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CA IOUs: LED Flicker Test Results and Repeatability Analysis

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LED Flicker Test Results and Repeatability Analysis

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1 Introduction

California's appliance regulations (Title 20) and building energy efficiency standards (Title 24, Part 6) have requirements related to reduced photometric flicker operation. These standards require certain light sources to provide reduced flicker operation when operated at full light output and 20% light output. Reduced flicker operation is defined in these California codes as "percent amplitude modulation (percent flicker) less than 30 percent at frequencies less than 200 Hz."[1] This requirement does not address problematic flicker at all frequencies, but addresses the most noticeable flicker at frequencies less than 200 Hz. It is the team's expectation that the flicker standard be steadily strengthened in subsequent code cycles, as the current requirement does not eliminate all photometric flicker. The 2016 version of the Title 24 standards (adopted May 2015, effective January 2017) included a test method for measuring flicker, including how to filter the data to identify flicker occurring only at frequencies less than 200 Hz, in Reference Joint Appendix JA10, "Test Method for Measuring Flicker of Lighting Systems and Reporting Requirements." This test method is applicable to the measurement of flicker from any light source, and it has been included as Appendix D to this report for easy reference. 2016 Title 24 also added requirements in Reference Joint Appendix JA8, "Qualification Requirements for High Efficacy Light Sources," which will apply to most light sources installed in residential new construction, including all screw-based sources. JA8 is included as Appendix E to this report. The JA8 standards require light sources to provide reduced flicker operation at 100% and 20% light output. For this testing, labs measured the light output with a photometer measuring lumens in the test chamber. Most recently, the CEC has proposed reduced flicker operation requirements in Title 20 that would apply to all dimmable LED lamps sold in California, effective January 2017.

The importance of controlling flicker has been widely documented[2] and due to the fast response of light emitting diodes (LEDs) to current, LEDs are now the subject of the standard IEEE PAR1789 "Recommended Practice for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers."[3] Excessive flicker, even imperceptible flicker, can have deleterious health effects, and lesser amounts can be annoying or impact productivity. The California reduced flicker operation definition is far less stringent than the recommended levels in IEEE PAR1789, but would impact approximately 50% of the LEDs that have been sold in the past. Once quantified by a repeatable test method, flicker can be substantially reduced through better design.[4] In fact, we have measured a number of LED designs that even have less flicker than incandescent lamps operating on AC current.

Previous measurements of 25 LED "A" shape general service omnidirectional lamps for LED flicker were conducted on behalf of Pacific Gas & Electric (PG&E) by the California Lighting Technology Center (CLTC) in 2014. The findings from this study were that approximately half of these LED lamps could meet the "reduced flicker operation" performance requirements. Four of these lamps

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[1] Section JA8.4.6, "Dimming, Reduced Flicker Operation and Audible Noise." *2016 Reference Appendices: for the 2016 Building Energy Efficiency Standards*. http://www.energy.ca.gov/2015publications/CEC-400-2015-038/CEC-400-2015-038-CMF.pdf

[2] Miller and Lehman. FLICKER: Understanding the New IEEE Recommended Practice http://energy.gov/sites/prod/files/2015/05/f22/miller%2Blehman_flicker_lightfair2015.pdf

[3] http://standards.ieee.org/findstds/standard/1789-2015.html

[4] B. Lehman & A. Wilkins, "Designing to Mitigate the Effects of Flicker in LED Lighting," IEEE Power Electronics Magazine, Vol. 1, No. 3, September 2014.

were also tested by the Pacific Northwest National Laboratories (PNNL) with very close correspondence which indicated the testing was repeatable between these two research labs. The previous report[5] with these test results is excerpted in Appendix C of this report for ready reference.

This report describes the findings of a more recent LED flicker study funded by PG&E to expand the scope to a broader range of lamp types including PAR shaped (large diameter directional) lamps, MR (small diameter directional) lamps, candle shaped lamps and recessed can downlight products. This round of flicker testing was conducted by two private test labs, Independent Testing Laboratories of Boulder Colorado (ITL) and Underwriters Laboratories (UL), using the JA10 Test Method. A total of 29 LED lamps were tested with and overlap of 9 lamps between the two labs to verify whether the test is repeatable and transferrable.

Overall, the results show that more than half of the products tested meet the California definition of "reduced flicker operation." This repeats the findings of our earlier A-lamp study, which also found that over half of the LED products tested were low flicker products. In addition, the flicker test results on the lamps measured by both labs ("round robin" testing) closely matched. This also replicates the findings of our earlier study, which was that the test method is repeatable across test labs.

Additional round robin analysis was conducted to compare results from testing of 6 PAR LED lamps originally completed by PNNL (different lamps from the four PNNL lamps mentioned above) with the results of the private test labs.[6] The lamps originally tested at PNNL were documented in a separate study for the Department of Energy's CALiPER program.[7] For this effort, the lamps were re-tested by ITL and UL, and the results were compared to the previously measured PNNL results. This testing found close correspondence between the PNNL results and the flicker results from private labs. Based on all of this testing we have concluded that meeting the flicker requirements adopted in Title 24 and proposed in Title 20 for LED lamps is feasible, and that the JA10 test procedure is repeatable.

While there was a majority of products that meet the flicker standard, there was a wide range of pass rates based on the lamp type. The only A-type LED that was tested passed the flicker standard. For lamp types with multiple products tested, PAR and Downlights both had the best pass rates at 83%, followed by MR low voltage lamps at 50%, candelabra type at 43%, and MR line voltage lamps had a 0% pass rate (out of four lamps tested).

[5] California Utilities Statewide Codes and Standards Team Residential Lighting CASE Report. October 2014 http://www.energy.ca.gov/title24/2016standards/rulemaking/documents/dru_title24_parts_01_06/2016%20T24%20CASE%20Report%20-%20Res%20Lighting%20-Oct2014-V5.pdf

[6] Including these 6 LED lamps tested at PNNL, a total of 35 LED lamps were tested through this initiative, including 15 that were tested across multiple labs in a round robin format.

[7] PNNL CALiPER Report 20.2: Dimming, Flicker, and Power Quality Characteristics of LED PAR38 Lamps. March 2014 http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_20-2_par38.pdf

2 Overview of Test Methodology

2.1 Summary of Products Tested

The two labs tested a total of 29 LED models, as well as a halogen bulb as a reference. The breakdown by lamp type is shown in Table 1. A more detailed table showing the performance specifications for each product tested is provided in Appendix A. Products were selected on the basis of several criteria. It was desired to use popular products that are readily available from national retailers. Products were also selected with a preference for high CRI, a CCT of 2700 K or 3000 K, and a range of low and high light output (roughly 200 to 1000 lumens). Twenty seven of the 29 LED products tested were marketed as dimmable, with the non-dimmable products being a candelabra and PAR lamp. The non-dimmable products were tested on a dimming circuit with the dimmer set to its maximum output.

Table 1: Summary of bulbs tested

Lamp Type	Bulbs Tested
A-type	2[8]
LED PAR	5
LED MR Line Voltage	4
LED MR Low Voltage	6
LED Candle	7[9]
LED Downlight	6

Each lamp was tested with seven different lamp-dimmer configurations. Three dimmers were chosen, one of which was compliant with the NEMA SSL7A standard which is a specification designed to ensure a minimum level of compatibility between compliant forward phase cut dimmers and compliant LED lamps (no data was available on whether the test lamps were compliant with NEMA SSL 7A). For the low voltage tests, two transformers were used, one magnetic and one electronic, depending on whether the dimmers were reverse or forward phase cut. Forward phase cut dimmers were used with magnetic transformers, and reverse phase cut dimmers were used with electronic transformers. Tables are provided Appendix A that show the performance specifications for each dimmer and transformer used in this testing.

Four of the test configurations were conducted with a single bulb, and three were tested with 4 bulbs in a circuit (though only one bulb was in the test chamber undergoing photometric flicker testing). All of the four bulb tests were conducted with products of the same make and model. The non-dimmable bulbs were tested on a circuit with the dimmer set to its maximum output. Table 2 summarizes the seven test configurations. ITL tested all seven test configurations for the line voltage products (A-type, PAR, MR line, candelabra, and downlight). UL tested all seven configurations for the MR low voltage products. Each lab also conducted testing of certain products that were sent between the labs. The terms "round robin bulb" and "round robin dimmer" in the table below refer to the equipment that was sent between the two labs for repeatability. All of the round robin tests are categorized as configuration 4.

[8] One of the A-type products is a reference halogen lamp

[9] One candle type product was on back order for several months and eventually only tested in configuration 4 by both ITL and UL.

Table 2: Summary of test configurations for all products

Test Configuration Number	Description	Transformer (low voltage MR only)
1	Single bulb, dimmer 1	Magnetic
2	Single Bulb, dimmer 2 (NEMA SSL7A compliant)	Magnetic
3	Single bulb, dimmer 3	Electronic
4	Round robin single bulb, round robin dimmer 2 (NEMA SSL7A compliant)	Magnetic
5	Four bulb circuit, dimmer 1	Magnetic
6	Four bulb circuit, dimmer 2	Magnetic
7	Four bulb circuit, dimmer 3	Electronic

2.2 Summary of Laboratory Test Equipment Used

The laboratories tested the lamp-dimmer combinations with standard equipment. This equipment is detailed below.

UL List of Test Equipment

- Agilent DSO-X 3054A Oscilloscope
- UDT S470 Optometer
- CSZ Z32 Temperature and Humidity Controlled Test Chamber
- Chroma 61604 AC Line Conditioner
- Xitron 2801 Power Analyzer
- UDT Gamma Scientific Trans-impedance Amplifier

ITL List of Test Equipment

- Pico 6 Digital Oscilloscope
- ITL High Speed Amplifier and Photocell
- ITL Custom Specialty Darkroom
- Elgar 6006B AC Line Conditioner
- Yokogawa WT210 Digital Power Meter
- Omega HH81 Digital Thermometer
- Satco 3PN1010B Variable Autotransformer

2.3 Summary of Laboratory Understanding of JA10 Test Method

Before the labs began to actually test the products, copies of the JA10 Test Method were circulated to the laboratories. The laboratories both indicated that they clearly understood the JA10 Test Method. Both labs commented that they can easily export the files to the csv format as required by the test procedure. UL commented that the "lowest dimmer setting" readings could be filled with noisy data, because the lamps would only be emitting less than 20 lumens at that point. This comment proved correct, as the lowest dimmer setting results were not very consistent (this

reading is not a part of the JA10 test procedure but was collected to give the team a full understanding of the lamp performance over the entire dimming range).

Both labs recorded instantaneous light output at a frequency of 20 kHz. For each test, ITL recorded data over a time interval of 2 seconds, and UL recorded data over a time interval of 3 seconds. The JA10 Test Method requires that data be collected at a minimum of 20 kHz over the interval of 1 second, meaning that both labs met the data collection requirement.

ITL did have some issues with lamp stabilization. The lab found that the lamps did not stabilize their temperature until 30 minutes or more between dimming levels. The lab said that they spent a minimum of 8 hours pre-warming the lamps, which is allowed by the LM-79 test procedure that is referenced by JA10. LM-79 allows for some variance between 15 minute temperature stabilization readings if the lamps were pre-warmed. The lab commented that they do not recommend that the JA10 test procedure be changed, but that rather than simply reference LM-79, that the lamp stabilization language be explicitly stated in JA10.

Aside from the minor lamp stabilization issues that ITL encountered, both labs were successfully able to complete the testing in accordance to JA10. The labs' feedback is that the test procedure is comprehendible and straightforward.

3 Test Results

3.1 Overview of the Graphical Display of Test Results

The "reduced flicker operation" definition in California code specifically targets flicker at frequencies less than 200 Hz, all of the test results shown in the graphs below display data that have been filtered with a 200 Hz virtual[10] low-pass filter. The black lines on the graphs represent the maximum allowable filtered flicker levels in California's Title 20 and Title 24 (30% flicker at both 100% light output and 20% light output). Filtered flicker levels below the black lines indicate "reduced flicker operation" according to California code.

Although all bulbs were tested at five dimming levels (100%, 80%, 50%, 20%, and lowest dimming level that still produces light), all plots in this section are shown without the lowest dimmer setting result. This is because it was determined that testing at the "lowest dimming setting" produced inconsistent results and was not a reliable and repeatable data point. Additional reasons for not including this data point is that different bulbs and dimmers resulted in different minimum light output levels, the data point is not required to test for the reduced flicker operation standard, and results have already been documented in a previous CASE report (which is excerpted in Appendix C. The Percent Flicker values at the lowest dimming setting do not figure into whether a light source passes the reduced flicker requirement, which is measured at 100% and 20% light output, so it has been omitted from these graphs. The Percent Flicker results at the lowest dimming setting can be found in Appendix B, along with the results at all other dimming settings.

[10] Using Fourier transforms as described in the JA10 test procedure.

The two numbers after the lamp shape designation represent the specific lamp model and the specific test configuration, respectively ("PAR - 1 – 3" represents the "PAR1" lamp model, tested in configuration 3). As mentioned above, all line voltage products were tested at ITL, and the MR low voltage products were tested at UL. The round robin tests are discussed below in the repeatability section.

3.2 Test Results by Dimmer / Test Configuration

Figures 1 and 2 show the filtered flicker levels of PAR model 1 and MR line voltage model 2, both with very consistent results across their seven test configurations (this was true of all of the test lamps; these two are provided as examples). This shows that the dimmer and circuit variations had very small effect on the measured flicker of a lamp, in our testing. In other words, if a product passed the flicker requirement on one dimmer, or in one configuration (i.e. number of lamps) it generally passed on all dimmers, and in all configurations. Flicker, in our testing, appears to be primarily a function of the LED lamp design itself (or possibly the driver within the LED lamp), and less dependent on the dimmer used or the number of lamps on a circuit.

Figure 1: Percent Flicker (Filtered <200 Hz) vs. dimming level for PAR 1, all 7 configurations

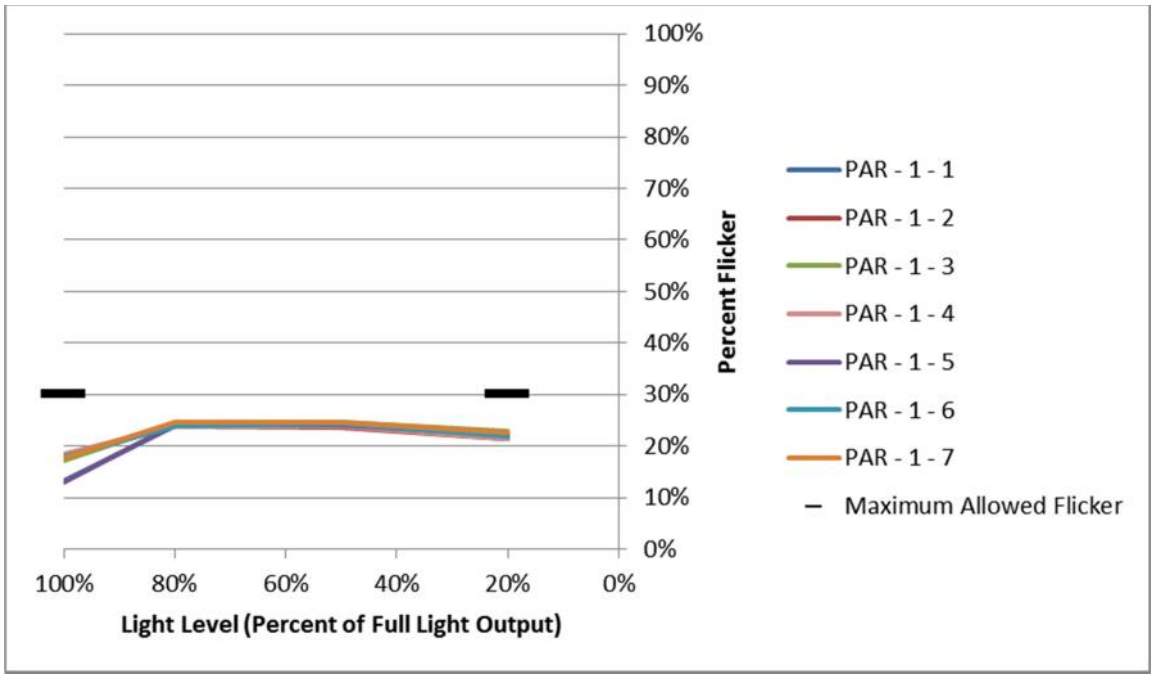
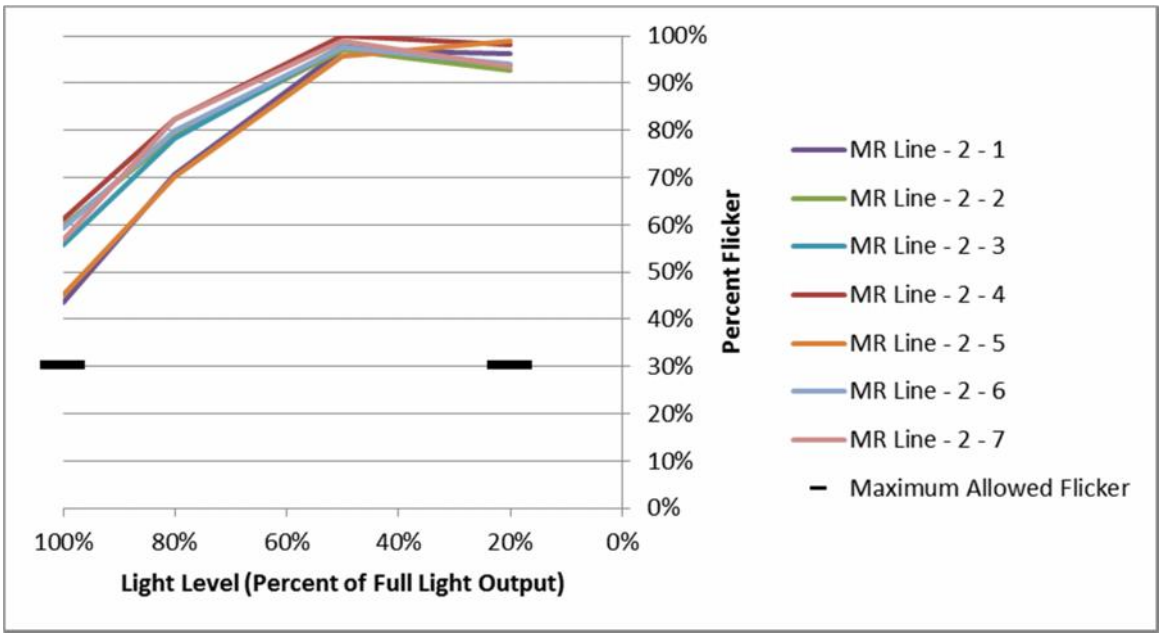


