted for sale. Promotional efforts will be conducted by PNNL through the program website which will provide descriptions of the lamps and links to the manufacturers' websites for electronic purchasing. PNNL will support promotional efforts through program partner organizations, through large volume retailers of lighting fixtures, and through utilities. PNNL will conclude the program with a program evaluation.

Because recessed cans are becoming such a significant portion of new residential lighting, ICAT hard-wired CFL fixtures could yield significant energy savings for years to come. The goal of the Recessed Downlight Technology Procurement is to bring at least three new models of energy-efficient recessed cans to market and to sell 400,000 of the fixtures, within the first three years of program implementation. PNNL anticipates these fixtures will sell at a price of $25 to $50, including the lamp.

Based on input from manufacturers, retailers, and program partners thus far, PNNL anticipates that technology procurement will be a successful approach for speeding the introduction of new, energy-efficient, recessed downlights into the market.

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