U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products

## Part 3: LED Environmental Testing

**DOE Solid-State Lighting Webcast**
2013-03-28

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Pacific Northwest National Laboratory

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Compa Industries

# Goals and Objectives

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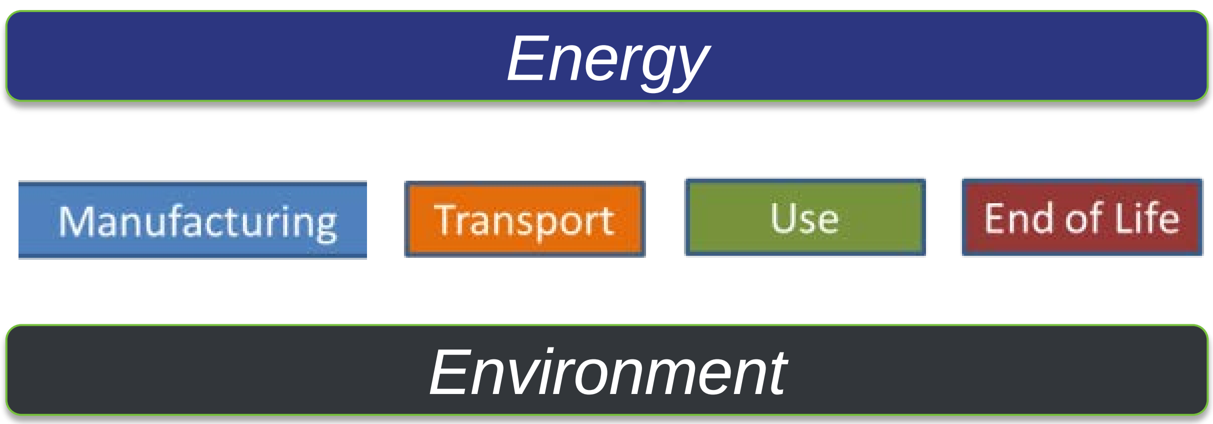
- Review existing literature on energy and environment assessments of lighting options.
- Determine environmental performance over the lifecycle of lighting options.
- Determine end of life impacts of LED products.

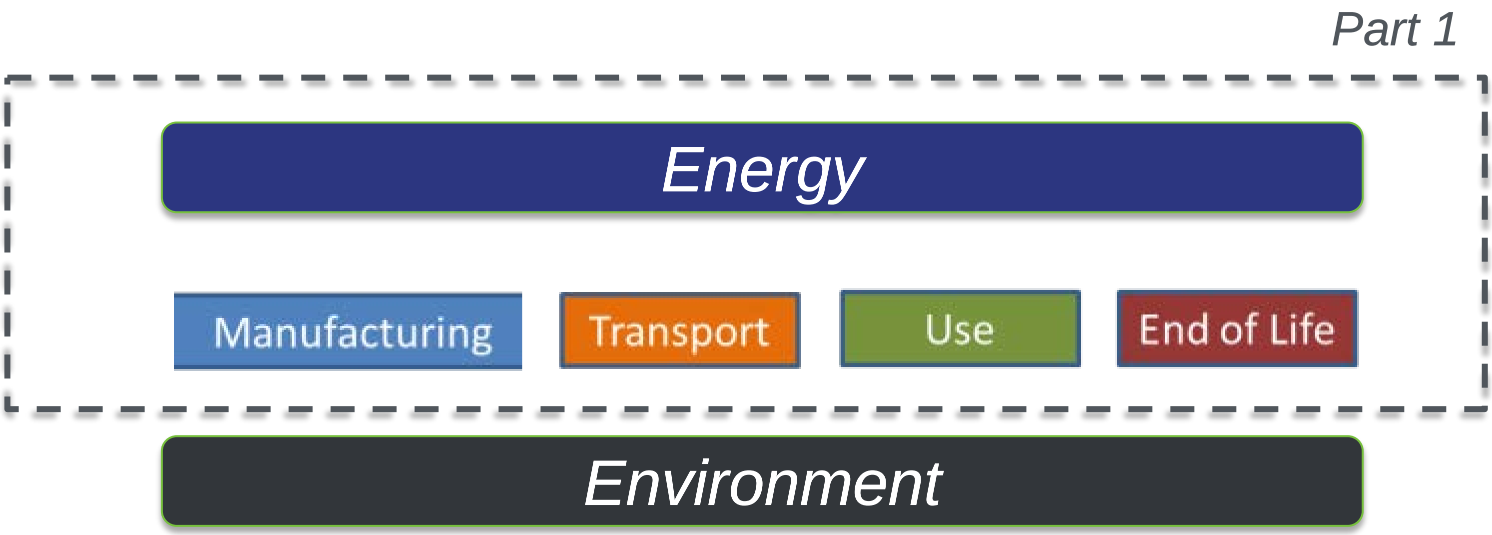
# Project Overview

- *Evaluate energy and environmental impacts of lighting options*



# Project Overview

- *Part 1: Focus on energy and LCA evaluations performed by prior researchers.*



# Project Overview

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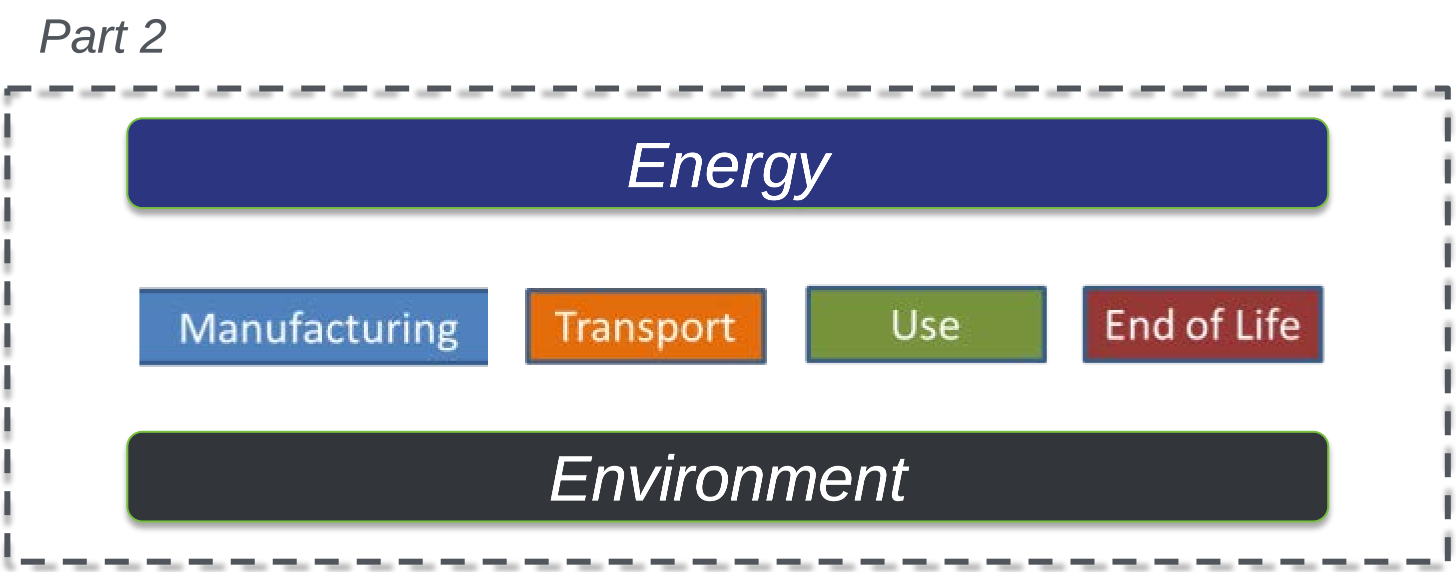
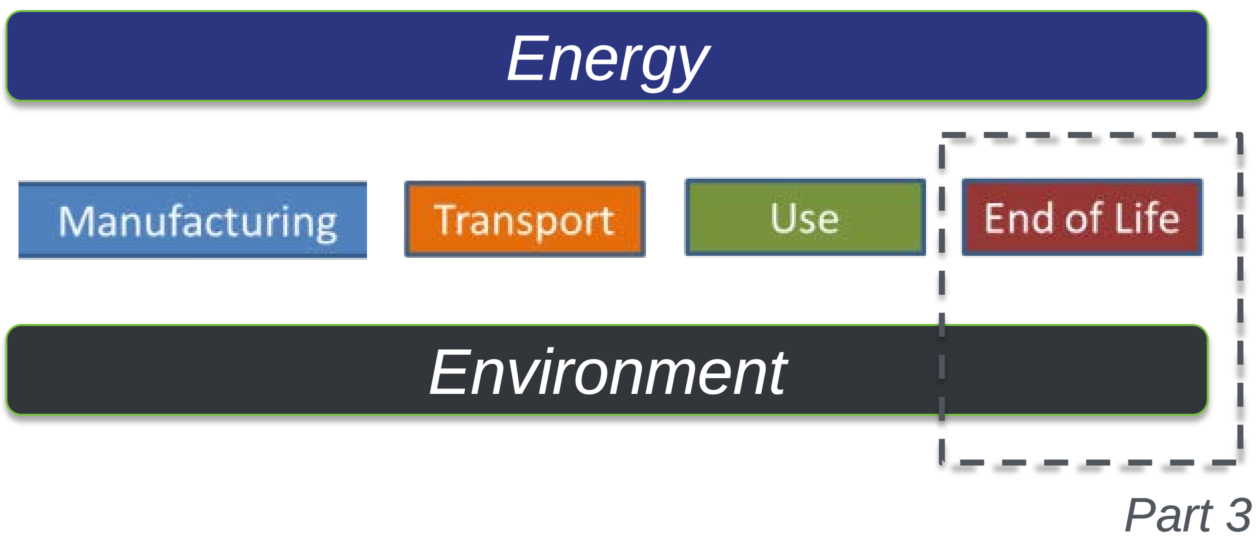
- *Part 2: Focus on energy and environment with manufacturing process not documented in prior reports.*