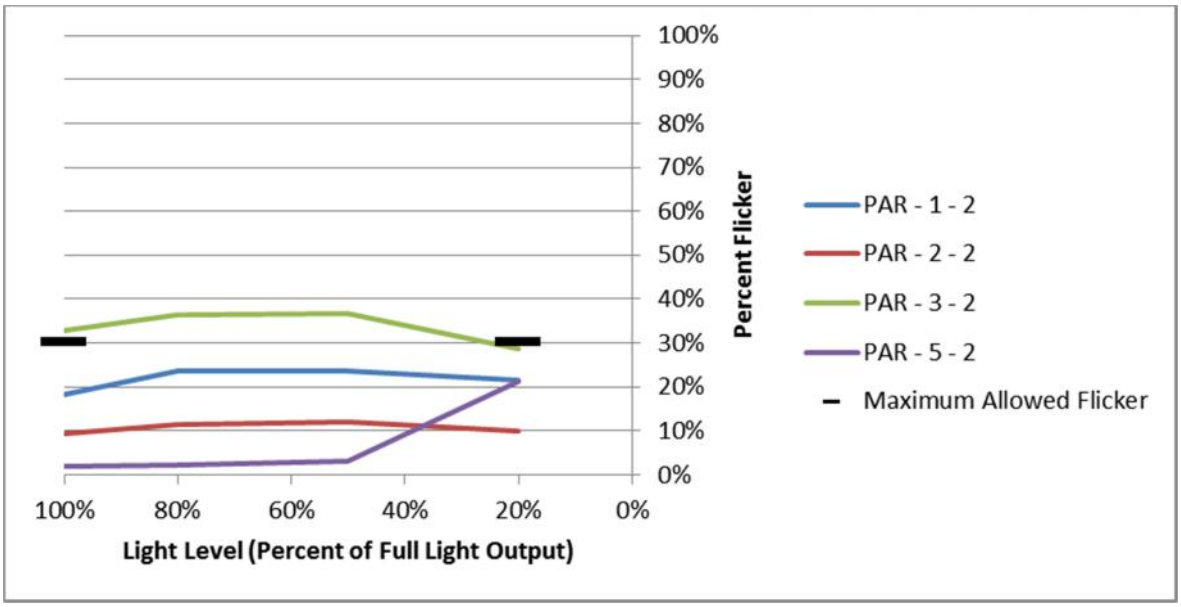
Figure 2: Percent Flicker (Filtered <200 Hz) vs. dimming level for MR Line 2, all 7 configurations



3.3 Test Results by Lamp Type

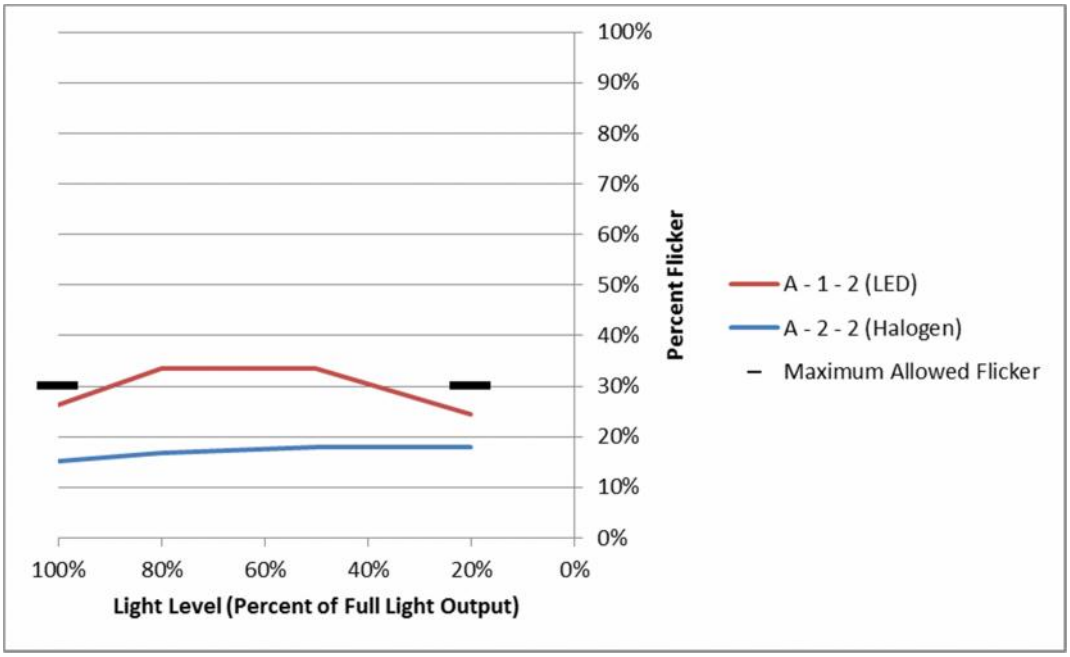
Much more significant is the variation across different bulbs and bulb types. Figure 3 shows the results for the four dimming PAR lamps in one specific configuration (configuration 2). Configuration 2 consists of a single lamp operated on the NEMA SSL7A-compliant dimmer. Note that one of the PAR samples ("PAR 4") was a non-dimmable product, so it was only tested at full output, and is not shown in Figure 3. Of these 4 lamps only lamp PAR 3 does not pass the flicker test as it exceeds 30 percent flicker at full output (100% dimming level). Note that we are plotting both the 50% and 80% of full light output results but the California standard only considers the performance at 20% and 100% of full output.

Figure 3: Percent Flicker (Filtered <200 Hz) vs. dimming level for all PAR lamps, configuration 2



Similarly, Figures 4 through 9 show the results for the other lamp types. As mentioned above, because each of the seven dimmer/number of lamp configurations produced similar results, one configuration (configuration 2) was chosen to demonstrate the results for each lamp.

Figure 4: Percent Flicker (Filtered <200 Hz) vs. dimming level for the A-type lamps, configuration 2



Note that in Figure 2 the LED A-Type lamp exceeds 30 Percent Flicker at 50% and 80% of rated light output. But because measured flicker at 20% and 100% full light output is less than 30 percent flicker, the lamp complies with the California flicker requirements.

Figure 5: Percent Flicker (Filtered <200 Hz) vs. dimming level for all MR Line Voltage lamps, configuration 2

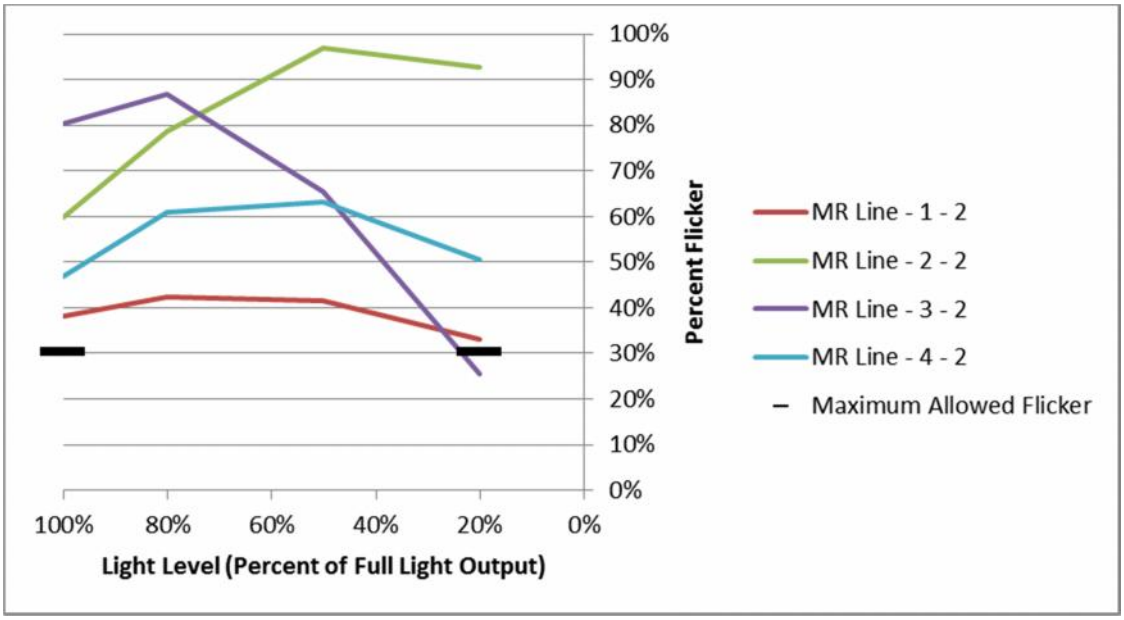


Figure 5 shows that none of the four line voltage MR lamps passed the reduced flicker operation requirements in configuration 2. In fact, none of the line voltage MR lamps meet the California flicker requirement in any of the seven configurations tested.

Figure 6: Percent Flicker (Filtered <200 Hz) vs. dimming level for all MR Low Voltage lamps, configuration 2 (forward phase cut dimmer and magnetic transformer)

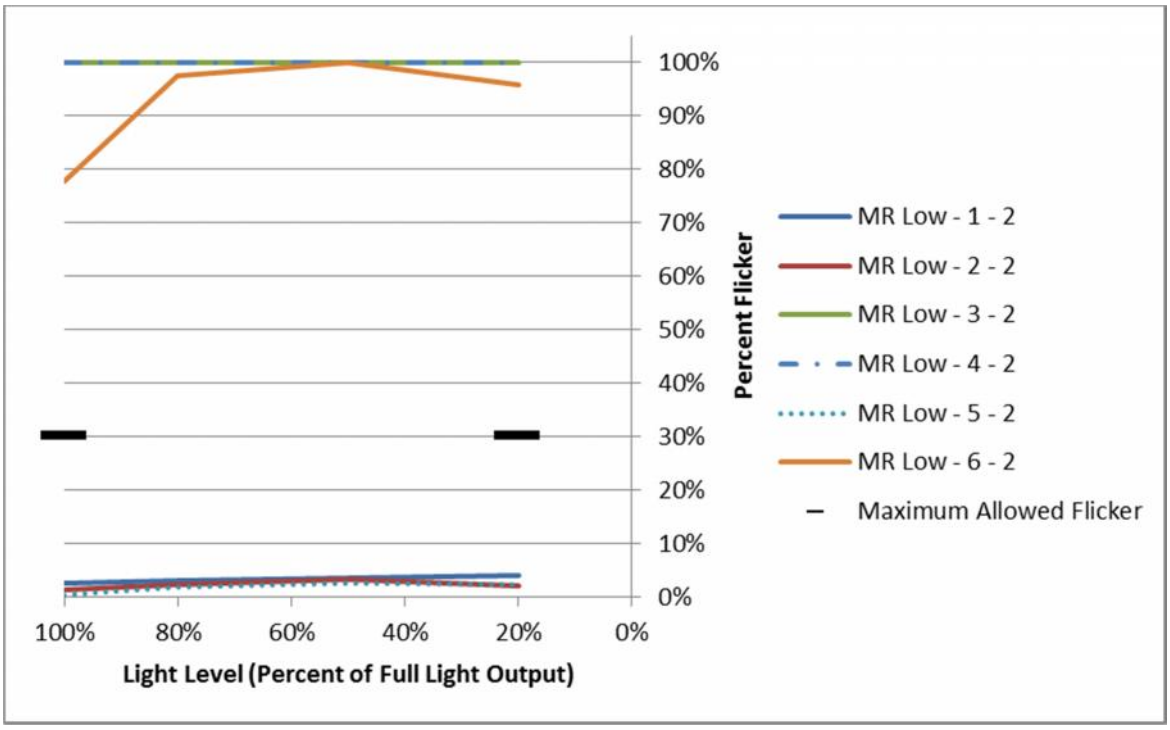


Figure 6 shows that low voltage MR lamps can vary widely in their Percent Flicker levels. These results were confirmed in round-robin testing. Two out of the five lamps had extremely low flicker (less than 5 Percent Flicker). This shows that it is possible to achieve low flicker with a small bulb size, though some lamps exhibit significant flicker.

Figure 7: Percent Flicker (Filtered <200 Hz) vs. dimming level for all Candle lamps, configuration 2 (Except for Candle – Phase 3, tested in configuration 4)

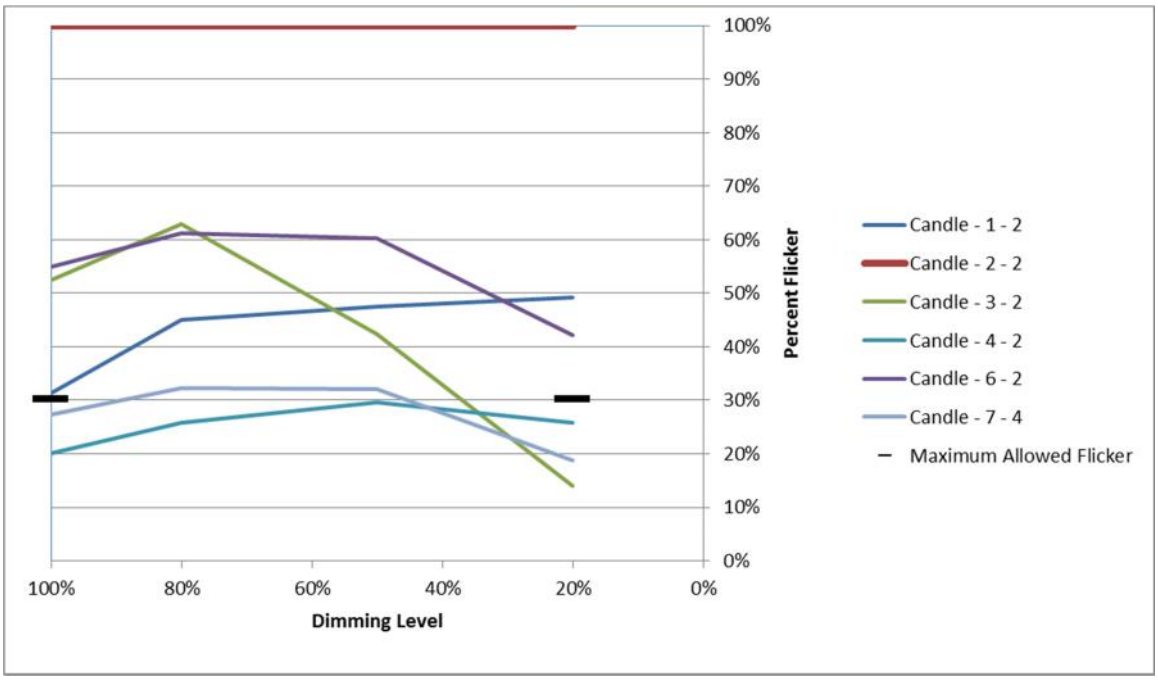


Figure 7 illustrates that two out of six candle lamps can meet the California flicker standard. One additional lamp passes the flicker standard at 20% dimming level but not at full output (Candle - 3-2). Three samples (candle 1, 2, and 6) fail at all dimming levels. Candle - 7 - 4 passed the California flicker standard (i.e. at 20% light output and full output) but it would not meet the flicker standard if a 30 Percent Flicker requirement were added at 80% or 50% light output. Note that for the candelabra results in Figure 7, "Candle 5" was a non-dimmable product and is not shown in the graph.

Figure 8: Percent Flicker (Filtered <200 Hz) vs. dimming level for all Downlights, configuration 2

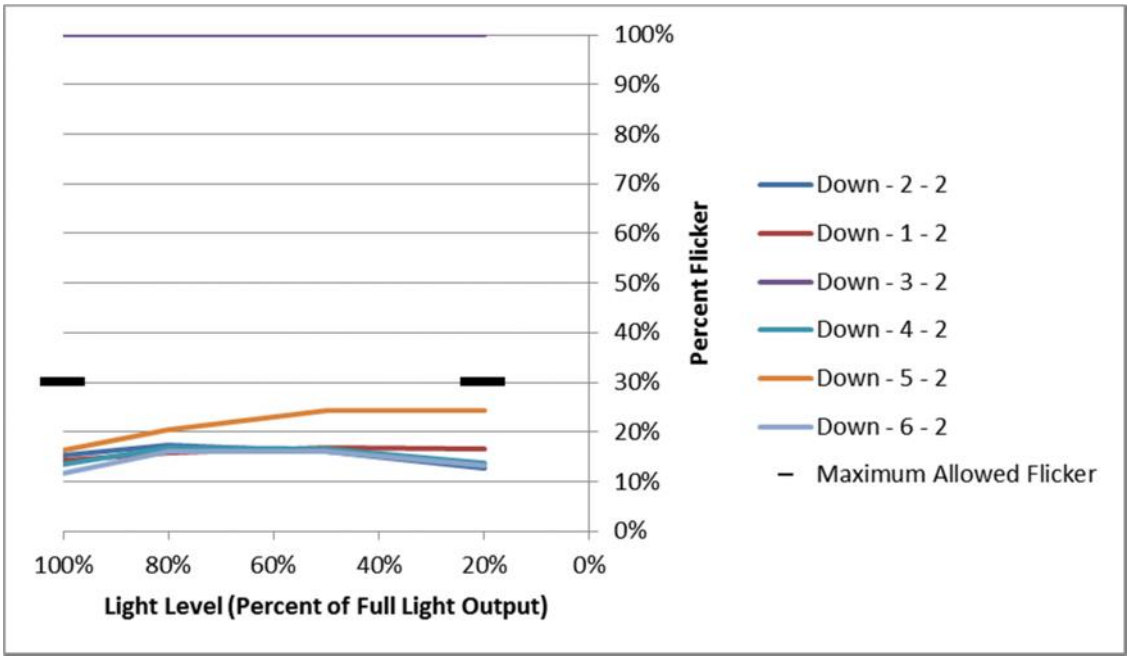


Figure 8 indicates that five out of six of the LED downlights pass the flicker test easily and the one source that fails the test fails poorly with 100 percent flicker. This suggests that even without a flicker test method or standard, much of the downlight market can easily meet the flicker standard, though there are still sources sold with very high flicker levels.

Table 3 summarizes the results of all the tests performed, along with results by lamp type. There were a total of 226 tests performed, including round robin tests. The round robin results are not included in Table 3. The label "all test configurations" refers to the pass rate for products that passed in all seven test configurations, whereas the "bulb pass rate" indicates a pass if at least *one* of the seven configurations resulted in low flicker operation. CEC's flicker standards in Title 24 only require lamps to pass dimming and flicker requirements with one dimmer, so this value is the most representative of whether or not a product is a passing product. As expected, the "bulb pass rate" is slightly higher than "all test configurations," but not significantly. This is because, as demonstrated in figures 1 and 2, the seven test configuration results were very similar and generally if a lamp passed on one dimmer, it passed on the other dimmers. The pass rate only differed for bulbs that were close to the 30% cutoff. As the table shows, slightly more than half of the test configurations (52%) resulted in passing measurements. 55% of the lamps tested passed the flicker requirement on at least one dimmer, and therefore would be considered to provide reduced flicker operation, per the CEC's definition. The pass rate varies significantly by bulb type, with 83% of the downlights and PAR lamps passing, and 30% of the MR16 bulbs passing.

Table 3: Results for all tests, with breakouts by lamp type

Test Type	Pass Rate
All Bulbs – all test configurations	52%
All Bulbs – bulb pass rate	**55%**
A-Type – all test configurations[11]	100%
A-Type – bulb pass rate	**100%[12]**
PAR – all test configurations	66%
PAR – bulb pass rate	**83%**
MR 16 Line Voltage – all test configurations	0%
MR 16 Line Voltage – bulb pass rate	**0%**
MR 16 Low Voltage – all test configurations	50%
MR 16 Low Voltage – bulb pass rate	**50%**
Candle – all test configurations	28%
Candle – bulb pass rate	**43%**
Downlights – all test configurations	83%
Downlights – bulb pass rate	**83%**

Table 4 summarizes the tests performed with results by configuration (i.e. dimmer types and number of lamps connected to dimmer). Lamps tested on the NEMA SSL7A compliant dimmer had a 55% pass rate whereas 51% of lamps passed on the other dimmer types. Similarly single lamp tests passed 53% of the time whereas the 4 lamp test configuration passed 51% of the time.

Table 4: Results for all tests, with breakouts by dimmer type and circuit configuration

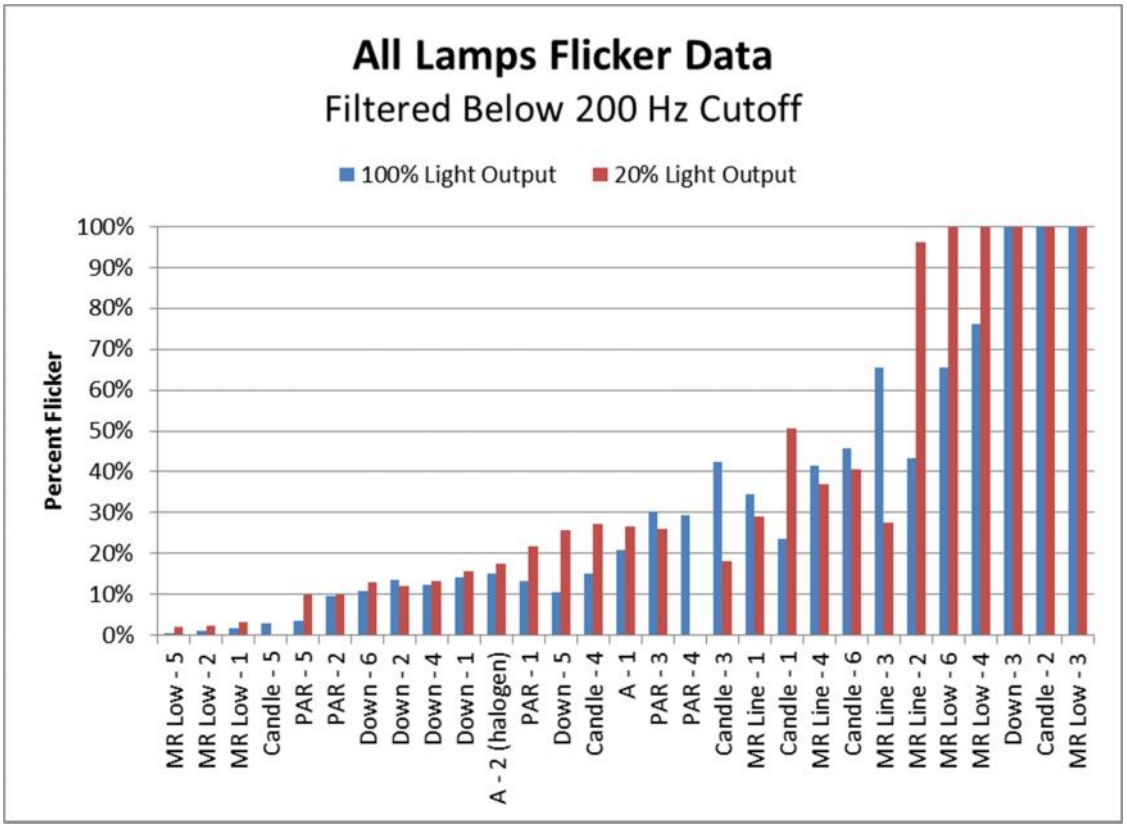
Test Type	Pass Rate
Test Configurations using **NEMA SSL7A** Compliant Dimmer	55%
Test Configurations using **Non-SSL7A** Compliant Dimmer	51%
Tests completed in 1 Bulb Configuration	53%
Tests completed in 4 Bulb Configuration	51%

Figure 9 summarizes all of the LED lamps that were tested, ranked by Percent Flicker level (filtered below 200 Hz). For each lamp, the best Percent Flicker outcome of the seven test configurations is displayed, because this is most representative of how products will be tested by manufacturers for the purposes of complying with CA standards. The Percent Flicker level at both 100% as well as 20% light output is shown. What is worth noting is that the flicker results range from very low (<5%) to very high (100%). Some of the low flicker lamps have even less flicker than the incandescent lamp which had a percent flicker of 17.4% when dimmed to 20% of full light

[11] All A-Type tests (including both LED and halogen) met the Reduced Flicker Operation standard. The halogen results are not included in the overall pass rate.
[12] Based on one bulb.

output. A complete table listing the filtered Percent Flicker test results for all products, all test configurations, and all dimmed levels is provided in Appendix B of this report.

Figure 9: Percent Flicker (filtered <200Hz) for all lamps, ranked from lowest to highest Percent Flicker rating[13]



3.4 Power Factor and Lamp Efficacy Analysis

Using efficacy and power factor data obtained from ENERGY STAR's Qualifying Product List, the Lighting Facts Database, and/or product cutsheets (where available), graphs were produced showing the potential correlation between the products' Percent Flicker, power factor, and efficacy. The results of this analysis are shown in Figures 10 – 13. Regarding power factor, the testing found that there are many products with very low Percent Flicker over a range of high power factors, from 0.8 up to 1.0. Regarding efficacy, the test results suggest that there is no obvious correlation between lamp efficacy and Percent Flicker. The halogen lamp was not included in these graphs.

[13] Candle 5 and PAR 4 are not dimmable and were only tested at full output.

Figure 10: Percent Flicker at 100% Light Output vs. Manufacturer Rated Power Factor[14]

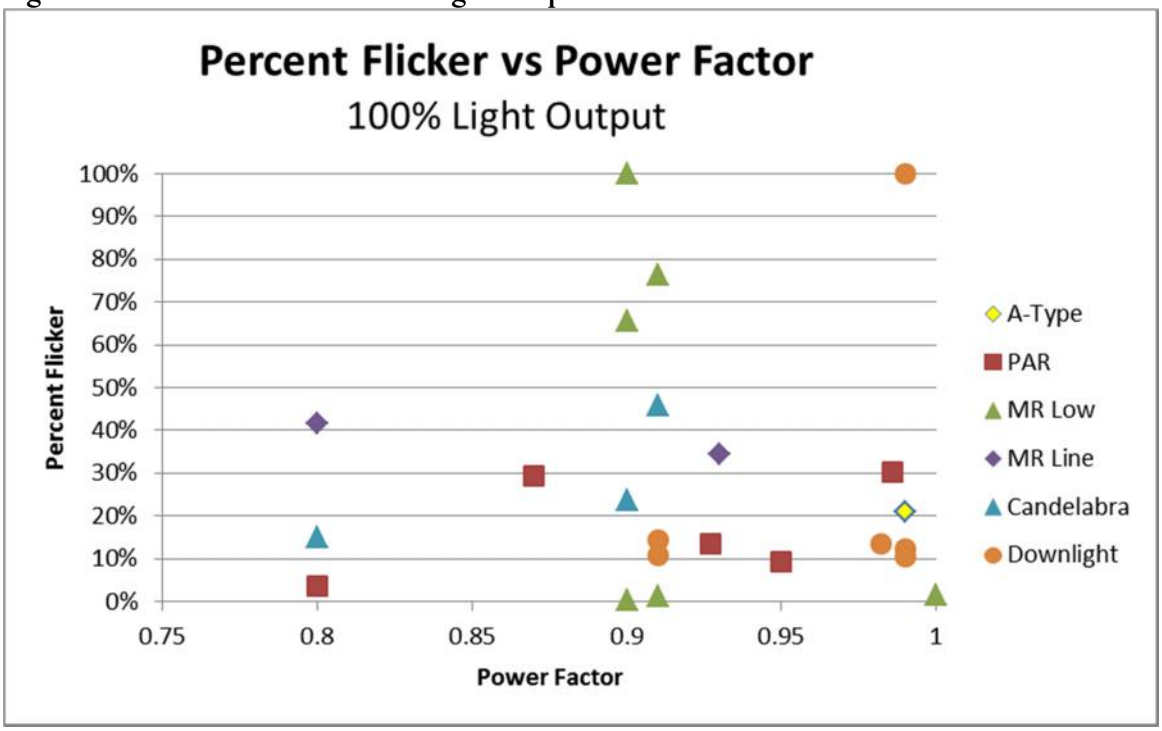
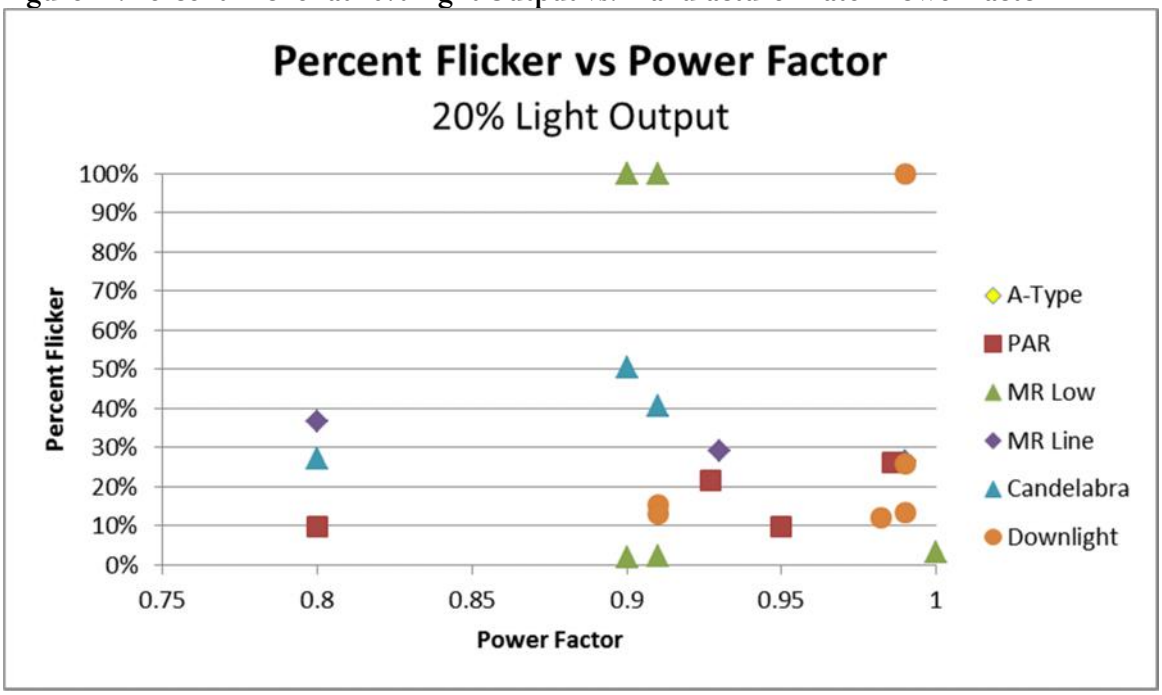


Figure 11: Percent Flicker at 20% Light Output vs. Manufacturer Rated Power Factor



[14] Five products did not have published power factor ratings. Of those, four failed the Title 24 Percent Flicker requirement.