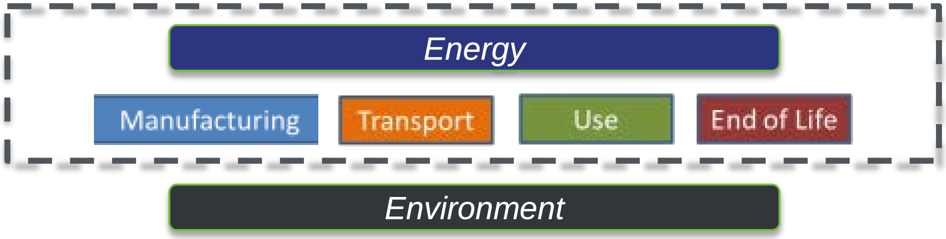


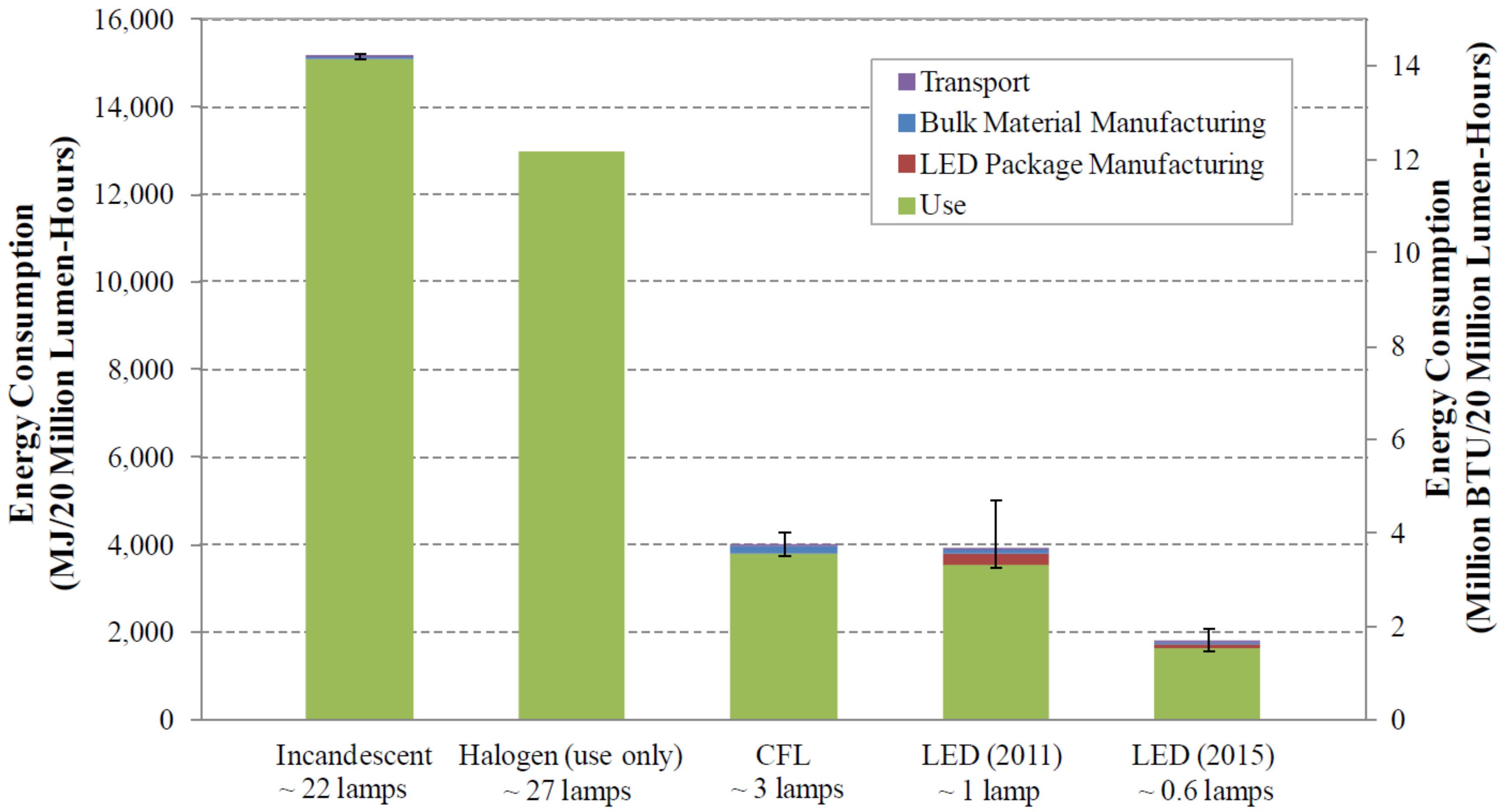
# Project Overview

- *Part 3: Focus on end of life disposal.*

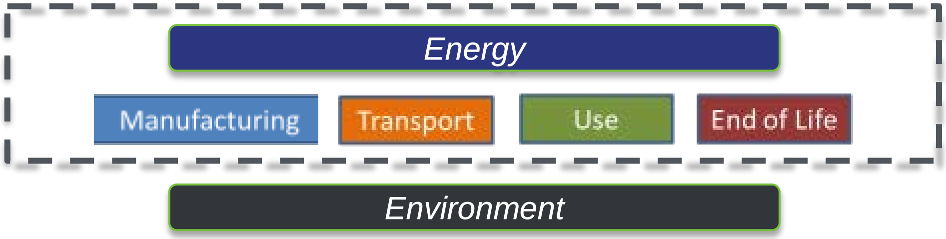


- Completed in February 2012 (www.ssl.energy.gov/tech_reports.html)
- Compared a currently-available LED life-cycle energy consumption to an incandescent lamp and CFL technologies based on 10 literature studies.
- Performed a meta-analysis based on a functional unit of 20 million lumen-hours to compare the studies.

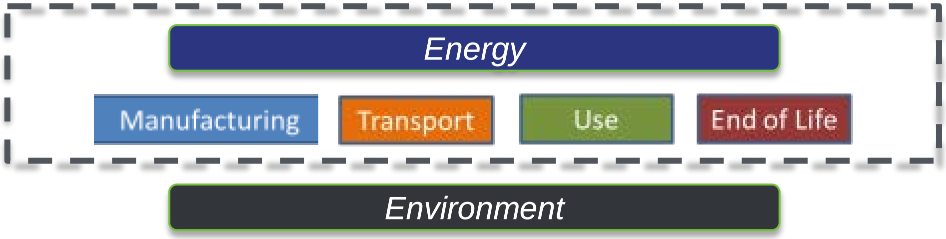



16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Energy Consumption (MJ/20 Million Lumen-Hours)
14
12
10
8
6
4
2
0
Energy Consumption (Million BTU/20 Million Lumen-Hours)
Transport
Bulk Material Manufacturing
LED Package Manufacturing
Use
Incandescent ~ 22 lamps
Halogen (use only) ~ 27 lamps
CFL ~ 3 lamps
LED (2011) ~ 1 lamp
LED (2015) ~ 0.6 lamps

- Concluded that the life cycle energy consumption of LED lamps and CFLs are similar at approximately 3,900 MJ per 20 million lumen-hours. Incandescent lamps consume significantly more energy (approximately 15,100 MJ per 20 million lumen-hours).
- Concluded that the use phase is the most important contributor to the energy consumption, followed by manufacturing of the lamps and finally transportation (less than 1% of energy consumption).

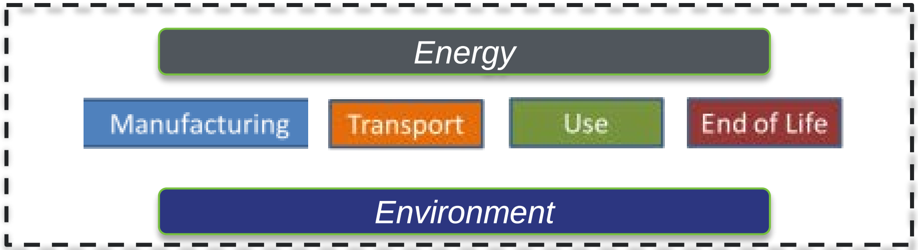


- Identified the high uncertainty in energy consumption associated with the manufacturing process estimates in surveyed literature range from 0.1% to 27% of the total life-cycle energy consumption.
- Due to this uncertainty the manufacturing process became a focus for Part 2.