Figure 12: Percent Flicker at 100% Light Output vs. Manufacturer Rated Efficacy

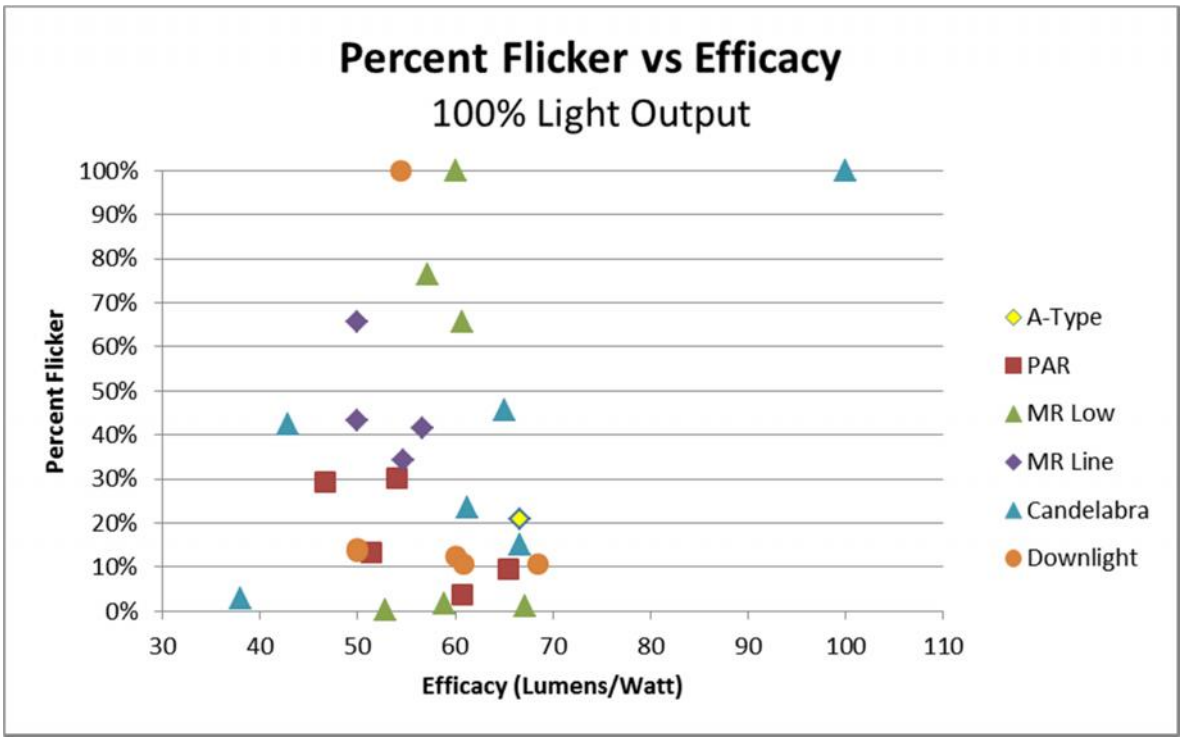
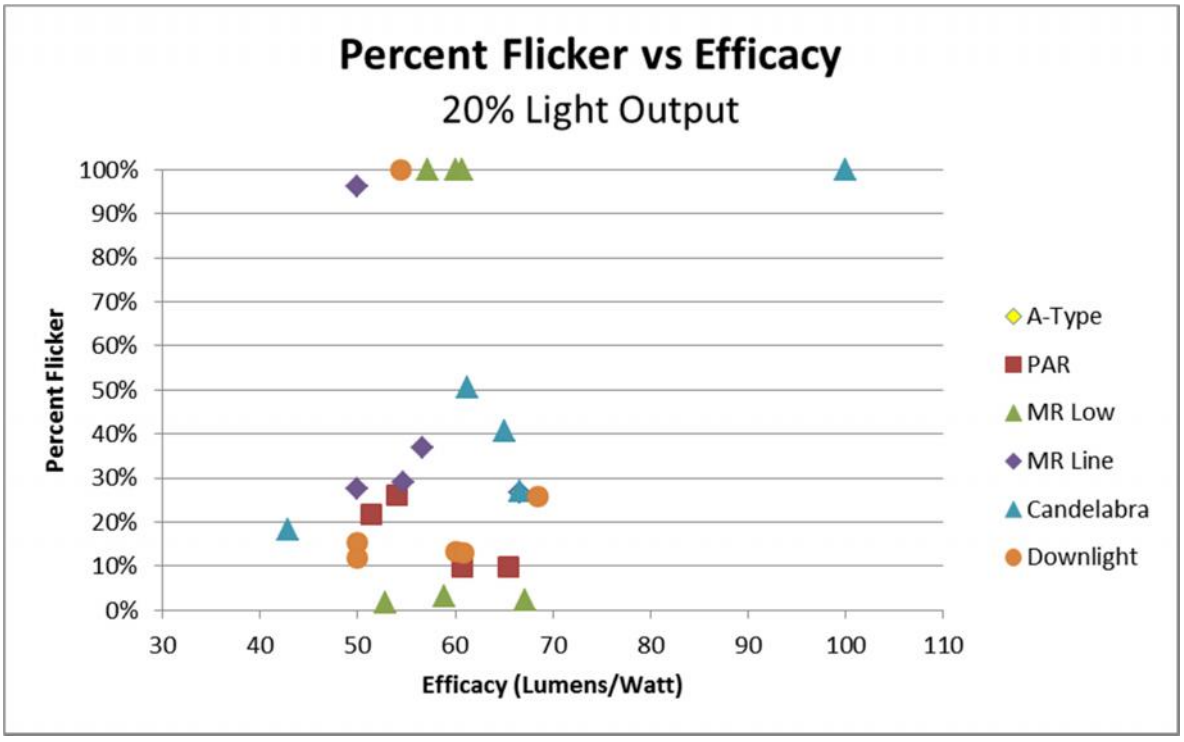


Figure 13: Percent Flicker at 20% Light Output vs. Manufacturer Rated Efficacy



3.5 Comparison of Filtered and Unfiltered Data

Filtering the raw flicker data to isolate flicker occurring at low frequency (below 200 Hz), using the Fourier transforms described in JA10, resulted in a noticeable reduction in the Percent Flicker measurements when compared to the unfiltered data. This is important to note because if products are tested but the data is not filtered, the results may be misleading. Sometimes the difference can be significant; a product that appears to have flicker levels above 30% based on its raw flicker data may in fact have flicker below 30% after the data is filtered. Figure 14 shows such a scenario for PAR 5 in configuration 1, where the unfiltered flicker is above 30% and the filtered flicker (at 200 Hz cutoff) is below 30%. Table 5 shows the average Percent Flicker both filtered and unfiltered, at 100% and 20% light output, for all tests. This table shows an increase of about 6% in Percent Flicker for unfiltered results as compared to filtered. Table 6 shows the number of products that have flicker below 30% when considering both filtered and unfiltered data. There are 4 products that only pass the CEC standards when their raw flicker data is filtered, highlighting the importance of filtering.

Figure 14: Filtered and unfiltered results for PAR 5, configuration 1

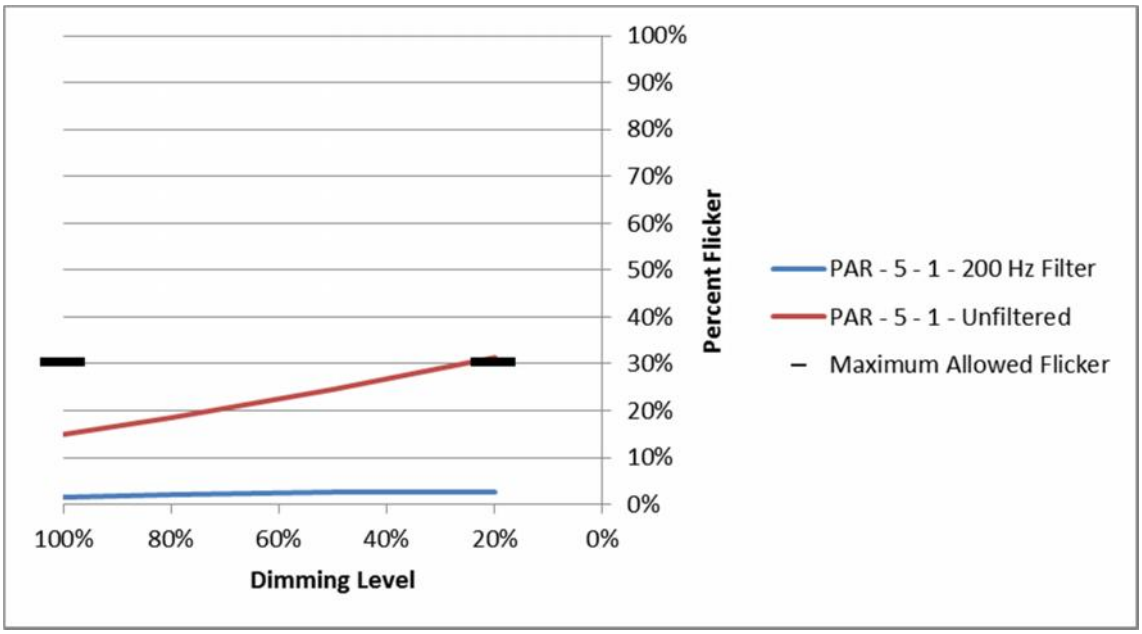


Table 5: Overall average Percent Flicker for filtered and unfiltered data at 100% and 20% light output

	100% Light Output	20% Light Output
Unfiltered	42%	47%
Filtered at 200 Hz	36%	40%
Difference	5.8%	6.7%

Table 6: Number of products that have Percent Flicker below 30% at both full output and 20% output, with and without filtering

	Unfiltered	Filtered at 200 Hz	Total Products Tested
A-Type	1	1	1
PAR	3	4	5
MR 16	3	3	10
Candelabra	0	3	7
Downlight	5	5	6

There were no instances where a product passed the flicker requirement with unfiltered data but not with filtered data. Filtering the data did result in some minor Percent Flicker rating increases over the unfiltered results. However, this only occurred for samples with high absolute Percent Flicker ratings (greater than 60%). The vast majority of lamps' filtered results were either lower or equal to their unfiltered results.

3.6 Test Repeatability

Three labs were involved in this testing initiative in order to assess test procedure repeatability. The two main labs contributed to nine comparison tests, and a third lab contributed six previously tested PAR lamps to the two test labs to each test, for a total of 15 samples tested at more than one lab. The graphs of the repeatability tests are shown for four of the nine products tested at ITL and UL in Figures 15 – 18. These four graphs were deemed representative of the results. Of the six PAR lamps tested at PNNL, ITL, and UL, Figures 19 – 20 show two PAR results from all three labs. These two graphs are representative of the results for other lamps. Full results can be found in Appendix B.

Figure 15: Round robin test results by lab (filtered <200 Hz) for PAR 3, configuration 4

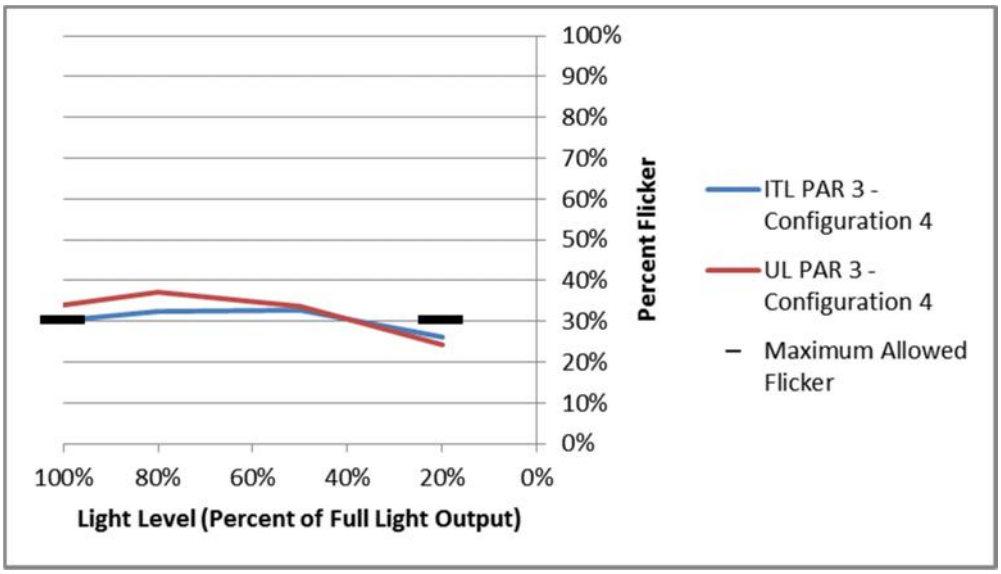


Figure 15 illustrates the problematic situation of where testing with one lab would find that the product fails the test method and another lab would find that it passes. For this particular lamp at full output the UL results measured 34.1 percent flicker and the ITL results were 30.2. Actually both fail but the ITL results are very close to passing.

Figure 16: Round robin test results by lab (filtered <200 Hz) for Candle 6, configuration 4

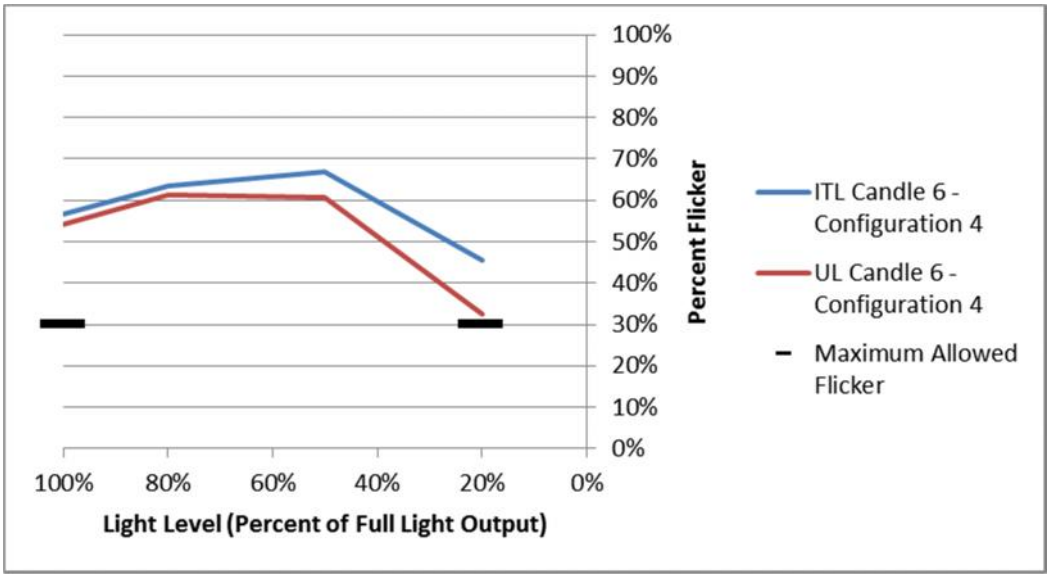


Figure 17: Round robin test results by lab (filtered <200 Hz) for MR Line 2, configuration 4

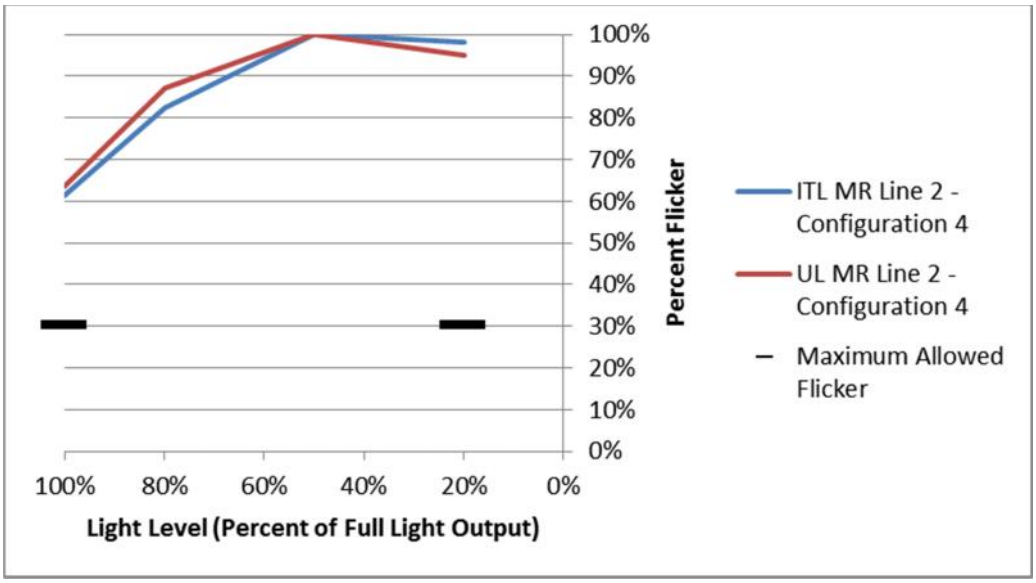
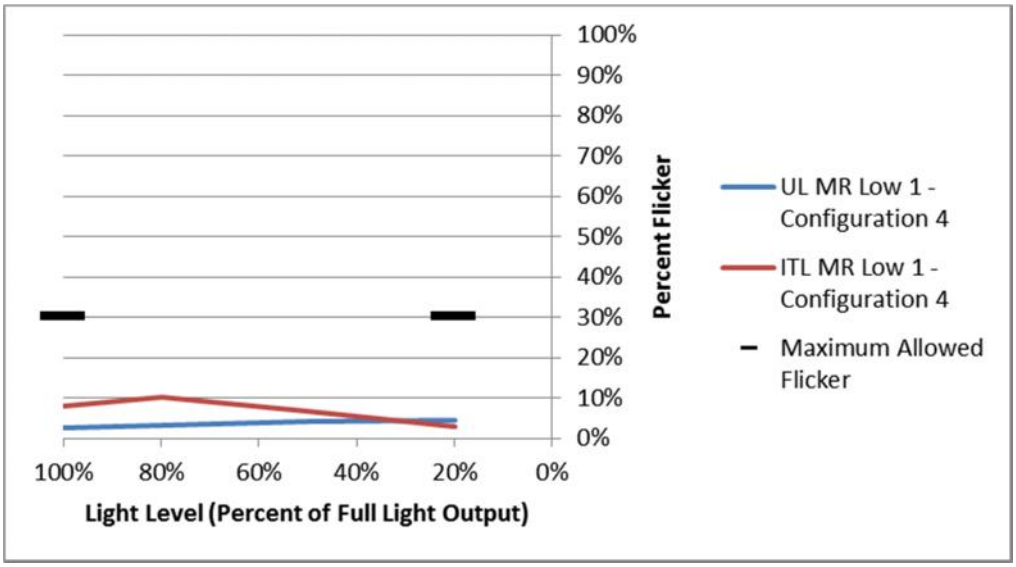


Figure 18: Round robin test results by lab (filtered <200 Hz) for MR Low 1, configuration 4



There were no lamps that passed at one lab but not the other. They all either passed at both, or failed at both. Furthermore, the graphs show that the Percent Flicker results tracked closely across the dimming spectrum. Table 4 shows the average difference and standard deviation of the Percent Flicker values across the dimming range. As the table shows, the standard deviation varies between 2-4%, meaning that for the 15 bulbs that were tested at two labs, the Percent Flicker ratings only deviate by a few percent by dimmer setting. The "average percent difference (absolute value)" row shows the average of the magnitude difference between the two labs' results. This value is shown to be very close across the dimming spectrum.

Table 4: Average difference and standard deviation of the Percent Flicker values measured at two labs, across dimming range

	100%	80%	50%	20%
Avg percent difference (absolute value)	1.99	2.00	1.26	2.70
Standard Deviation (of %)	1.82	2.12	1.79	3.36

In addition to round robin testing at the two labs, a third set of PAR lamps was obtained from PNNL during a previous round of testing. As mentioned previously, the PNNL results were provided from their unrelated, 2014 study, but the physical lamp samples were provided by PNNL to our team for additional testing through this study. These 6 PAR lamps were circulated to ITL and UL to verify that the three labs can produce similar outcomes. As demonstrated in Figures 19 and 20, the three labs produced similar Percent Flicker results. This further demonstrates that the test is repeatable across multiple test laboratories.

Figure 19: Flicker test data (filtered <200 Hz) three lab comparison, PAR P2[15]

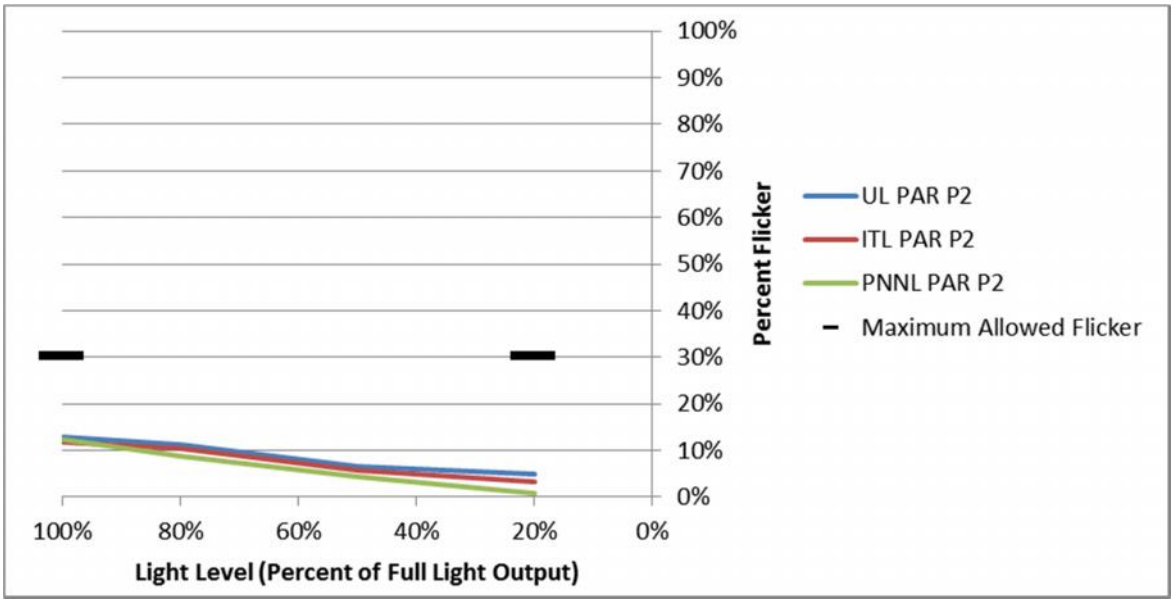
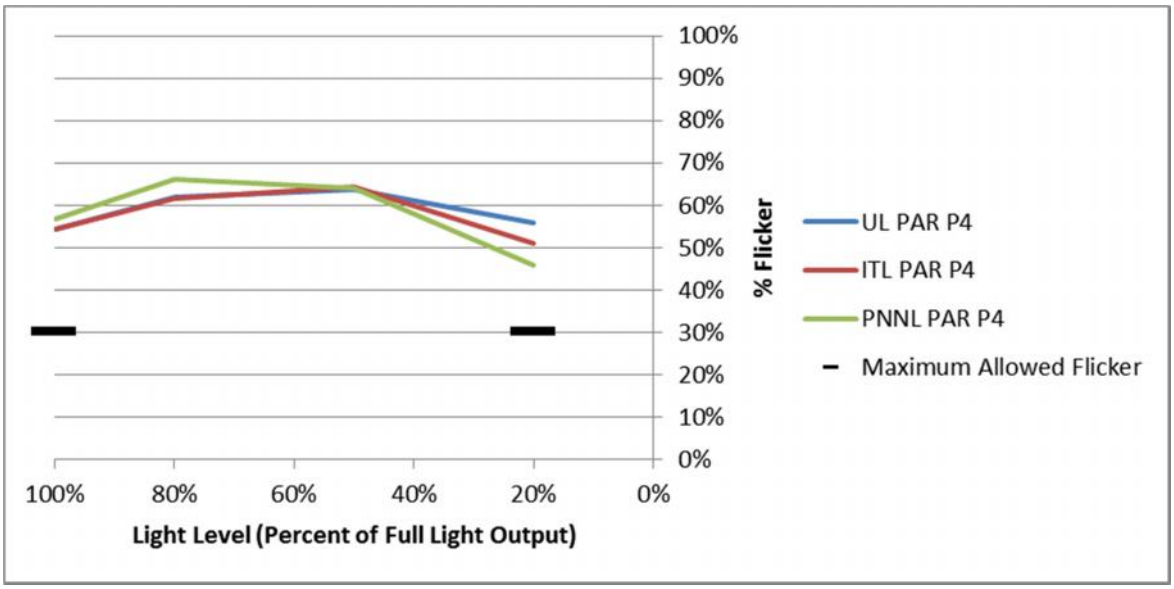


Figure 20: Flicker test data (filtered <200 Hz) three lab comparison, PAR P4



[15] The PAR Lamps with the "P" designation (e.g. PAR P2) means that they originally were tested at PNNL. These lamps are different from the 5 PAR lamps tested with the 7 test configurations.

4 Conclusion

The testing completed in this study found that 55% of the products tested, including a wide range of shapes and sizes, meet California's definition of reduced flicker operation. This testing also demonstrates the wide range of flicker performance among products available in the market today, including some with very high levels of low frequency flicker that is very likely to be noticeable and potentially even introduce negative health impacts. On the other hand, this testing also found that many current LED products are capable of providing extremely low levels of flicker that far surpass California's minimum performance requirements. The fact that a wide range of low frequency flicker exists in the marketplace both underscores the need to introduce a flicker standard and shows that manufacturers are already capable of producing products that meet that standard.

The testing showed that the products performed very similarly over the seven test configurations, which varied the dimmer and number of bulbs in the electrical circuit. This indicates that the bulb itself had a larger impact on flicker performance than the dimmer or number of lamps operated on the dimmer.

It was also shown that filtering the flicker data plays an important role in whether the products will pass or fail the flicker requirement. The unfiltered data resulted in 12 of 29 bulbs under 30% flicker, while the filtered data resulted in 16 of 29 bulbs under 30%. The filtering of the flicker data must be performed before assessing whether a product provides meets the CEC flicker standard.

The results showed that there may be value in requiring testing of the Percent Flicker at a dimmer setting between 100% light output and 20% light output in a future code cycle. The Percent Flicker profile over the dimming range showed a clear parabolic shape for some products, with the maximum Percent Flicker value often occurring in the mid-range of the dimming profile. Since we only took measurements at 100%, 80%, 50%, 20%, and minimum light output, the location of the peak Percent Flicker value along the dimming range is not known very precisely. The team recommends that future research into this topic take more granular measurements along the dimming range in order to learn the exact shape of the Percent Flicker curve. In our results, the average Percent Flicker value in the mid-range of the dimming spectrum is 21% higher than on the extreme ends of the dimming spectrum. Our results showed that if additional requirements for low flicker operation were added at 80% and 50% of the dimming range were included, there would be 10 more individual lamp-dimmer tests that failed and two bulbs overall that move from "pass" to "fail." This suggests that a mid-range test should be considered in future testing and in future standards revisions processes.

Additionally, it was shown that it is possible to manufacture an LED product with high power factor that also has low Percent Flicker.

Lastly, this testing found that the JA10 test procedure is repeatable. There were a total of 15 products tested at multiple laboratories (9 products tested at ITL and UL, and 6 tested at PNNL, ITL, and UL), and all 15 products produced similar Percent Flicker results. All lamps either passed at all labs or failed at all of them. This strongly indicates that laboratories can successfully execute the JA10 test procedure and that the results are repeatable.

Appendix A: Summary Table of all Product Specifications

Table A-1: Summary of Lamps and Manufacturer-Reported Specifications

Lamp Code	Light Output (Lm)	Power Draw (Watts)	Efficacy (Lm/W)	CRI	CCT (K)	Power Factor	Dimmable
A - 1	800	12	66.7	92	2700	0.99	Y
A - 2[16]	750	43	17.4	100	2920	1.00	Y
PAR - 1	770	15	51.3	93	3000	0.93	Y
PAR - 2	850	13	65.4	95	3000	0.95	Y
PAR - 3	1000	18.5	54.1	95	3000	0.99	Y
PAR - 4	700	15	46.7	89	2700	0.87	N
PAR - 5	850	14	60.7	85	3000	0.80	Y
MR Low - 1	500	8.5	58.8	80	3000	1.00	Y
MR Low - 2	584	8.7	67.1	90	3000	0.91	Y
MR Low - 3	420	7	60.0	95	2700	0.90	Y
MR Low - 4	400	7	57.1	95	3000	0.91	Y
MR Low - 5	370	7	52.9	83	2700	0.90	Y
MR Low - 6	425	7	60.7	92	2700	0.90	Y
MR Line - 1	410	7.5	54.7	95	2700	0.93	Y
MR Line - 2	350	7	50.0	82	2700	NA	Y
MR Line - 3	300	6	50.0	85	3000	NA	Y
MR Line - 4	340	6	56.7	83	3000	0.80	Y
Candelabra - 1	300	4.9	61.2	94	2700	0.90	Y
Candelabra - 2	400	4	100.0	92	2200	NA	Y
Candelabra - 3	150	3.5	42.9	90	2700	NA	Y
Candelabra - 4	300	4.5	66.7	82	2700	0.80	Y
Candelabra - 5	110	2.9	37.9	81	3000	NA	N
Candelabra - 6	325	5	65.0	80	2700	0.91	Y
Candelabra - 7[17]	200	4	50.0	82	2700	0.90	Y
Downlight - 1	525	10.5	50.0	92	3000	0.91	Y
Downlight - 2	625	12.5	50.0	90	2700	0.98	Y
Downlight - 3	610	11.2	54.5	93	3000	0.99	Y
Downlight - 4	1250	20.8	60.1	94	2700	0.99	Y
Downlight - 5	650	9.5	68.4	90	2700	0.99	Y
Downlight - 6	670	11	60.9	90	2700	0.91	Y

[16] Halogen
[17] Lamp only tested in Round 3 as a round robin sample

Table A-2: Summary of PNNL PAR Lamps and Manufacturer-Reported Specifications

Lamp Code	Light Output (Lm)	Power Draw (Watts)	Efficacy (Lm/W)	CRI	CCT (K)	Power Factor	Dimmable
PAR – P1	1050	17	61.8	83	3000	0.89	Y
PAR – P2	607	11	55.2	80	3000	0.79	Y
PAR – P3	850	15	56.7	80	2700	NA	Y
PAR – P4	1100	18	61.1	82	3000	0.99	Y
PAR – P5	1210	20	62.1	86	3000	0.72	Y
PAR – P6	1000	16	62.9	85	3000	0.94	Y

Table A-3: Summary of Dimmer Specifications

Dimmer Code	Dimmer Type	NEMA SSL7A Compliant	Wattage
Dimmer 1	Forward Phase Cut	No	600
Dimmer 2	Forward Phase Cut	Yes	600
Dimmer 3	Reverse Phase Cut	No	300

Table A-4: Summary of Transformer Specifications

Transformer Code	Transformer Type	Wattage
Transformer 1	Magnetic	50
Transformer 2	Electronic	60

Appendix B: Summary Table of Filtered Test Results

Table A-5: ITL and UL Results, First Round

Lab	Bulb Code	Test Config-uration	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
				100% Output	80% Output	50% Output	20% Output	Low Output
ITL	A - 1	1	0.2%	20.8%	33.1%	33.8%	27.0%	99.9%
ITL	A - 1	2	0.2%	26.3%	33.6%	33.6%	24.5%	41.4%
ITL	A - 1	3	0.8%	25.6%	34.4%	32.8%	23.9%	11.2%
ITL	A - 1	4	0.2%	25.9%	32.9%	31.9%	24.5%	84.9%
ITL	A - 1	5	0.5%	20.9%	31.8%	34.0%	26.6%	46.3%
ITL	A - 1	6	0.7%	26.5%	33.1%	33.4%	24.6%	76.9%
ITL	A - 1	7	1.0%	26.2%	33.7%	32.9%	23.8%	7.6%
ITL	A - 2	1	0.4%	13.5%	16.4%	18.1%	19.7%	99.8%
ITL	A - 2	2	0.4%	15.3%	16.7%	17.9%	17.9%	99.9%
ITL	A - 2	3	0.5%	15.2%	16.9%	17.8%	17.4%	5.4%
ITL	A - 2	4	0.5%	15.3%	16.8%	17.7%	17.6%	96.3%
ITL	A - 2	5	0.4%	14.5%	16.3%	18.0%	19.2%	85.2%
ITL	A - 2	6	0.4%	15.3%	16.6%	17.6%	18.0%	79.2%
ITL	A - 2	7	0.5%	15.3%	16.7%	17.9%	17.4%	98.8%
ITL	PAR - 1	1	3.0%	13.4%	23.8%	23.9%	21.8%	25.9%
ITL	PAR - 1	2	1.0%	18.3%	23.8%	23.7%	21.5%	2.9%
ITL	PAR - 1	3	3.4%	17.2%	24.3%	24.7%	23.0%	14.4%
ITL	PAR - 1	4	0.9%	18.4%	23.9%	23.9%	21.4%	5.6%
ITL	PAR - 1	5	0.3%	13.0%	24.0%	24.2%	22.2%	24.8%
ITL	PAR - 1	6	1.2%	17.9%	23.8%	24.4%	21.9%	4.1%
ITL	PAR - 1	7	3.3%	17.6%	24.7%	24.6%	22.7%	20.0%
ITL	PAR - 2	1	6.9%	9.3%	11.4%	13.1%	11.7%	8.9%
ITL	PAR - 2	2	3.4%	9.4%	11.5%	12.1%	9.8%	4.7%
ITL	PAR - 2	3	5.9%	9.7%	12.0%	12.0%	9.8%	3.2%
ITL	PAR - 2	4	3.5%	10.2%	12.4%	13.5%	15.6%	1.7%
ITL	PAR - 2	5	6.5%	9.2%	11.5%	13.4%	12.1%	10.0%
ITL	PAR - 2	6	4.1%	9.3%	11.5%	11.8%	10.1%	11.9%
ITL	PAR - 2	7	4.7%	9.8%	12.0%	12.4%	10.1%	4.6%
ITL	PAR - 3	1	1.3%	28.4%	34.0%	37.7%	33.5%	2.6%
ITL	PAR - 3	2	0.1%	32.7%	36.3%	36.7%	28.7%	99.8%
ITL	PAR - 3	3	1.8%	32.8%	35.4%	36.6%	27.6%	23.7%
ITL	PAR - 3	4	0.1%	30.3%	32.3%	32.8%	26.1%	46.7%
ITL	PAR - 3	5	1.2%	28.4%	33.1%	37.6%	33.5%	2.0%
ITL	PAR - 3	6	0.3%	32.7%	35.3%	37.1%	28.5%	99.8%
ITL	PAR - 3	7	1.5%	32.2%	35.2%	35.6%	27.7%	5.9%