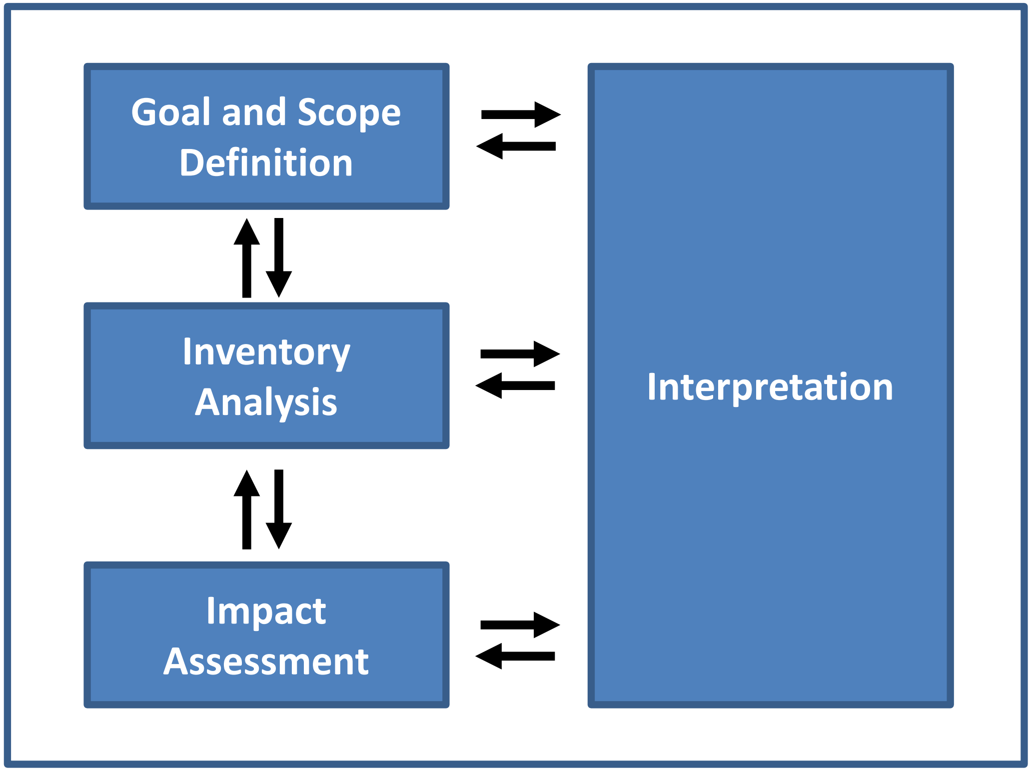


# Overview

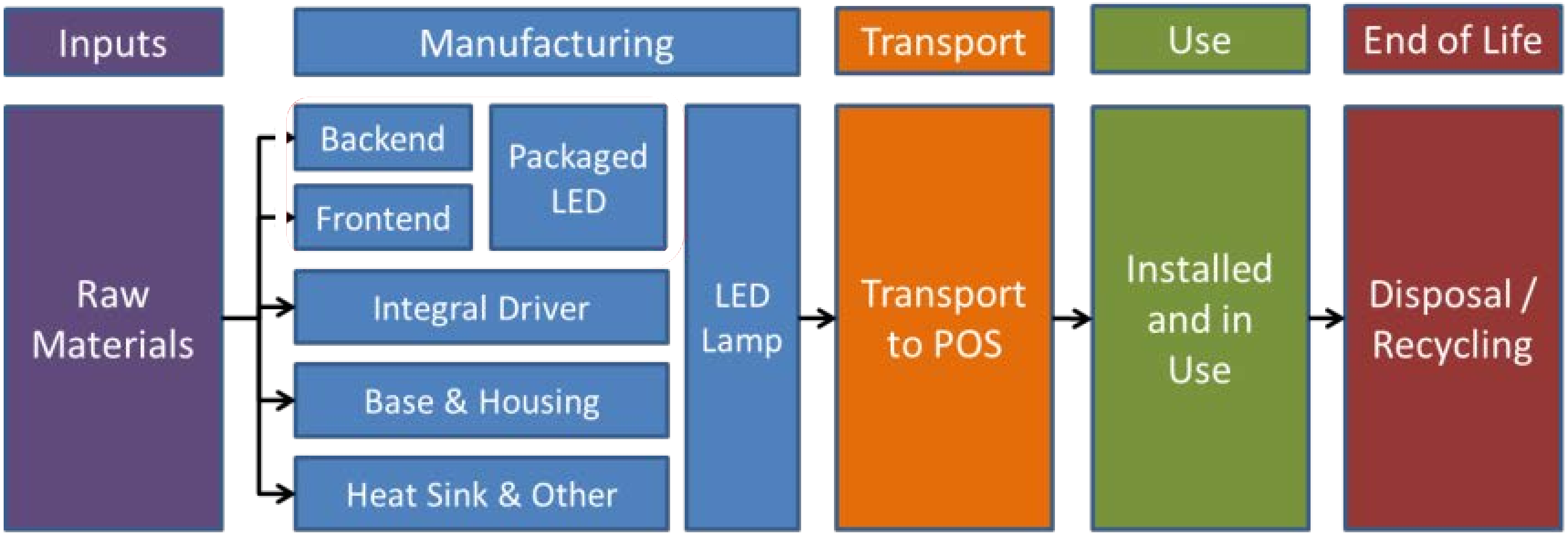
- Completed in June 2012 (www.ssl.energy.gov/tech_reports.html)
- Produced a more detailed assessment of the manufacturing process for LED products used in lighting applications. No publicly available LCA had provided this before.
- Provided a comparative LCA with other currently-available lighting products based on the improved manufacturing analysis, and considering a wider range of environmental impacts.
- Included comparison with projected characteristics of an LED lamp available in 2017.



LCA Framework

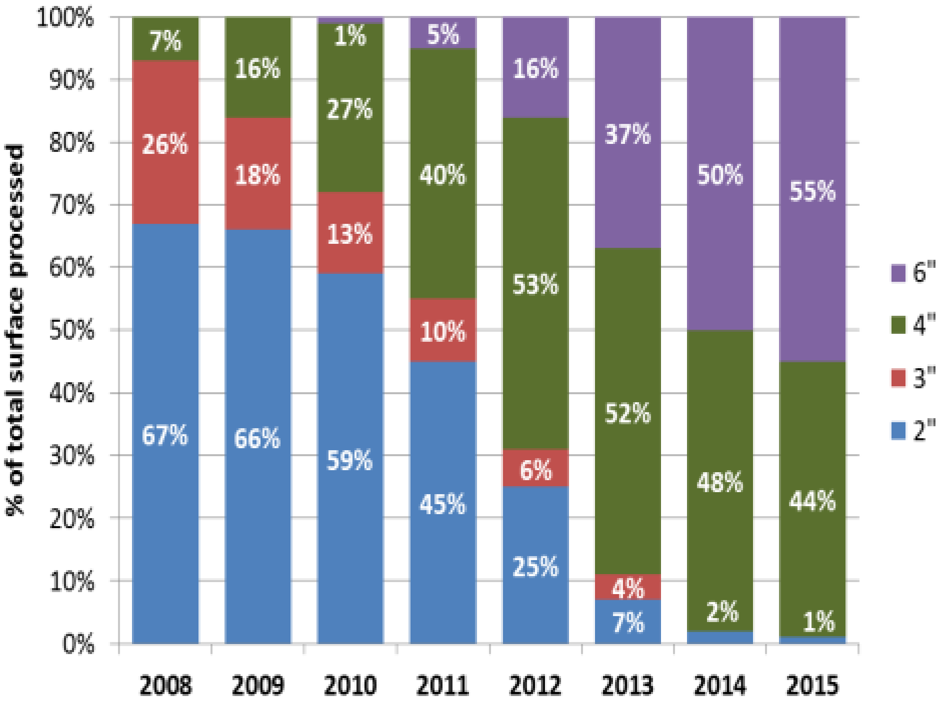



Source: ISO 14044:2006



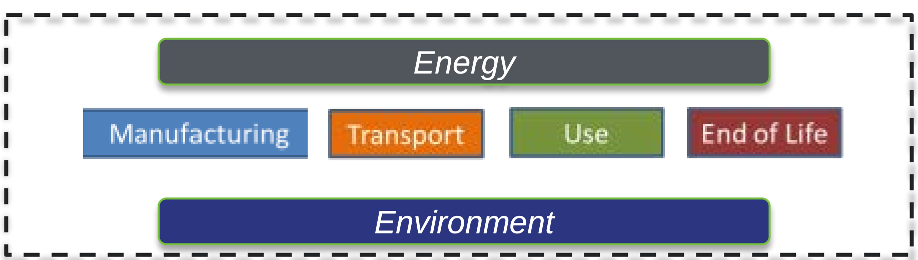

*For more information on Ecoinvent database, see Swiss Center for Life Cycle Inventories at: http://www.ecoinvent.org/documentation/*

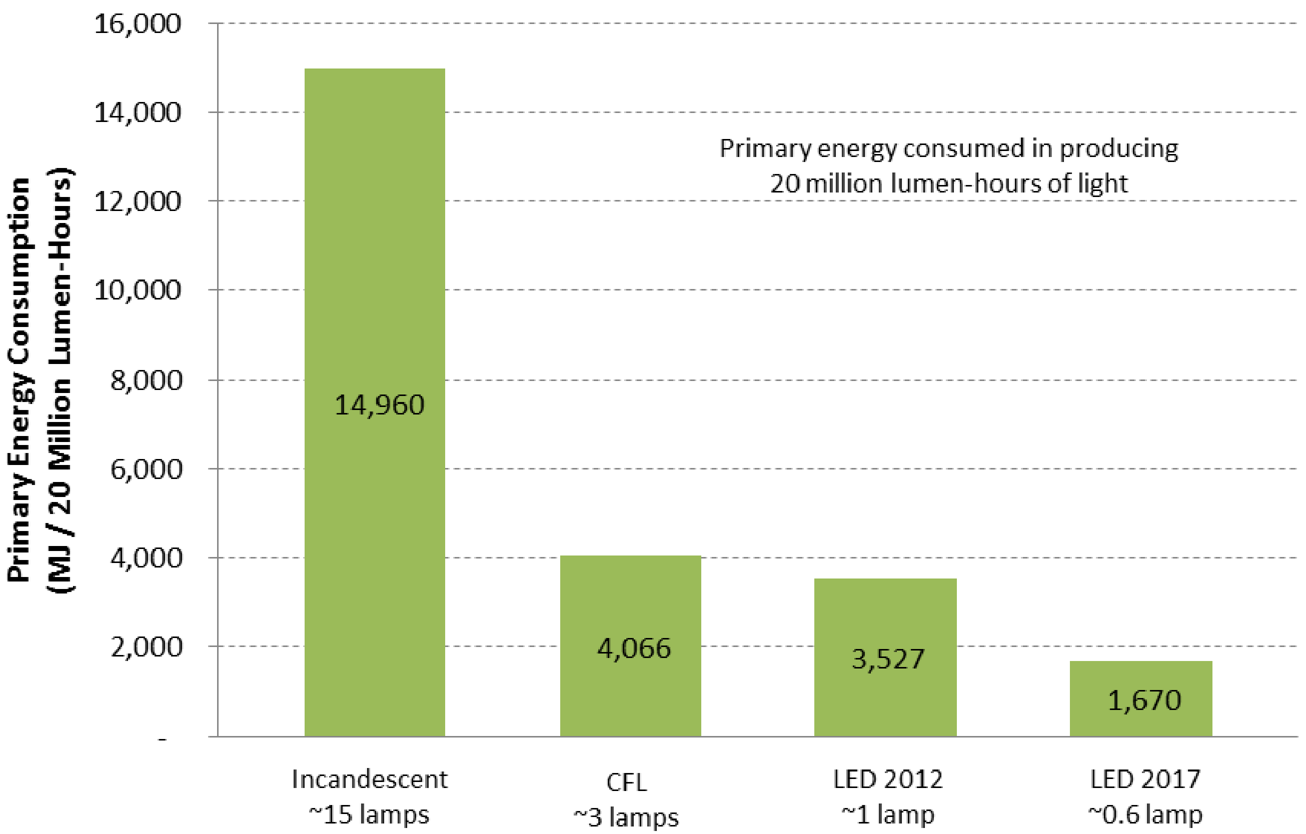
- Three-inch sapphire wafer substrate
- Indium-Gallium Nitride grown on sapphire substrate
- High brightness LED packages (i.e., greater than 0.5 watt / package)
- Deep-blue LEDs (which are pumping a remote phosphor)
- Figure Source: Yole Développement, 2011 as published in Compound Semiconductor, December 2011



# Lamp Characteristics

| Characteristics | Incandescent | CFL | LED lamp – 2012 | LED lamp – 2017 |
|---|---|---|---|---|
| Power Consumption | 60 watts | 15 watts | 12.5 watts | 6.1 watts |
| Lumen Output | 900 lumens | 825 lumens | 812 lumens | 824 lumens |
| Efficacy | 15 lm/W | 55 lm/W | 65 lm/W | 134 lm/W |
| Lamp Lifetime | 1500 hours | 8000 hours | 25,000 hours | 40,000 hours |
| Total Lifetime Light Output | 1.35 Mlm-hr | 6.6 Mlm-hr | 20.3 Mlm-hr* | 33.0 Mlm-hr |
| Impacts Scalar | 15.04 | 3.08 | 1.00 | 0.61 |




Primary Energy Consumption (MJ / 20 Million Lumen-Hours)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
-
Primary energy consumed in producing 20 million lumen-hours of light
14,960
4,066
3,527
1,670
Incandescent ~15 lamps
CFL ~3 lamps
LED 2012 ~1 lamp
LED 2017 ~0.6 lamp

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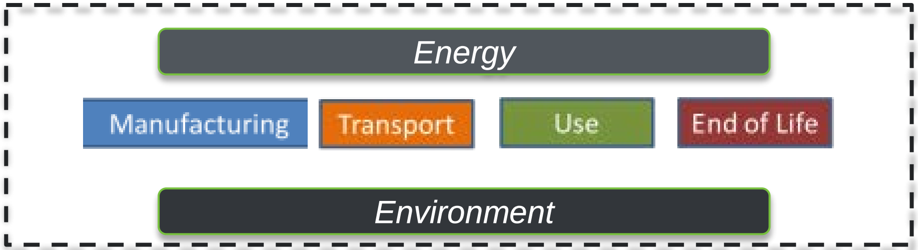
- Confirmed that energy-in-use is the dominant environmental impact, with the 12.5-watt LED lamps and 15-watt CFL performing better than the 60-watt incandescent lamp.
- Concluded that energy-in-use phase of the life-cycle dominates both energy and environmental impacts.
- Concluded the CFL is slightly more harmful than the 2012 integrally ballasted LED lamp against all but one criterion – hazardous waste landfill – where the large aluminum heat sink causes the impacts to be slightly greater for the LED lamp than for the CFL.



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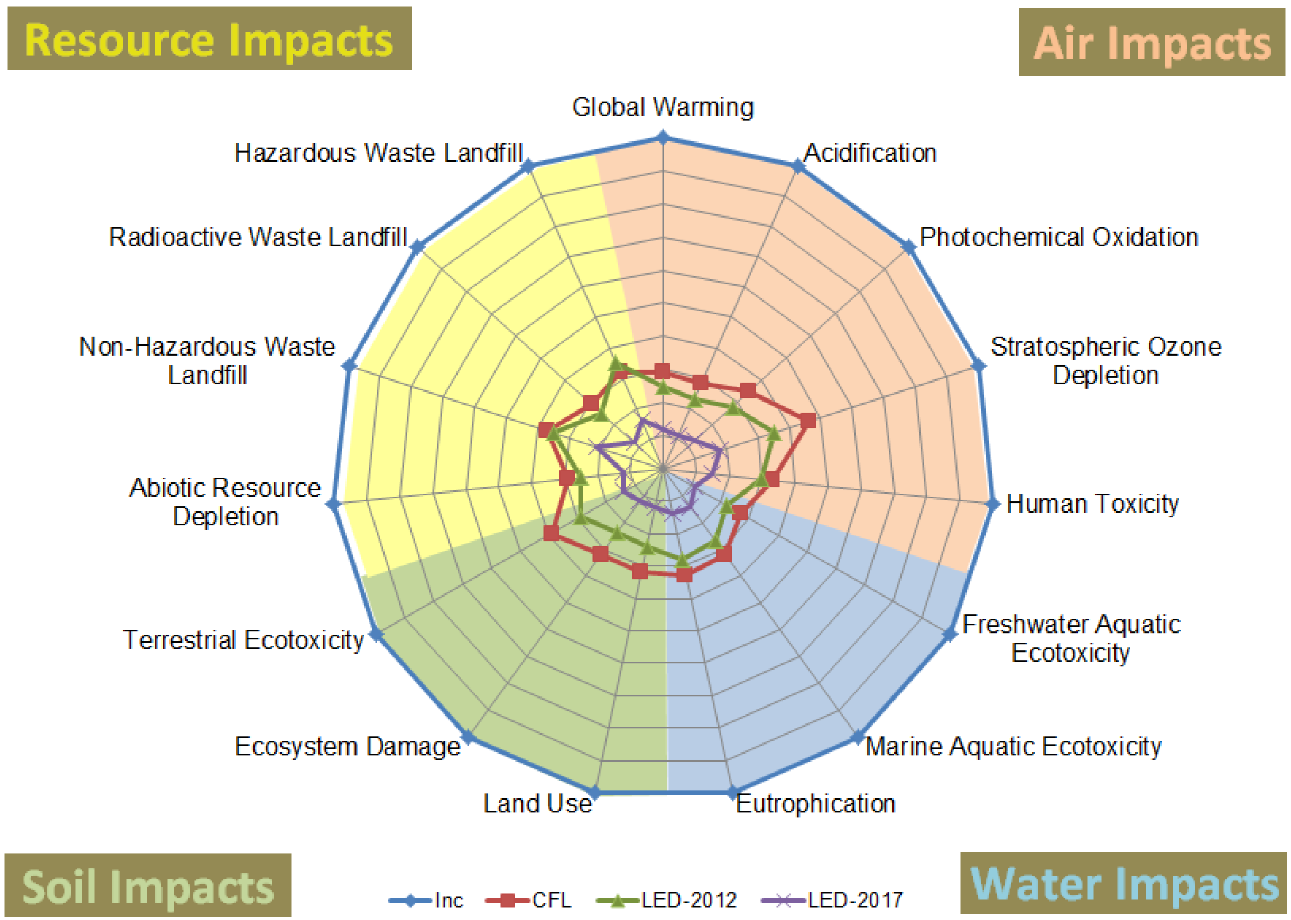
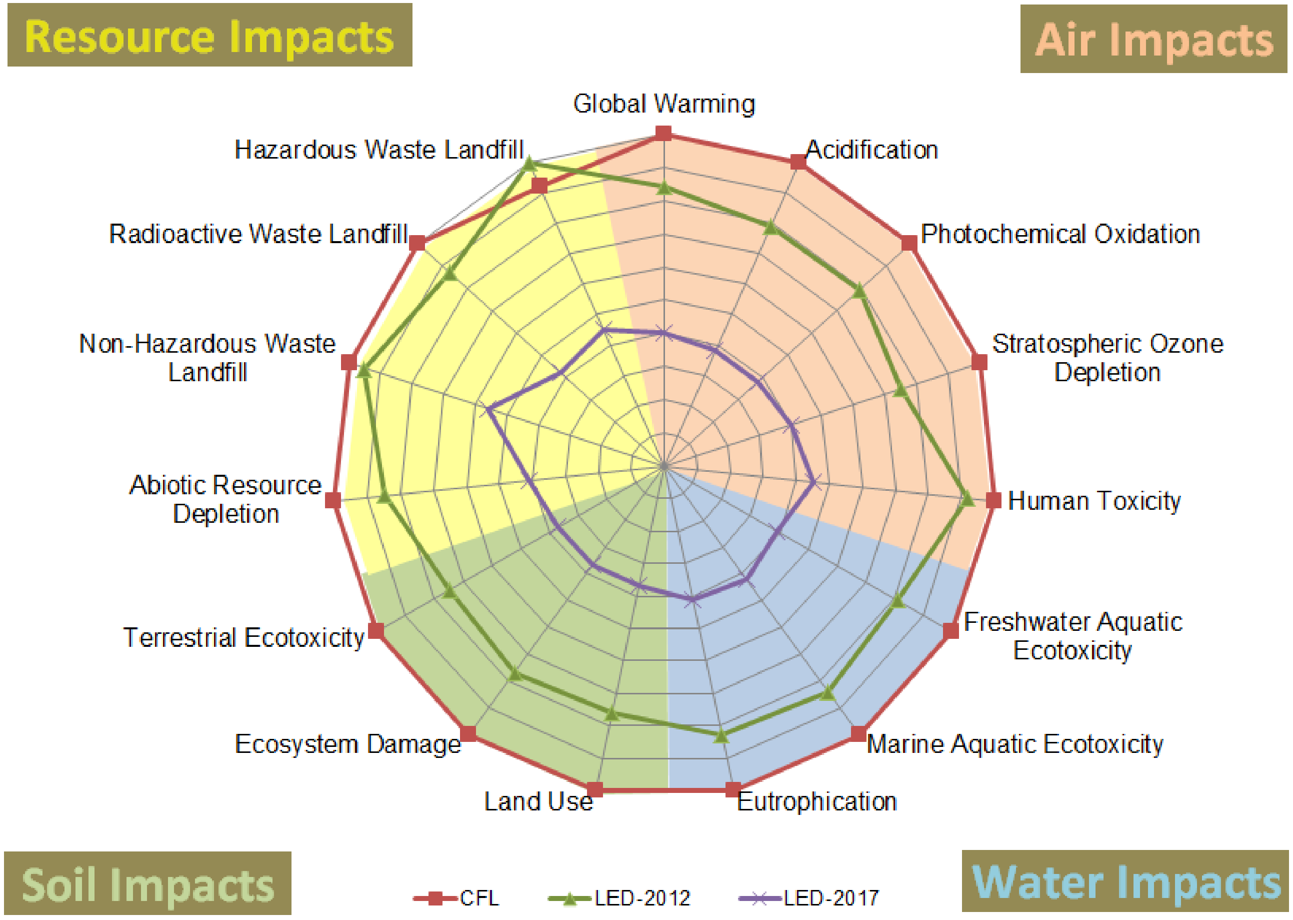
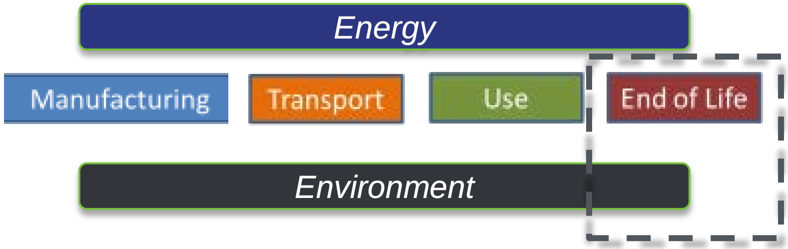