Lab	Bulb Code	Test Config-uration	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
				100% Output	80% Output	50% Output	20% Output	Low Output
ITL	PAR - 4	1	97.7%	30.6%				47.4%
ITL	PAR - 4	2	98.6%	29.5%				43.7%
ITL	PAR - 4	3	99.3%	37.1%				51.1%
ITL	PAR - 4	4	97.3%	29.3%				44.7%
ITL	PAR - 4	5	97.4%	29.6%				46.0%
ITL	PAR - 4	6	98.4%	29.4%				44.2%
ITL	PAR - 4	7	99.4%	37.2%				50.7%
ITL	PAR - 5	1	0.3%	1.9%	2.2%	3.1%	21.8%	99.9%
ITL	PAR - 5	2	0.1%	1.8%	2.3%	3.1%	21.3%	62.2%
ITL	PAR - 5	3	50.1%	4.1%	58.5%	100.0%		100.0%[18]
ITL	PAR - 5	4	3.1%	3.6%	5.2%	13.9%	9.9%	73.7%
ITL	PAR - 5	5	0.2%	1.8%	2.2%	3.1%	18.6%	100.0%
ITL	PAR - 5	6	0.1%	1.9%	2.1%	3.0%	22.0%	100.0%
ITL	PAR - 5	7	40.4%	4.2%	53.4%	100.0%		100.0%
ITL	MR Line - 1	1	1.9%	32.3%	39.9%	42.9%	38.6%	41.4%
ITL	MR Line - 1	2	0.1%	38.3%	42.3%	41.6%	33.0%	99.9%
ITL	MR Line - 1	3	4.8%	36.0%	41.2%	43.5%	32.2%	18.8%
ITL	MR Line - 1	4	0.1%	34.4%	37.8%	37.8%	29.1%	99.9%
ITL	MR Line - 1	5	2.3%	32.4%	40.0%	43.2%	39.2%	18.0%
ITL	MR Line - 1	6	0.1%	37.7%	41.2%	41.6%	33.5%	100.0%
ITL	MR Line - 1	7	4.2%	36.4%	42.8%	43.1%	32.9%	14.0%
ITL	MR Line - 2	1	15.0%	43.4%	70.6%	97.2%	96.1%	89.7%
ITL	MR Line - 2	2	7.1%	59.7%	78.7%	97.1%	92.7%	65.9%
ITL	MR Line - 2	3	16.9%	55.8%	78.3%	97.8%	93.7%	89.1%
ITL	MR Line - 2	4	7.6%	61.3%	82.5%	100.0%	98.0%	76.5%
ITL	MR Line - 2	5	13.3%	45.1%	70.3%	95.8%	98.9%	92.6%
ITL	MR Line - 2	6	7.2%	59.3%	80.1%	97.5%	94.1%	71.6%
ITL	MR Line - 2	7	15.6%	56.7%	82.4%	98.9%	93.6%	88.8%
ITL	MR Line - 3	1	1.1%	70.7%	87.5%	75.8%	33.5%	5.6%
ITL	MR Line - 3	2		80.5%	86.9%	65.3%	25.5%[19]	
ITL	MR Line - 3	3	11.6%	78.5%	85.8%	84.5%	44.2%	29.1%
ITL	MR Line - 3	4		80.4%	87.4%	62.9%	21.8%	
ITL	MR Line - 3	5	0.6%	65.5%	83.1%	77.9%	27.7%	39.2%
ITL	MR Line - 3	6	0.0%	80.8%	85.5%	62.9%	25.7%	100.0%

[18] Lowest dimming level found to be greater than 20%
[19] Lowest dimming level found to be 20%

Lab	Bulb Code	Test Config-uration	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
				100% Output	80% Output	50% Output	20% Output	Low Output
ITL	MR Line - 3	7	7.5%	76.6%	83.3%	85.0%	47.5%	20.6%
ITL	MR Line - 4	1	0.7%	36.8%	55.0%	64.4%	54.9%	12.1%
ITL	MR Line - 4	2	0.6%	46.7%	61.0%	63.2%	50.5%	44.7%
ITL	MR Line - 4	3	0.1%	39.9%	56.2%	59.7%	40.2%	100.0%
ITL	MR Line - 4	4	0.1%	44.9%	58.3%	61.4%	47.0%	100.0%
ITL	MR Line - 4	5	0.1%	35.6%	54.0%	62.7%	53.5%	100.0%
ITL	MR Line - 4	6	0.1%	46.8%	59.8%	60.8%	46.0%	100.0%
ITL	MR Line - 4	7	0.1%	41.5%	57.6%	57.8%	36.8%	60.3%
ITL	Candle - 1	1	10.0%	23.7%	43.9%	47.9%	50.6%	42.8%
ITL	Candle - 1	2	4.0%	31.3%	45.0%	47.5%	49.1%	28.6%
ITL	Candle - 1	3	13.0%	29.6%	49.1%	51.3%	48.5%	43.7%
ITL	Candle - 1	4	5.0%	31.9%	46.1%	48.5%	46.6%	27.0%
ITL	Candle - 1	5	9.0%	23.5%	46.2%	48.6%	52.4%	45.1%
ITL	Candle - 1	6	5.0%	31.2%	44.9%	46.9%	51.1%	30.2%
ITL	Candle - 1	7	12.0%	32.5%	51.0%	51.1%	48.2%	41.6%
ITL	Candle - 2	1	5.6%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Candle - 2	2	11.0%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Candle - 2	3	15.3%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Candle - 2	4	10.6%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Candle - 2	5	1.3%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Candle - 2	6	2.9%	100.0%	100.0%	100.0%	100.0%	99.9%
ITL	Candle - 2	7	10.3%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Candle - 3	1	2.1%	44.0%	63.0%	52.9%	19.1%	24.0%
ITL	Candle - 3	2	0.1%	52.5%	62.9%	42.3%	14.0%	100.0%
ITL	Candle - 3	3	14.7%	49.0%	59.6%	50.9%	22.4%	15.7%
ITL	Candle - 3	4	0.1%	55.6%	67.9%	49.3%	13.7%	100.0%
ITL	Candle - 3	5	10.3%	42.5%	61.1%	52.1%	18.2%	15.5%
ITL	Candle - 3	6	0.1%	52.8%	62.6%	43.7%	13.0%	100.0%
ITL	Candle - 3	7	8.9%	48.9%	60.1%	50.6%	25.6%	13.1%
ITL	Candle - 4	1	15.0%	15.0%	23.8%	30.6%	27.1%	24.4%
ITL	Candle - 4	2	2.8%	20.1%	25.7%	29.7%	25.7%	13.9%
ITL	Candle - 4	3	20.9%	15.9%	23.3%	29.0%	26.6%	26.6%
ITL	Candle - 4	4	3.1%	19.9%	25.6%	29.5%	26.0%	24.6%
ITL	Candle - 4	5	12.0%	14.9%	23.8%	30.6%	31.3%	27.8%
ITL	Candle - 4	6	2.5%	20.0%	25.6%	30.6%	26.1%	5.6%
ITL	Candle - 4	7	24.4%	25.9%	28.4%	29.3%		26.4%
ITL	Candle - 5	1	100.0%	8.7%				

Lab	Bulb Code	Test Config-uration	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
				100% Output	80% Output	50% Output	20% Output	Low Output
ITL	Candle - 5	2	100.0%	2.9%				
ITL	Candle - 5	3	100.0%	19.0%				
ITL	Candle - 5	4	100.0%	51.7%				
ITL	Candle - 5	5	100.0%	5.9%				
ITL	Candle - 5	6	100.0%	3.6%				
ITL	Candle - 5	7	100.0%	16.5%				
ITL	Candle - 6	1	18.7%	45.7%	58.1%	62.5%	40.6%	39.2%
ITL	Candle - 6	2	1.5%	54.9%	61.1%	60.3%	42.1%	3.1%
ITL	Candle - 6	3	30.0%	40.6%	54.2%	61.9%		54.8%
ITL	Candle - 6	4	1.4%	56.5%	63.4%	67.0%	45.7%	6.5%
ITL	Candle - 6	5	11.7%	44.3%	56.4%	64.6%	54.4%	46.1%
ITL	Candle - 6	6	0.1%	54.9%	61.5%	62.9%	47.1%	99.9%
ITL	Candle - 6	7	26.7%	38.8%	54.6%	64.1%		56.7%
ITL	Downlight - 1	1	1.1%	12.5%	15.5%	17.3%	19.5%	3.4%
ITL	Downlight - 1	2	0.0%	14.3%	15.9%	16.8%	16.5%	100.0%
ITL	Downlight - 1	3	2.8%	14.3%	15.9%	17.4%	15.5%	12.5%
ITL	Downlight - 1	4	0.0%	19.9%	21.5%	22.6%	20.1%	97.4%
ITL	Downlight - 1	5	1.2%	12.2%	15.5%	17.9%	19.0%	5.7%
ITL	Downlight - 1	6	0.0%	14.1%	15.6%	16.4%	16.7%	100.0%
ITL	Downlight - 1	7	2.2%	14.0%	15.8%	17.2%	16.2%	6.1%
ITL	Downlight - 2	1	7.1%	13.9%	17.7%	17.7%	14.0%	12.2%
ITL	Downlight - 2	2	0.8%	15.2%	17.3%	16.0%	12.6%	2.7%
ITL	Downlight - 2	3	8.8%	14.8%	17.4%	16.2%	12.4%	9.7%
ITL	Downlight - 2	4	0.9%	13.6%	16.2%	15.5%	12.0%	1.3%
ITL	Downlight - 2	5	7.1%	14.0%	18.0%	17.7%	13.8%	12.1%
ITL	Downlight - 2	6	0.8%	15.1%	17.3%	16.0%	11.9%	8.3%
ITL	Downlight - 2	7	7.9%	14.8%	17.2%	15.9%	11.8%	8.1%
ITL	Downlight - 3	1	7.4%	100.0%	100.0%	100.0%	100.0%	99.0%
ITL	Downlight - 3	2	2.5%	100.0%	100.0%	100.0%	100.0%	77.9%
ITL	Downlight - 3	3	7.1%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Downlight - 3	4	2.6%	100.0%	100.0%	100.0%	100.0%	75.9%
ITL	Downlight - 3	5	4.9%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Downlight - 3	6	1.6%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Downlight - 3	7	6.5%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	Downlight - 4	1	3.2%	11.7%	16.2%	16.7%	14.4%	20.3%
ITL	Downlight - 4	2	1.9%	13.4%	16.8%	16.6%	13.7%	17.7%
ITL	Downlight - 4	3	4.3%	12.8%	16.4%	16.9%	15.3%	18.3%

Lab	Bulb Code	Test Config-uration	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
				100% Output	80% Output	50% Output	20% Output	Low Output
ITL	Downlight - 4	4	1.8%	12.4%	15.5%	15.4%	13.3%	20.1%
ITL	Downlight - 4	5	3.2%	11.8%	15.8%	16.9%	14.5%	14.3%
ITL	Downlight - 4	6	1.9%	13.2%	16.2%	16.2%	13.5%	7.6%
ITL	Downlight - 4	7	4.1%	13.1%	16.4%	16.9%	14.5%	16.7%
ITL	Downlight - 5	1	8.8%	10.9%	19.6%	23.8%	25.7%	23.0%
ITL	Downlight - 5	2	4.2%	16.2%	20.4%	24.4%	24.4%	18.5%
ITL	Downlight - 5	3	9.3%	15.6%	20.8%	24.3%	23.3%	19.3%
ITL	Downlight - 5	4	4.2%	16.1%	19.9%	24.0%	22.2%	18.6%
ITL	Downlight - 5	5	8.0%	10.6%	19.6%	24.2%	25.8%	24.0%
ITL	Downlight - 5	6	3.9%	15.9%	20.0%	23.6%	23.7%	16.4%
ITL	Downlight - 5	7	8.9%	15.4%	19.8%	24.0%	23.6%	19.2%
ITL	Downlight - 6	1	9.8%	9.3%	17.9%	17.9%	16.0%	13.9%
ITL	Downlight - 6	2	2.7%	11.5%	16.1%	16.1%	13.1%	16.1%
ITL	Downlight - 6	3	11.3%	10.9%	16.3%	15.7%	13.0%	11.4%
ITL	Downlight - 6	4	2.3%	11.7%	16.4%	16.2%	13.9%	3.0%
ITL	Downlight - 6	5	9.7%	9.3%	17.4%	18.0%	16.1%	14.1%
ITL	Downlight - 6	6	2.7%	11.6%	16.1%	16.0%	13.6%	16.2%
ITL	Downlight - 6	7	10.4%	10.8%	16.4%	15.7%	13.5%	10.8%
UL	MR Low - 1	1	7.3%	1.7%	2.0%	3.3%	4.1%	3.6%
UL	MR Low - 1	2	7.7%	2.6%	3.2%	3.6%	4.1%	4.8%
UL	MR Low - 1	3	11.4%	2.1%	2.5%	3.5%	3.6%	3.3%
UL	MR Low - 1	4	7.6%	2.4%	3.3%	4.0%	4.5%	5.6%
UL	MR Low - 1	5	5.5%	2.4%	2.3%	3.4%	4.1%	4.9%
UL	MR Low - 1	6	8.3%	2.5%	3.5%	4.5%	6.2%	9.2%
UL	MR Low - 1	7	6.2%	1.7%	2.6%	3.3%	3.2%	2.7%
UL	MR Low - 2	1	14.1%	1.1%	2.1%	4.1%	2.4%	2.3%
UL	MR Low - 2	2	5.9%	1.5%	2.4%	3.3%	2.2%	4.1%
UL	MR Low - 2	3	11.3%	1.3%	1.6%	2.7%	16.6%	0.9%
UL	MR Low - 2	4	5.7%	1.5%	2.4%	4.0%	2.7%	4.2%
UL	MR Low - 2	5	5.3%	1.3%	1.9%	4.1%	3.0%	2.4%
UL	MR Low - 2	6	5.9%	1.6%	2.3%	4.0%	2.7%	3.7%
UL	MR Low - 2	7	8.5%	1.6%	4.3%	5.8%	5.1%	1.9%
UL	MR Low - 3	1	2.3%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 3	2	9.5%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 3	3	16.7%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 3	4	9.7%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 3	5	0.3%	100.0%	100.0%	100.0%	100.0%	100.0%

Lab	Bulb Code	Test Config-uration	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
				100% Output	80% Output	50% Output	20% Output	Low Output
UL	MR Low - 3	6	8.6%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 3	7	19.9%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 4	1	12.1%	76.3%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 4	2	9.8%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 4	3	19.7%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 4	4	9.9%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 4	5	9.6%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 4	6	8.5%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 4	7	12.7%	100.0%	100.0%	100.0%	100.0%	100.0%
UL	MR Low - 5	1	12.3%	0.4%	2.4%	3.8%	1.8%	2.4%
UL	MR Low - 5	2	8.3%	0.4%	1.9%	2.7%	2.5%	3.7%
UL	MR Low - 5	3	17.1%	1.1%	3.3%	3.9%	3.2%	3.3%
UL	MR Low - 5	4	9.6%	0.4%	2.0%	2.8%	1.9%	3.1%
UL	MR Low - 5	5	4.6%	0.3%	2.2%	3.2%	1.9%	4.7%
UL	MR Low - 5	6	5.8%	0.4%	2.0%	2.8%	2.7%	4.5%
UL	MR Low - 5	7	19.0%	0.4%	2.2%	2.8%	1.9%	2.0%
UL	MR Low - 6	1	10.8%	65.6%	87.5%	100.0%	100.0%	95.6%
UL	MR Low - 6	2	7.2%	77.7%	97.5%	100.0%	95.8%	75.1%
UL	MR Low - 6	3	18.7%	84.0%	100.0%	100.0%	100.0%	1.6%
UL	MR Low - 6	4	7.5%	75.8%	97.6%	100.0%	99.7%	76.6%
UL	MR Low - 6	5	7.1%	78.6%	100.0%	100.0%	100.0%	83.0%
UL	MR Low - 6	6	7.6%	87.9%	100.0%	100.0%	100.0%	81.2%
UL	MR Low - 6	7	16.9%	83.4%	100.0%	100.0%	98.9%	94.2%