Resource Impacts
Air Impacts
Soil Impacts
Water Impacts
Global Warming
Acidification
Photochemical Oxidation
Stratospheric Ozone Depletion
Human Toxicity
Freshwater Aquatic Ecotoxicity
Marine Aquatic Ecotoxicity
Eutrophication
Land Use
Ecosystem Damage
Terrestrial Ecotoxicity
Abiotic Resource Depletion
Non-Hazardous Waste Landfill
Radioactive Waste Landfill
Hazardous Waste Landfill
CFL
LED-2012
LED-2017

## Overview



- Disassembly and chemical testing of LED and conventional lamps to ascertain whether potentially toxic elements are present in concentrations exceeding regulatory thresholds for hazardous waste
  - Completed March 2013 (www.ssl.energy.gov/tech_reports.html)



# Part 3: LED Environmental Testing
## Overview



- Used standard testing procedures from the U.S. Environmental Protection Agency (EPA) and the State of California (CA)
  - Conservative due to specified milling for environmental availability
  - Process modeled after SB 20 Report, “Determination of regulated elements in discarded laptop computers, LCD monitors, Plasma TVs and LCD TVs” (Hazardous Material Laboratory, California Department of Toxic Substances Control, December 2004)
    - References CA Standard Operating Procedure (SOP) 914-S for special handling of mercury-containing lamps (e.g., CFLs)
  - Testing conducted by two independent laboratories accredited through the National Environmental Laboratory Accreditation Program (NELAP) or the CA Environmental Laboratory Accreditation Program (ELAP)
- Evaluated results against CA and Federal regulations

## Standard test methods

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- EPA Method 3050, Acid Digestion of Sediments, Sludges, and Soils
  - Determines the "***total***" amount of a given element in a lamp (excluding silicates) relative to the mass of the lamp
  - Test results for 17 elements can be compared with their respective CA Total Threshold Limit Concentrations (TTLC), measured in mg/kg
- CA Waste Extraction Test (WET)
  - Estimates the ***soluble*** amount of a given element that might be dissolved and transmitted to groundwater by fluids passing through a landfill
  - Test results for 17 elements can be compared with their respective CA Soluble Threshold Limit Concentrations (STLC), measured in mg/L
- EPA Toxic Characteristic Leaching Procedure (TCLP)
  - Estimates the ***soluble*** amount of a given element that might be dissolved and transmitted to groundwater by fluids passing through a landfill
  - Test results for 8 of the 17 elements regulated in CA can be compared with their respective Federal Regulatory Levels (FRL), measured in mg/L

- CA Title 22, Chapter 11, Article 3
  - Characteristics of Hazardous Waste
- 40 CFR 261.24
  - Toxicity Characteristic

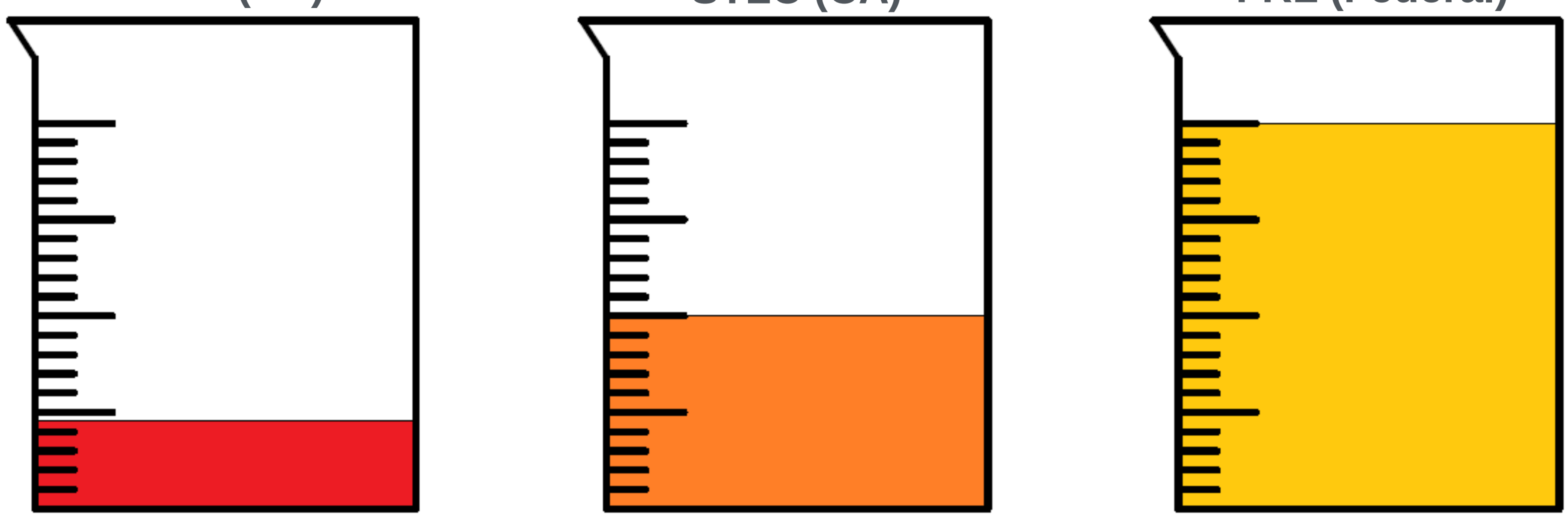
| Element | TTLC (mg/kg) | STLC (mg/L) | FRL (mg/L) |
|---|---|---|---|
| Antimony | 500 | 15 | - |
| Arsenic | 500 | 5 | 5 |
| Barium | 10,000 | 100 | 100 |
| Beryllium | 75 | 0.75 | - |
| Cadmium | 100 | 1 | 1 |
| Chromium | 2,500 | 5 | 5 |
| Cobalt | 8,000 | 80 | - |
| Copper | 2,500 | 25 | - |
| Lead | 1,000 | 5 | 5 |
| Mercury | 20 | 0.2 | 0.2 |
| Molybdenum | 3,500 | 350 | - |
| Nickel | 2,000 | 20 | - |
| Selenium | 100 | 1 | 1 |
| Silver | 500 | 5 | 5 |
| Thallium | 700 | 7 | - |
| Vanadium | 2,400 | 24 | - |
| Zinc | 5,000 | 250 | - |

## Part 3: LED Environmental Testing
## Process based on SB 20 report



- Test methods differ in terms of type and volume of acid used
  - Figure below illustrates relative concentrations (decreasing from left to right) for a given aliquot mass and a single element
    - Relative volume shown for Method 3050 is one of many possibilities
  - Method 3050 typically results in a more complete digestion, and can be used to estimate maximum possible extraction for WET or TCLP
  - CA is considered significant *and* more stringent than Federal

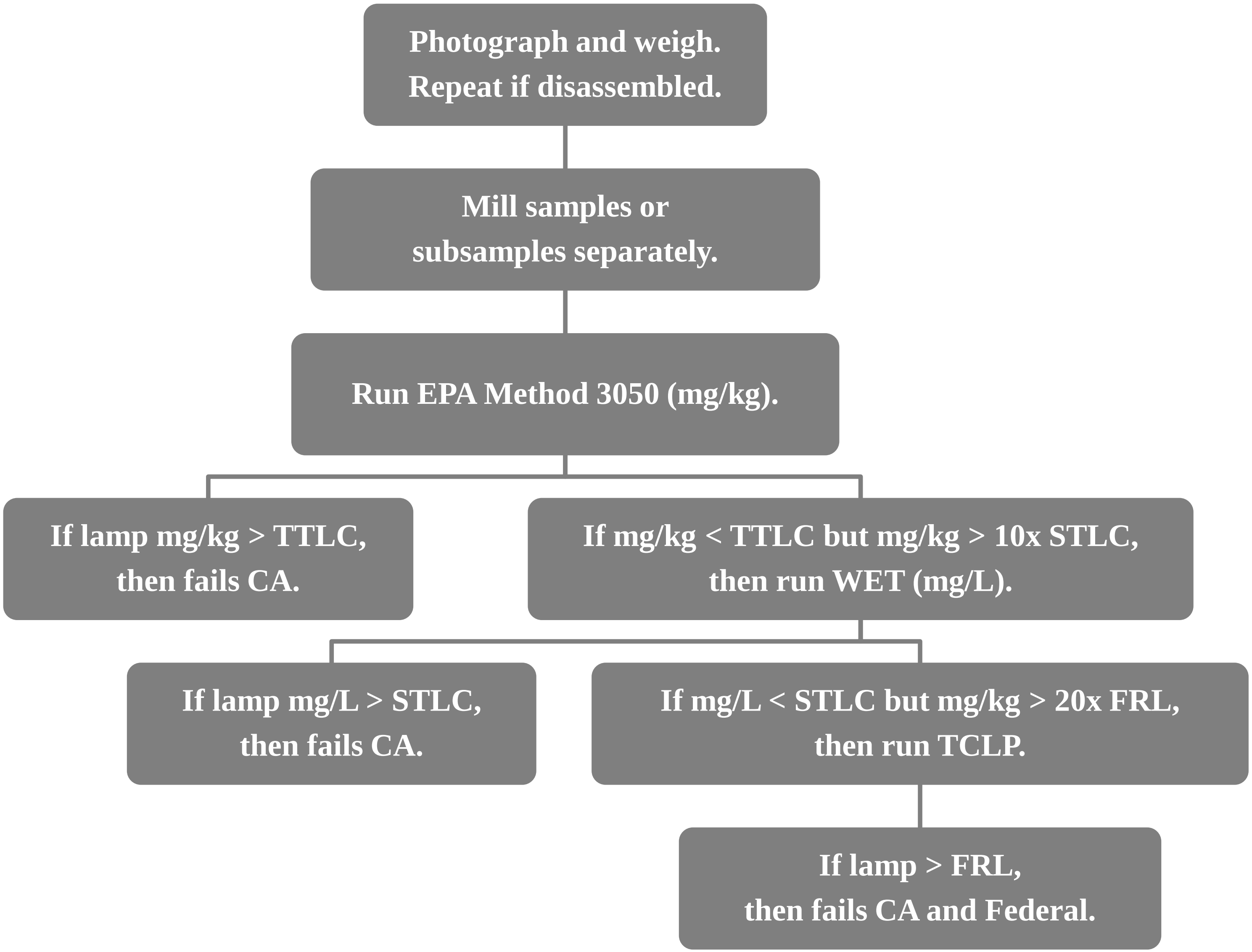
**TTLC (CA)** | **STLC (CA)** | **FRL (Federal)**



**Method 3050** | **WET ≤ 0.10 Method 3050** | **TCLP ≤ 0.05 Method 3050**

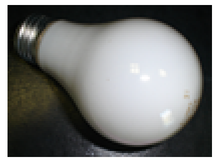
# Process based on SB 20 report





## Models evaluated

- Tested 22 samples, representing 11 different models

| | Incandescent | CFL | LED |
|---|---|---|---|
| Omnidirectional (60W equivalent) |  INC-1(a,b,c,d) <br>  HAL-1(a,b) |  CFL-1(a,b) <br>  CFL-2(a,b,c) |  LED-1(a,b) <br>  LED-2(a,b) |
| Directional (65W equivalent) |  INC-2(a) <br>  HAL-2(a) |  CFL-3(a) |  LED-3(a,b) <br>  LED-4(a,b) |

## Models evaluated

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- Omnidirectional lamps

| Model | Sample | Test lab | Disassembled | Rated output (lm) | Rated input (W) | Rated life (h) |
|---|---|---|---|---|---|---|
| INC-1 | (a) | A | ✓ | 860 | 60 | 1,000 |
| | (b) | B | ✓ | | | |
| | (c) | A | - | | | |
| | (d) | A | ✓ | | | |
| HAL-1 | (a) | A | ✓ | 785 | 43 | 1,000 |
| | (b) | A | ✓ | | | |
| CFL-1 | (a) | A | ✓ | 825 | 13 | 8,000 |
| | (b) | A | ✓ | | | |
| CFL-2 | (a) | A | ✓ | 900 | 14 | 10,000 |
| | (b) | A | - | | | |
| | (c) | A | ✓ | | | |
| LED-1 | (a) | A | ✓ | 850 | 13.5 | 50,000 |
| | (b) | A | - | | | |
| LED-2 | (a) | A | ✓ | 800 | 12.5 | 25,000 |
| | (b) | A | ✓ | | | |

# Models evaluated



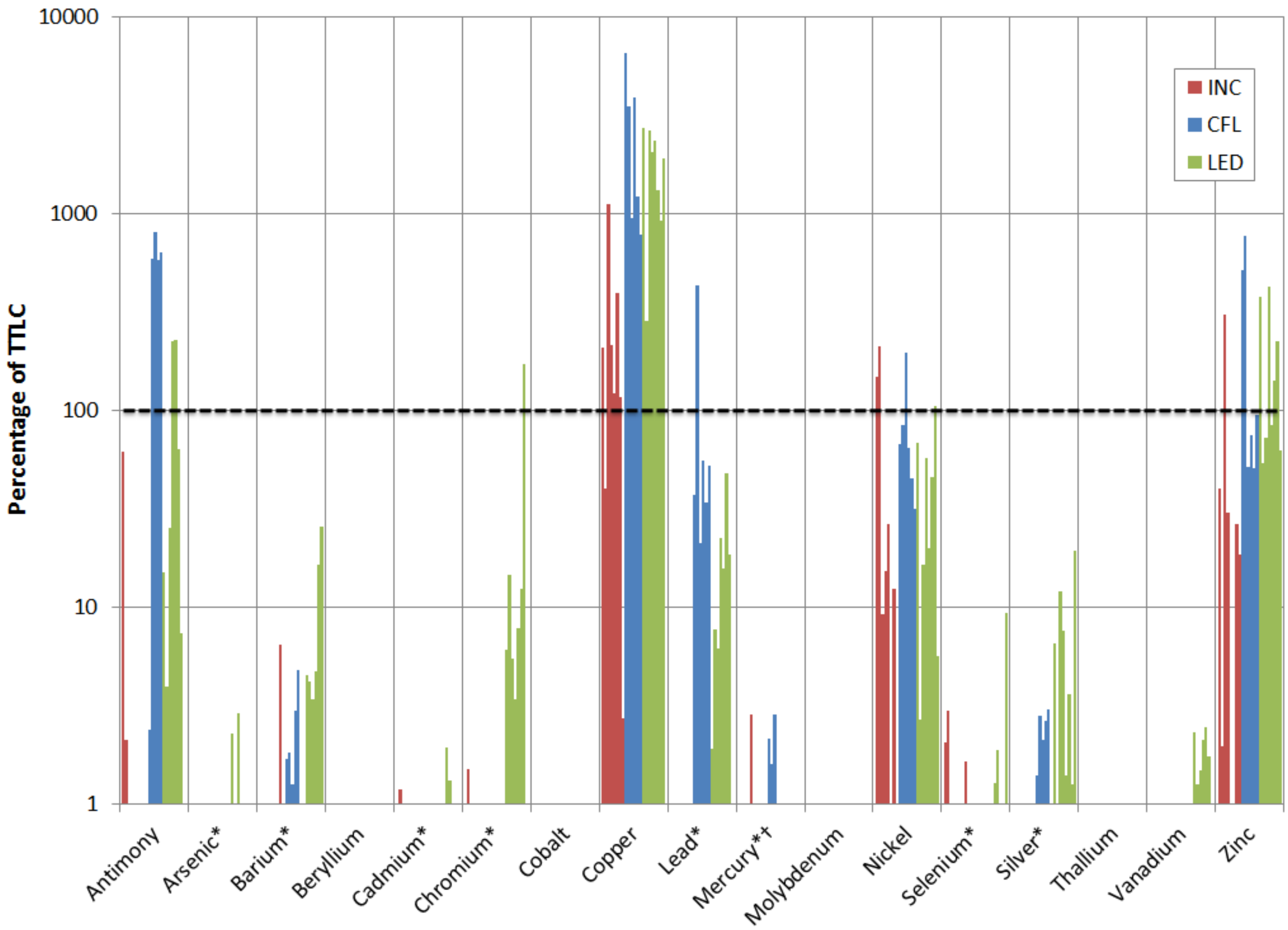
- Directional lamps

| Model | Sample | Test lab | Disassembled | Rated output (lm) | Rated input (W) | Rated life (h) |
|---|---|---|---|---|---|---|
| INC-2 | (a) | A | ✓ | 635 | 65 | 2,000 |
| HAL-2 | (a) | A | ✓ | 600 | 40 | 3,000 |
| CFL-3 | (a) | A | ✓ | 720 | 15 | 6,000 |
| LED-3 | (a) | A | ✓ | 600 | 12 | 35,000 |
| | (b) | B | ✓ | | | |
| LED-4 | (a) | A | ✓ | 575 | 10.5 | 50,000 |
| | (b) | B | ✓ | | | |

- Samples initially acquired in January-April 2012
  - Supplemental sample of LED-1(a) acquired in June 2012
  - Replacement sample of LED-4(a) acquired in October 2012

# Results for all samples: whole-lamp analysis






* Federally-regulated element.