Table A-6: ITL and UL Results, Second Round (Round Robin)

Lab	Bulb Code	Test Setup	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
				100% Output	80% Output	50% Output	20% Output	Low Output
ITL	MR Low - 1	4	9.2%	8.0%	10.2%	6.6%	2.8%	2.4%
ITL	MR Low - 2	4	7.3%	6.6%	6.0%	4.0%	1.3%	1.1%
ITL	MR Low - 3	4	6.6%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	MR Low - 4	4	7.3%	100.0%	100.0%	100.0%	100.0%	100.0%
ITL	MR Low - 5	4	2.1%	2.9%	3.8%	3.5%	1.5%	42.9%
ITL	MR Low - 6	4	1.4%	69.8%	93.8%	99.8%	82.7%	24.0%
UL	PAR - 3	4	0.4%	34.1%	37.2%	33.6%	24.4%	2.7%
UL	Candle - 6	4	1.4%	54.3%	61.2%	60.7%	32.4%	12.6%
UL	MR Line - 2	4	9.3%	63.6%	87.1%	100.0%	95.1%	77.4%

Table A-7: PNNL, ITL, and UL Results, Third Round (Round Robin with PNNL-donated Samples)

Lab	Bulb Code	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
			100% Output	80% Output	50% Output	20% Output	Low Output
PNNL	PAR - P1	10%[20]	1.2%	1.4%	2.1%	2.6%	3.5%
PNNL	PAR - P2		12.2%	8.6%	4.3%	0.8%	0.1%
PNNL	PAR - P3		25.7%	29.9%	26.3%	17.8%	13.3%
PNNL	PAR - P4		56.7%	66.1%	64.0%	46.0%	33.4%
PNNL	PAR - P5		0.1%	0.2%	0.6%		
PNNL	PAR - P6		83.5%	100.0%	100.0%	100.0%	34.7%
ITL	PAR - P1	0.03%	1.6%	2.0%	2.6%	2.5%	8.1%
ITL	PAR - P2	0.03%	11.8%	10.4%	5.8%	3.2%	2.9%
ITL	PAR - P3	0.01%	25.5%	29.7%	27.6%	20.0%	1.8%
ITL	PAR - P4	5.94%	54.4%	61.6%	64.2%	51.1%	32.8%
ITL	PAR - P5	1.73%	1.3%	1.4%	1.2%	0.9%	1.9%
ITL	PAR - P6	2.24%	83.1%	100.0%	100.0%	100.0%	14.9%
UL	PAR - P1	0.84%	1.4%	1.8%	2.5%	1.4%	15.7%
UL	PAR - P2	0.51%	13.0%	11.2%	6.6%	4.9%	3.9%
UL	PAR - P3	9.32%	27.5%	31.7%	30.1%	23.4%	18.9%
UL	PAR - P4	10.00%	54.3%	62.0%	63.8%	55.7%	48.5%
UL	PAR - P5	5.40%	1.1%	0.9%	0.7%	1.2%	1.2%
UL	PAR - P6	7.76%	86.3%	100.0%	100.0%	100.0%	87.0%

Table A-8: ITL and UL Results, Third Round (Round Robin of Candle – 7, tested in configuration 4)

Lab	Bulb Code	Lowest Dimmer Setting Achieved	Percent Flicker - Filtered at 200 Hz				
			100% Output	80% Output	50% Output	20% Output	Low Output
ITL	Candle - 7	7.1%	27.4%	32.2%	32.1%	18.7%	10.1%
UL	Candle - 7	10.7%	29.1%	34.3%	35.7%	24.3%	13.6%

[20] PNNL's original tests intentionally brought each lamp down to 10% and didn't test the lowest possible dimmer setting.

Appendix C: Earlier Published Flicker Results in 2016 Title 24 Residential Lighting CASE Report

This excerpt is from the Residential Lighting CASE report which supported changes to the 2016 Title 24 building energy efficiency standards.[21] This is repeated here to indicate the larger sample of lamps that have been tested for flicker and how they compare to the "reduced flicker operation" requirements.

Reference Joint Appendix JA10

Reference Joint Appendix JA10 "Test Method for Measuring Flicker of Lighting Systems and Reporting Requirements" describes a test method for quantifying the amount of flicker from lighting systems. The Title 24 standards have had requirements to minimize flicker for over 20 years as it is recognized as a feature of lighting that is so annoying that it can result in lost energy savings due to the associated controls being disabled and efficient light sources being removed. However until the addition of this appendix there has not been a consistent reliable test method for enforcing the flicker requirements.

The Title 24 standards have had requirements for flicker starting in the 1988 standards and in the 1992 standard contained the following definition: *"REDUCED FLICKER OPERATION is the operation of a light, in which the light has a visual flicker less than 30% for frequency and modulation."* The 1992 Title 24 standards in mandatory Section 119[e] required that dimming daylighting controls *"provide electrical outputs to lamps for reduced flicker operation through the dimming range and without causing premature lamp failure…"*

This requirement remained unchanged until the 2008 Title 24 development process where LED manufacturers commented that LED systems using pulse width modulation for dimming could have amplitude modulation as high as 100% but that this did not result in perceptible flicker because this amplitude modulation was occurring at very high frequencies. After review of the research on flicker it was determined that flicker was a function of both percent amplitude modulation (also known as percent flicker) and the frequency at which the amplitude modulation takes place. In 2008 the definition and the requirement for daylighting controls were combined so that the requirement for daylighting controls include the following: *"If the device is a dimmer controlling incandescent or fluorescent lamps, provide electrical outputs to lamps for reduced flicker operation through the dimming range, so that the light output has an amplitude modulation of less than 30 percent for frequencies less than 200 Hz, and without causing premature lamp failure."* This requirement was expanded to cover all dimmers including manual dimmers. Manufacturers have asked how they can comply with the standard but up to this point were not given guidance on a test method.

Percent Amplitude Modulation of any signal is given by the following equation:

$$\text{Percent Amplitude Modulation} = \frac{(\text{Max} - \text{Min})}{(\text{Max} + \text{Min})} \times 100$$

[21] California Utilities Statewide Codes and Standards Team **Residential Lighting CASE Report**. October 2014 http://www.energy.ca.gov/title24/2016standards/rulemaking/documents/dru_title24_parts_01_06/2016%20T24%20CASE%20Report%20-%20Res%20Lighting%20-Oct2014-V5.pdf

During the 2013 Title 24 revision process, the flicker requirement for dimmers and daylight dimming controls were moved to the California Title 20 Appliance Efficiency Standards Section 1605.3(l)2 "Self Contained Lighting Controls." In Section 110.9(b), each lighting control system has to meet the requirements in the Title 20 standards including those for reduced flicker operation.

The ENERGY STAR program recognizes that flicker is a concern for the widespread adoption of efficient lighting products and this is especially an issue when lighting is dimmed as some (but not all) dimming methods have the potential to increase flicker. However the ENERGY STAR program only requires that percent flicker and flicker index (a similar metric as percent flicker) be measured and does not set any requirements based on the results of the measurements. In addition, the ENERGY STAR program does not require that these results be filtered by frequency which is needed to address the concerns by the LED industry that the problems with flicker are a function of both amplitude modulation and frequency; something California addressed in 2008 by including a frequency specification.[22] By including flicker testing for light sources with the dimming controls they are intended to be used with, ENERGY STAR explicitly recognized that flicker is not just a function of a particular dimmer control but is a function of the combination of the dimmer, ballast or driver and light source and they are combining this information as part of the process for certifying lamps as ENERGY STAR qualified.

The proposed Reference Joint Appendix JA10 would take the ENERGY STAR flicker protocol a couple of steps further by specifying the minimum sampling rate, sample duration for measuring light output and providing specifications and tools for filtering the higher frequency components of the digitized signal before conducting the percent amplitude modulation calculations.

The filtering of the high sample rate data is performed mathematically using Fourier Transform analysis. The details of this manipulation are described in an IEEE paper: (Lehman et al. 2011) "Proposing Measures of Flicker in the Low Frequencies for Lighting Applications." The key steps of the process are to convert the time series data into the frequency domain as a Fourier Series having the form:

$$x(t) = Xavg + \sum_{m=1}^{\infty} c_m \cos(m\,\omega t + \phi_m)$$

To filter the data in a low-pass format, the Fourier Series terms that are above the cut-off frequency are deleted. This modified or truncated Fourier Series is then converted back into the time domain. The filtered time series data is then used to calculate percent amplitude modulation for frequencies below the cut-off frequency. The proposed Reference Joint Appendix JA10 requires that percent amplitude modulation be reported for unfiltered data as well as data filtered with the following cut-off frequencies: 1,000 Hz, 400 Hz, 200 Hz, 90 Hz, and 40 Hz. The data required for meeting the reduced flicker requirements in Reference Joint Appendix JA8.6 is only the percent amplitude modulation at full light output and dimmed to 20% of full light output when the data is filtered for 200 Hz. The rest of the percent amplitude modulation data is stored in the CEC database and is available to lighting designers who may want to compare product

[22] The California flicker specification is written to be technology neutral so it does not assume for instance that modulation occurs at 120 Hz as has been often the case for LED with poorly filtered drivers, but could be at other frequencies as might be the case with an unstable arc of a discharge source.

performance across all of the different frequencies and at the four dimming levels (100%, 80%, 50% and 20%).

In addition to the summary data, the entity submitting data would be required to submit the unfiltered raw high frequency digitized light output data which is used to validate the percent amplitude modulation values submitted to the California Energy Commission.

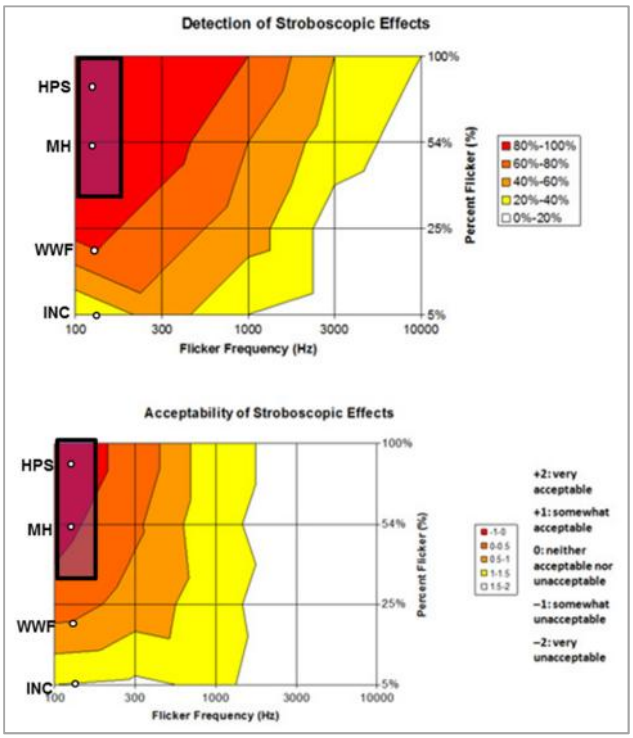


Figure 1: Detection and Acceptability of Stroboscopic Effects (LRC 2012)

The "reduced flicker operation" requirements in the current Title 20 appliance standards and proposed for Reference Joint Appendix JA8 are: "reduced flicker operation is defined as having percent amplitude modulation (percent flicker) less than 30% at frequencies less than 200Hz." In addition we are proposing that this definition would be enforced though the test method in JA10. This flicker requirement is not particularly stringent but prohibits the most objectionable flicker in light sources complying with JA8. Once flicker data is available for a broader range of products through this test and list requirement, the Commission may decide that even more stringent flicker requirements are justified in the future revisions to the standards.

Flicker can be related headaches and eyestrain even when the light source is not perceived to flicker (Wilkins et al. 1989). Wilkins compared the number of headaches reported by office workers under two types of fluorescent lamp—a 50Hz AC lamp with an amplitude modulation of around 50%, and a 32kHz lamp with a modulation of around 7%, neither of which gave perceptible flicker. Subjects reported an average of 0.52 headaches per week, a value which halved after the installation of the high-frequency lighting. These results apply to frequencies above the perceptible range of flicker. Thus it seems prudent to reduce flicker significantly below the perceptible range to avoid the possibility of adverse non-visual effects.

Performance can also be impacted by imperceptible flicker. Veitch (1995) found that the visual performance of 48 undergraduate students was reduced under 60Hz AC lamps compared with 20-60kHz lamps, despite the absence of perceptible flicker.

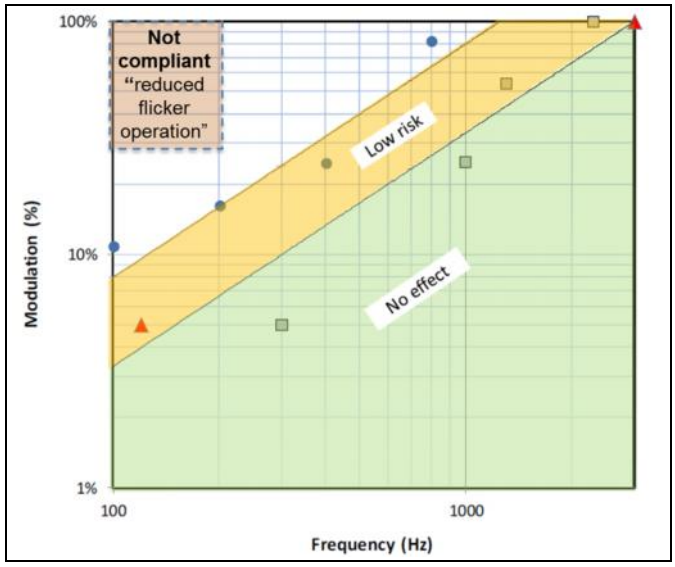


Figure 2: Low risk and no observable effect regions for flicker (Lehman et .a 2014) overlaid with region of graph not compliant with "reduced flicker operation" requirement

More recent research by the Light Research Center (LRC 2012) evaluated stroboscopic effects from flickering light sources to evaluate both when people notice these effects and what levels of percent flicker (percent amplitude modulation) were considered unacceptable. The results of this study are graphed in **Figure 1**. Overlaid on top of these figures is a rectangle in the upper left corner; this rectangle indicates the performance characteristics of products that would not satisfy the Title 24 requirements for "reduced flicker operation," where amplitude modulation (percent flicker) is greater than 30% for frequencies less than 200 Hz. This region of frequencies and amplitude modulation is detectable by at least 80% of the population and the stroboscopic effects are considered very unacceptable.

Another reference point on the relative stringency of the reduced flicker operation requirement is obtained by comparing this requirement to regions of frequency and amplitude modulation that are considered low risk and no effect for flicker by Lehman et al. (2014). **Figure 2** in the upper left corner overlays the region not compliant with "reduced flicker operation" on top of the regions that are considered low risk by Lehman. It is readily apparent that the regions of amplitude modulation and frequency that do not comply with the T-24 definition of low flicker operation are well above the region defined as being low risk for affects from flicker, indicating that the Title 24 specification may not be stringent enough. Early tests of filtered amplitude modulation measurements of LED A lamps indicates that at least 40% of products tested were considered to achieve "reduced flicker operation" at full light output and when lamps were dimmed to 20% of full light output.

In support of a proposal to the California Appliance Standards on LED Replacement Lamp Quality, (PG&E/SDG&E 2013), flicker testing was conducted on omni-directional LED A-lamps controlled by phase cut dimmers. The results of these initial tests of filtered amplitude modulation measurements of LED A lamps indicates that 52% of products tested were considered to achieve "reduced flicker operation" at full light output and when lamps were dimmed to 20% of full light output.