† Some mercury in CFLs is presumed to have escaped detection.

# Incandescent lamps exceeding TTLC, STLC, or FRL

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| Element | INC-1 | | | | INC-2 | HAL-1 | | HAL-2 |
|---|---|---|---|---|---|---|---|---|
| | (a) | (b)‡ | (c) | (d) | (a) | (a) | (b) | (a) |
| Antimony | - | - | - | - | - | - | - | - |
| Arsenic* | - | - | - | - | - | - | - | - |
| Barium* | - | - | - | - | - | - | - | - |
| Beryllium | - | - | - | - | - | - | - | - |
| Cadmium* | - | - | - | - | - | - | - | - |
| Chromium* | - | - | - | - | - | - | - | - |
| Cobalt | - | - | - | - | - | - | - | - |
| Copper | TTLC | TTLC | TTLC | TTLC | - | TTLC | - | TTLC |
| Lead* | - | - | - | - | - | - | - | - |
| Mercury* | - | - | - | - | - | - | - | - |
| Molybdenum | - | - | - | - | - | - | - | - |
| Nickel | - | - | - | - | - | TTLC | TTLC | - |
| Selenium* | - | - | - | - | - | - | - | - |
| Silver* | - | - | - | - | - | - | - | - |
| Thallium | - | - | - | - | - | - | - | - |
| Vanadium | - | - | - | - | - | - | - | - |
| Zinc | - | - | - | - | - | - | - | TTLC |

* Federally regulated element.

‡ Lamp sample tested by Lab B.

# CFLs exceeding TTLC, STLC, or FRL

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| Element | CFL-1 | | CFL-2 | | | CFL-3 |
|---|---|---|---|---|---|---|
| | (a) | (b) | (a) | (b) | (c) | (a) |
| Antimony | - | - | TTLC | TTLC | TTLC | TTLC |
| Arsenic* | - | - | - | - | - | - |
| Barium* | - | - | - | - | - | - |
| Beryllium | - | - | - | - | - | - |
| Cadmium* | - | - | - | - | - | - |
| Chromium* | - | - | - | - | - | - |
| Cobalt | - | - | - | - | - | - |
| Copper | TTLC | TTLC | TTLC | TTLC | TTLC | TTLC |
| Lead* | *STLC?* | TTLC | *FRL?* | STLC | *FRL?* | FRL |
| Mercury*† | - | - | - | - | - | - |
| Molybdenum | - | - | - | - | - | - |
| Nickel | *STLC?* | STLC | TTLC | STLC | STLC | STLC |
| Selenium* | - | - | - | - | - | - |
| Silver* | - | - | - | - | - | - |
| Thallium | - | - | - | - | - | - |
| Vanadium | - | - | - | - | - | - |
| Zinc | TTLC | TTLC | - | - | - | - |

* Federally regulated element.

† Some mercury is presumed to have escaped detection.

# LED lamps exceeding TTLC, STLC, or FRL

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| Element | LED-1 | | LED-2 | | LED-3 | | LED-4 | |
|---|---|---|---|---|---|---|---|---|
| | (a) | (b) | (a) | (b) | (a) | (b)‡ | (a) | (b)‡ |
| Antimony | - | - | - | TTLC | TTLC | - | - | - |
| Arsenic* | - | - | - | - | - | - | - | - |
| Barium* | - | - | - | - | - | - | - | - |
| Beryllium | - | - | - | - | - | - | - | - |
| Cadmium* | - | - | - | - | - | - | - | - |
| Chromium* | - | - | - | - | - | - | - | TTLC |
| Cobalt | - | - | - | - | - | - | - | - |
| Copper | TTLC | TTLC | TTLC | TTLC | TTLC | TTLC | TTLC | TTLC |
| Lead* | - | - | - | STLC | - | - | - | - |
| Mercury* | - | - | - | - | - | - | - | - |
| Molybdenum | - | - | - | - | - | - | - | - |
| Nickel | *STLC?* | - | - | - | - | - | - | TTLC |
| Selenium* | - | - | - | - | - | - | STLC | - |
| Silver* | - | - | - | - | - | - | - | - |
| Thallium | - | - | - | - | - | - | - | - |
| Vanadium | - | - | - | - | - | - | - | - |
| Zinc | TTLC | - | - | TTLC | - | TTLC | - | TTLC |

* Federally regulated element.

‡ Lamp sample tested by Lab B.

# Discussion



- Antimony
  - Plastic materials caused 3 of 5 CFLs to exceed TTLC
  - Plastic materials caused 2 of 7 LED lamps to approach or exceed TTLC
- Copper
  - Metal materials including the screw base caused 13 of 19 lamps to exceed TTLC
  - Ballast or driver caused all CFLs and LED lamps (12 of 12) to exceed TTLC
- Nickel
  - Wires caused two of the incandescent lamps to exceed TTLC
  - Screw base caused 3 of 5 CFLs to exceed STLC
- Zinc
  - Metal materials including the screw base caused 6 of 19 lamps to exceed TTLC

➢ The selected models were generally found to be below thresholds for Federally regulated elements

➢ The LED light sources installed in LED lamps generally did not cause these products to exceed CA or Federal thresholds

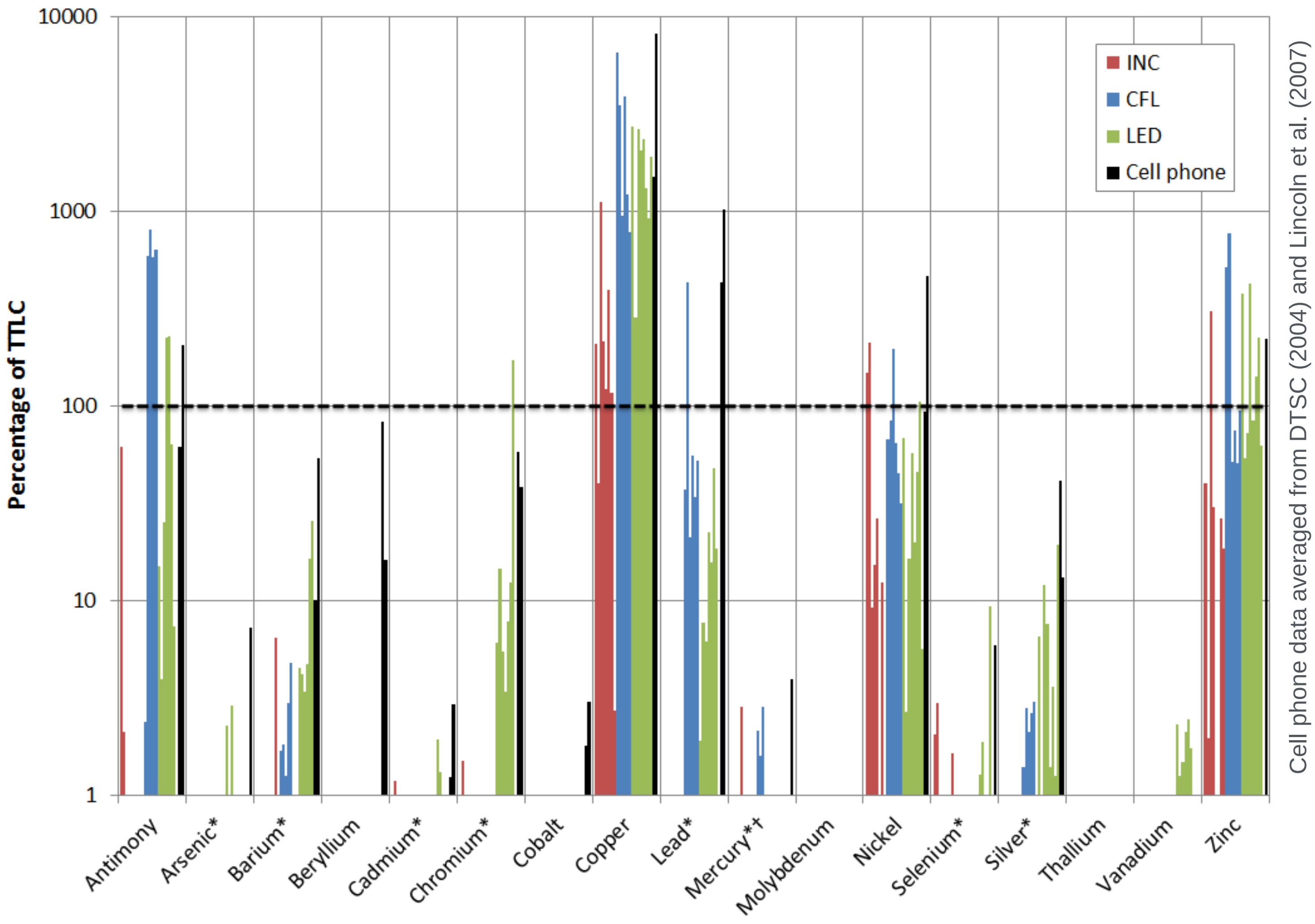
# Discussion



- Results compare well with similar testing by others
  - Lim et al. (2013) also evaluated lamps based on these three technologies
  - CFLs selected by DOE were found to contain more nickel
  - Both studies presume (volatile) mercury in CFLs escaped detection
- Results are comparable to similar investigations of cell phones and other types of electronic devices
  - DTSC (2004) excluded batteries and capacitors from cell phone testing but included their weight, thereby assuming these components were inert
  - Lincoln et al. (2007) also excluded batteries from cell phone testing
  - Most consumer electronics tested were found to exceed CA thresholds for hazardous waste

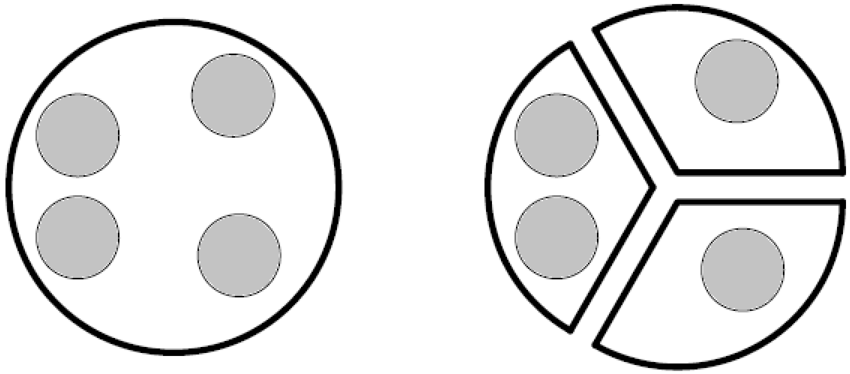
# Discussion






* Federally-regulated element.
† Some mercury in CFLs is presumed to have escaped detection.

- Study Limitations
  - Homogeneity is assumed, but some possible inhomogeneity was detected
    - Might be attributed to relatively small sample sizes (from limited material)
  - Exploratory test results should not be interpreted as absolute characterization
    - Of a given technology, e.g., incandescent or LED
    - Of a given model, e.g., CFL-1
    - Of a given sample, e.g., CFL-1(a)
  - Many regulated substances were not evaluated (e.g., hexavalent chromium)
  - Hazardous waste testing does not provide an indication of product safety during use



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- CA and Federal regulations consider *concentration* (mg/kg or mg/L)
  - To account for longevity, cumulative *mass* must be considered (mg)

| Model | Sample | Assumed lamp life (h) | Lamps used per 25,000 h | Mass per lamp (g) | Cumulative lamp mass per 25,000 h (g) |
|---|---|---|---|---|---|
| INC-1 | (a) | 1,000 | 25 | 27.6 | 690 |
| | (b) | | | 27.1 | 679 |
| | (c) | | | 27.6 | 690 |
| | (d) | | | 25.4 | 635 |
| HAL-1 | (a) | 1,000 | 25 | 37.0 | 925 |
| | (b) | | | 36.6 | 915 |
| CFL-1 | (a) | 8,000 | 3.1 | 59.4 | 186 |
| | (b) | | | 56.8 | 178 |
| CFL-2 | (a) | 10,000 | 2.5 | 49.7 | 124 |
| | (b) | | | 48.5 | 121 |
| | (c) | | | 48.3 | 121 |
| LED-1 | (a) | 25,000 | 1.0 | 166 | 166 |
| | (b) | | | 161 | 161 |
| LED-2 | (a) | 25,000 | 1.0 | 178 | 178 |
| | (b) | | | 180 | 180 |

# Life-adjusted limits for omnidirectional models

- Limits calculated for hypothetical benchmark: 50 g and 10,000 h

| Element | TTLC (mg/kg) | Maximum elemental mass (mg) |
|---|---|---|
| Antimony | 500 | 63 |
| Arsenic* | 500 | 63 |
| Barium* | 10,000 | 1,250 |
| Beryllium | 75 | 9 |
| Cadmium* | 100 | 13 |
| Chromium* | 2,500 | 313 |
| Cobalt | 8,000 | 1,000 |
| Copper | 2,500 | 313 |
| Lead* | 1,000 | 125 |
| Mercury* | 20 | 3 |
| Molybdenum | 3,500 | 438 |
| Nickel | 2,000 | 250 |
| Selenium* | 100 | 13 |
| Silver* | 500 | 63 |
| Thallium | 700 | 88 |
| Vanadium | 2,400 | 300 |
| Zinc | 5,000 | 625 |

* Federally regulated element.

# Omnidirectional lamps @ 25,000 hours

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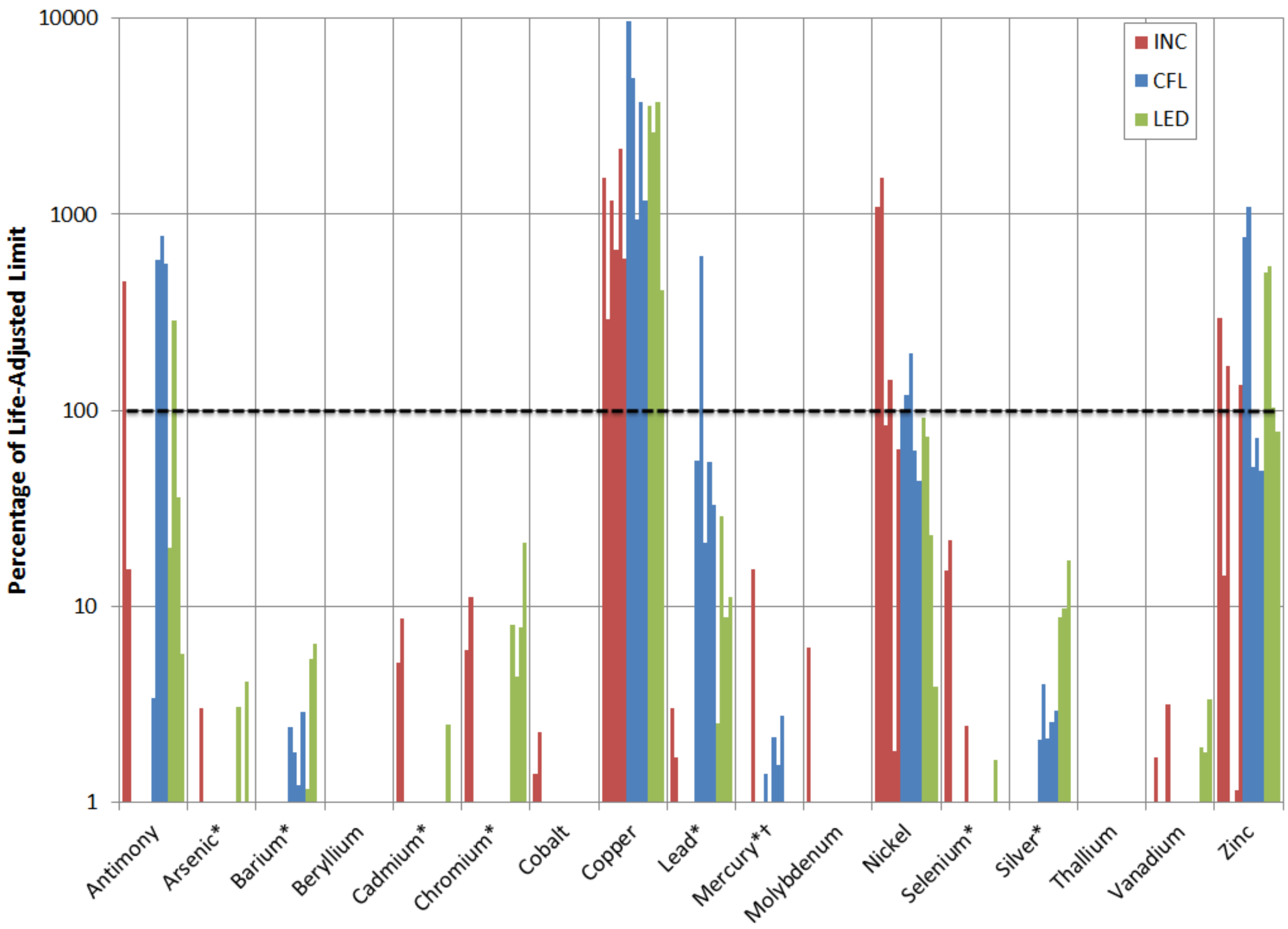


* Federally-regulated element.

† Some mercury in CFLs is presumed to have escaped detection.

## Conclusions and Recommendations

- The selected models were generally found to be below thresholds for Federally regulated elements
  - However, volatile mercury in the CFLs is presumed to have escaped detection
  - In addition, several CFLs exceeded a threshold for lead (TTLC, STLC or FRL)
- Nearly all of the lamps (regardless of technology) exceeded at least one California threshold
  - Typically for copper, zinc, antimony, or nickel
- The greatest contributors were the metal screw bases, drivers, ballasts, and wires or filaments
  - Internal LED light sources generally did not cause LED lamps to exceed thresholds
- Concentrations of regulated elements in LED lamps appear to be comparable to other types of electronic devices (e.g., cell phones)
  - These products, like most of the tested lamps, exceed at least one of the stringent CA thresholds for hazardous waste

- LCA Parts 1 and 2
  - Evaluated a variety of impacts, including end-of-life
  - Found that energy-in-use is the most important factor when evaluating lighting products on a life-cycle basis
    - Luminous efficacy (lumens output per input watt) thus merits high priority when designing or selecting products
  - Found that hazardous waste landfill impacts for the conservatively modeled LED lamp were comparable to the CFL, largely due to the aluminum heat sink
    - Impacts expected to lessen with improved LED efficacy from successive generations
    - Impacts could also be lessened via increased recycling
    - Longevity must be considered when comparing products
- LCA Part 3
  - Test results provide additional impetus for lamp recycling




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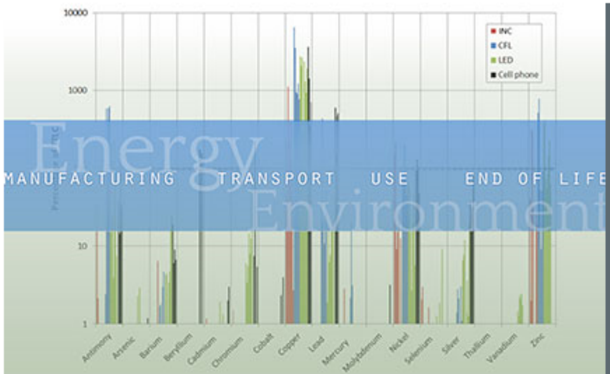


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1 2 3 4

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