In **Figure 3**, the results are filtered so that only the low frequency data less than 200 Hz is evaluated for percent amplitude modulation (percent flicker). If one observes the results in **Figure 3**, one can see that 13 out of 25 A-lamps are able to pass the "low flicker operation" specification; they have less than 30% amplitude modulation at 100 % full light output and when dimmed down to 25% of full light output. Lamp 13 fails for having too much amplitude modulation at full light out and lamps 15 through 25 fail mostly at both dimming levels. These results indicate the cup is both half full and half empty. Half full in regards to the market being able to provide plenty of products that can meet the flicker requirements before there is a quantitative metric for flicker. But with half of the LED products failing the flicker test indicates that the cup is also half empty; these findings indicate that the market is not self-policing; as has occurred numerous times in the past with food, drugs, and consumer goods, inferior products are sold into markets without testing, labeling and minimum standards. It should be noted that 12% or 3 of the samples out of 25 lamps filtered for frequencies less than 200 Hz had amplitude modulation of 100%! Comments that all lamp manufacturers have a quality control expert with a "golden eye" that detects and prevents problematic flicker do not withstand the scrutiny of objective physical testing. Clearly some products are significantly exceeding the modest flicker requirements proposed here, but a few are failing badly.

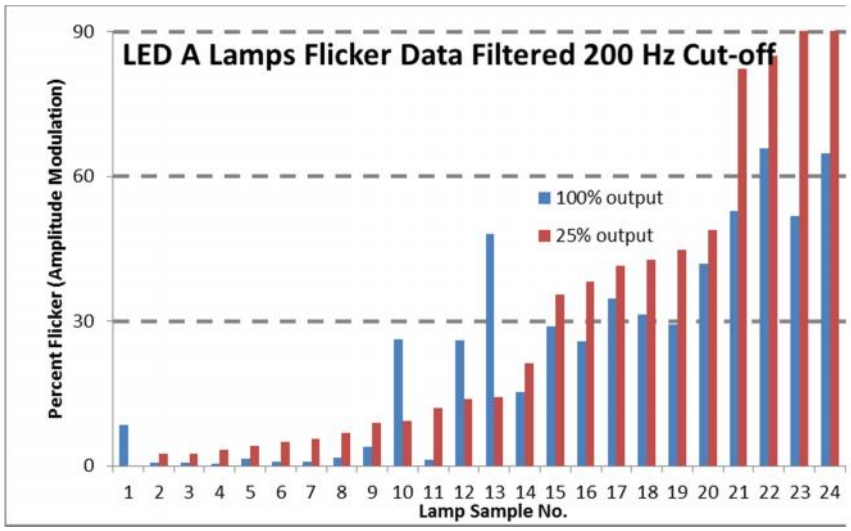


Figure 3: Filtered Flicker Test Data for 25 LED A-lamps (filtered flicker proposed for CA standards)

Currently the ENERGY STAR test protocol does not have the Fourier method filtering as part of their test method. The results of the ENERGY STAR test method without filtering bring up the issues that the CEC addressed in 2008 with the redefinition of "low flicker operation" that accounts for both amplitude modulation (percent flicker) and frequency. **Figure 4** illustrates what happens if the high frequency photometric data for the same A-lamps is not filtered; only one product is able achieve amplitude modulation less than 30%. Thus unless the manufacturers of the 52% of the LED products that are passing the proposed California flicker criteria have filtered their photometric data with a 200 Hz low pass filter they might believe that their products don't comply when they actually do satisfy the filtered flicker criteria.

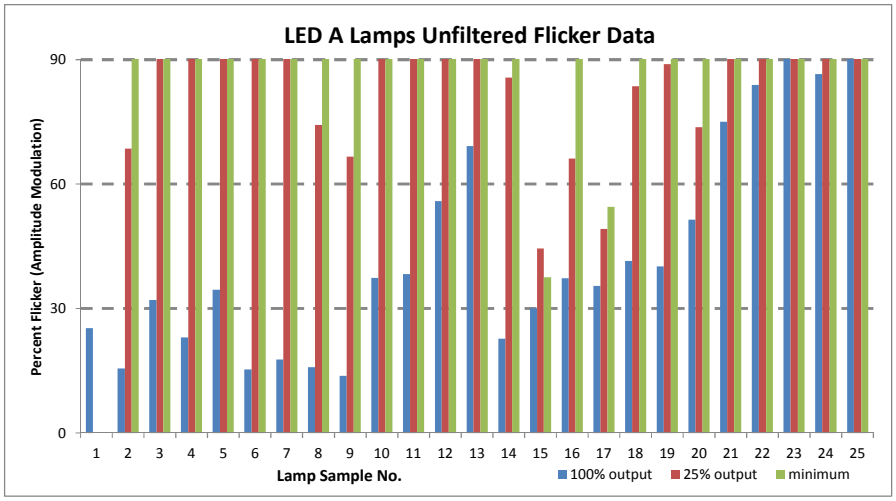


Figure 4: Unfiltered Flicker Test Data for 25 LED A-Lamps (unfiltered flicker <u>not</u> proposed for CA standards)

We have proposed that the CEC host a public domain tool that will filter the flicker data automatically for manufacturers submitting data. However for the use of interested parties, the CASE team has attached a sample of public domain command language for use with the mathematical software MATLAB in Appendix C. If test data is placed in the data format as outlined in TABLE JA-10 this command language will read in the csv (comma separated variables) data file and write a similar data file but insert the correct filtered amplitude modulation. The file must have four strings of data at 100%, 80%, 50% and the greater of 20% or minimum fraction of light output. The CASE team is looking for feedback on how this system of evaluation works and whether this approach alleviates the fears raised about flicker testing.

Thus we anticipate that once flicker testing is widely conducted, that lamp manufacturers will be designing most of their products to comply with this standard. This proposal also encourages the use of NEMA SSL 7A compliant phase cut dimmers as one can test with their product with only one NEMA SSL7A compliant dimmer and be considered compliant for all NEMA 7A qualified dimmers.

Repeatability of Flicker Test Procedure

In addition to the flicker testing performed at CLTC, "round robin" testing was also completed by the Statewide CASE Team in collaboration with Pacific Northwest National Laboratory (PNNL) to compare raw, unfiltered flicker test data taken in different labs. In the winter of 2013/2014, four of the LED replacement lamps that were tested for flicker at CLTC, were also sent to PNNL for flicker testing. The four samples tested in this round robin testing were from four different manufacturers, and included two products with very high Percent Flicker (at or near 100%), one product with Percent Flicker near the proposed cut-off (~30%), and one product with low Percent Flicker (~10%), to represent a range of performance. The results collected at PNNL were consistent with the results collected at CLTC. The largest measured difference between labs was 1.98%, while the average difference was 0.81%. While limited in scope to four products, this initial round robin testing indicated strong repeatability of the flicker test procedure. It should be noted that the test procedure requires a maximum interval of 50 microseconds between data points (data recording rate no less than 20,000 Hz). CLTC conducted their test at a data recording rate of 125,000 Hz and PNNL used a data recording rate

of 1 Megahertz. The data recording rates were both well in excess of the minimum required and though they used different data recording rates, the results from both labs closely matched each other. We anticipate that with the relatively low frequency of the virtual low pass filter associated with Fourier filtering of the data for "reduced flicker operation" (200 Hz) this will reduce error associated with high frequency noise that might be present in some test apparatus. We welcome additional round robin testing with other test labs.

Table 1: Comparison of unfiltered percent flicker results between two test labs

	CLTC	PNNL	Difference
Product 1	100.00	99.80	0.20%
Product 2	29.79	30.10	-1.05%
Product 3	11.22	11.00	1.96%
Product 4	100.00	100.00	0.00%

References

LRC 2012 "Flicker Parameters for Reducing Stroboscopic Effects from Solid-state Lighting Systems" Volume 11, Issue 1. *Light Research Center on behalf of Alliance for Solid-State Illumination Systems and Technologies*. May 2012. http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/AR-Flicker.pdf

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B. Lehman & A. Wilkins, "Designing to Mitigate the Effects of Flicker in LED Lighting," *IEEE Power Electronics Magazine*, Vol. 1, No. 3, September 2014.

[PG&E/SDG&E] 2013 Pacific Gas & Electric Company and San Diego Gas & Electric Company. "LED Lamp Quality; Codes and Standards Enhancement (CASE) Initiative For Program Year 2013: Title 20 Standards Development; Docket # 12–AAER-2B." July 2013. http://www.energy.ca.gov/appliances/2013rulemaking/documents/proposals/12-AAER-2B_Lighting/PG_and_E_and_SDG_and_Es_Responses_to_the_Invitation_for_Standards_Proposals_for_LED_Quality_Lamps_2013-07-29_TN-71758.pdf. Accessed April 1, 2014

Veitch J A and McColl S L. 1995. "Modulation of fluorescent light: Flicker rate and light source effects on visual performance and visual comfort — including Discussion," *Lighting Research and Technology*, Vol 27, No 4, 1995, pp 243-256, Correspondence Vol 29, No 1, 1997, pp 54-56.

Wilkins A J, Nimmo-Smith I, Slater A I and Bedocs L. 1989. "Fluorescent lighting, headaches and eyestrain," *Lighting Research and Technology*, Vol 21, No 1, 1989, pp 11-18, Correspondence Vol 21, No 4, 1989, p 197.

Appendix D: California 2016 Title 24, Part 6 Joint Appendix JA10

The 2016 version of the Title 24 standards (adopted May 2015, effective January 2017) included a test method for measuring flicker, including how to filter the data for frequencies less than 200 Hz in Reference Joint Appendix JA10, "Test Method for Measuring Flicker of Lighting Systems and Reporting Requirements." This section is part of the Reference Appendices to the 2016 Title 24, part 6 standards and can be accessed at: http://www.energy.ca.gov/2015publications/CEC-400-2015-038/CEC-400-2015-038-CMF.pdf The text of Joint Appendix JA10 is reprinted here for ease of use.

Appendix JA10 – Test Method for Measuring Flicker of Lighting Systems and Reporting Requirements

JA10.1 Introduction

This test method quantifies flicker from lighting systems which may include all of the following components: lamps, light sources, transformers, ballasts or drivers, and dimming controls. This test method measures the fluctuation of light from lighting systems and processes this signal to quantify flicker as a percent amplitude modulation (percent flicker) below a given cut-off frequency. Signal processing is used to remove high frequency components above the cut off-frequency.

JA10.2 Equipment Combinations

The test results measured using this method are specific to each combination of:

- Light source and a representative dimmer; or
- Low voltage lamp together with a representative transformer and a representative dimmer (if applicable); or
- Light source and a representative dimming control (if applicable); or
- Light source together with a representative driver, and a representative dimming control (if applicable); or
- Light source together with a representative ballast, and a representative dimming control (if applicable).

If the control or transformer requires a greater load than what is provided by a single sample of the unit under test, additional load will be created by adding quantities of the identical light source, and ballast or driver if applicable on the same circuit receiving the control signal.

Flicker measurements of a phase cut dimmer controlling an incandescent line voltage lamp shall be considered representative for that dimmer with any line voltage incandescent lamp.

Flicker measurements of a phase cut dimmer controlling a transformer for low voltage incandescent lamps shall be representative only for that combination of dimmer and transformer with any incandescent lamp.

Flicker measurements of all non-incandescent lamp sources controlled by a phase cut dimmer represents only the specific combination of phase cut dimmer, ballast or driver, and lamp. These results cannot be applied to other combinations of dimmer, ballast, driver or lamp.

Flicker measurements of light sources controlled by 0-10 volt control, digital control, wireless control or powerline carrier control, the flicker measurement is specific to that combination of control type and ballast or driver and lamp. Test results of the lamp and ballast or driver combination can be applied to other systems that have another control of the same type (0-10 volt, digital, etc.) providing the control signal.

JA10.3 Test Equipment Requirements

Test Enclosure: The test enclosure does not admit stray light to ensure the light measured comes only from the UUT (unit under test). Provision shall be made so the test enclosure is able to maintain a constant temperature of 25°C ±5°C.

Device for data collection: Light output waveform shall be measured with a photodetector with a rise time of 10 microseconds or less, transimpedance amplifier and oscilloscope. An alternate measurement system providing the same accuracy and function as the specified equipment may be used.

Temporal response, amplification and filtering characteristics of the system shall be designed to capture the photometric data at intervals of 50 microseconds or less, corresponding to a data recording rate of no less than 20 kHz, and shall be capable of capturing at least 1 second of data.

JA 10.4 Flicker Test Conditions

Product wiring setup: Fluorescent ballasts shall be wired in accordance to the guidelines provided in the DOE ballast luminous efficiency test procedure in 10 CFR 430.23(q).

Product pre-conditioning: All fluorescent lamps shall be seasoned (operated at full light output) at least 100 hours before initiation of the test. Seasoning of other lamps types is not required.

Input power: Input power to UUT (unit under test), shall be provided at the rated primary voltage and frequency within 0.5 percent for both voltage and frequency. When ballasts are labeled for a range of primary voltages, the ballasts should be operated at the primary application voltage. The voltage shall have a sinusoidal wave shape and have a voltage total harmonic distortion (THD) of no greater than 3 percent.

Temperature: Temperature shall be maintained at a constant temperature of 25°C ±5°C.

Dimming levels: Measurements shall be taken within 2 percent of the following increments of full light output: 100 percent, 20 percent, and minimum dimming level where 100 percent full light output is defined as operating the light source at the maximum setting provided by the control. When the minimum light output of the systems is greater than 20 percent of full light output, then the flicker measurements are taken at the minimum light output. For dimming fluorescent ballasts,

lamp arc power may be used as a proxy for light output for the purpose of setting dimming levels for collecting test measurements.

JA10.5 Test Procedure

Lamp stabilization: Lamp stabilization shall be determined in accordance with:

IES-LM9 for circleline, and U-tube fluorescent systems;

Code of Federal Regulations - 10 CFR 430.23(q) for linear fluorescent systems;

IES-LM66 for compact fluorescent systems and induction lighting systems;

IES_LM-79 for light emitting diode systems; and

IES-LM-46 for high intensity discharge systems.

Lamp light output shall be stabilized in advance of taking measurements at each dimming level. Light output shall be considered stabilized when consecutive measurements taken at one minute intervals deviate by no more than 0.5%.

Recording interval: Measured data shall be recorded to a digital file with an interval between each measurement no greater than 0.00005 sec (50 microseconds) corresponding to an equipment measurement rate of no less than 20kHz, and capture at least 1 second of data. For each dimming level after the lamps have stabilized, record lighting measurements (in footcandles or volts) from test equipment with readings taken at intervals of no greater than 50 microseconds. These readings shall be recorded for a test period of no less than one second.

JA 10.6 Calculations

Perform the following data manipulation and calculation tasks for each dimming level (100 percent, 20 percent and minimum dimming level claimed by the manufacturer):

Calculate percent amplitude modulation (percent flicker) of unfiltered data over the duration of the test for a given dimming level using the following equation:

$$\text{Percent Amplitude Modulation} = \frac{(\text{Max} - \text{Min})}{(\text{Max} + \text{Min})} \times 100$$

Where:

Max is the maximum recorded light level or voltage from the test apparatus during the duration of the test for a given dimming level.

Min is the minimum recorded light level or voltage from the test apparatus during the duration of the test for a given dimming level.

Conduct a Fourier analysis to transform data for each dimming level into the frequency domain.

Filter frequency data to evaluate the data under four additional different conditions: frequencies under 40 Hz (data above 40 Hz is set to 0), and frequencies under 90 Hz, 200 Hz, 400 Hz, and 1,000 Hz.

Perform inverse Fourier transform to place data back in time domain.

Calculate percent amplitude modulation on resulting time domain data for each filtered dataset over the full sampling duration.

JA 10.7 Test Report and Data Format

For all systems where reporting of flicker is required, the test data shall be submitted to the California Energy Commission in the format specified in Table JA-10. For two years from the date of certification, the entity submitting the test report shall keep all documentation required for compliance, stored and shall provide copies of this documentation to the Energy Commission within 10 days of written request received from the Commission. This documentation shall also include for each measured system, a digital file containing the raw photometric data as described in Section JA10.5.

TABLE JA-10-1. FLICKER DATA TO BE RECORDED AND SUBMITTED TO THE CALIFORNIA ENERGY COMMISSION	
Data	Units/Format
Test Date	
Test Operator	Company Name, Contact Name, Address, Phone Number, e-mail address
Entity submitting results	Company Name, Contact Name, Address, Phone Number, e-mail address
	Manufacturer or Brand
Tested lighting system component: Dimmer	Dimmer type, Manufacturer or Brand, model number
Tested lighting system component: light source (lamp or light engine)	Light source type (lamp, light engine, etc), Manufacturer or Brand, model number
Tested lighting system component: Ballast or Driver	Ballast or Driver, Manufacturer or Brand, model number
Recording interval	seconds (no greater than 0.00005 seconds)
Equipment Measurement Period	seconds (no less than 1 second)
Fraction of rated light output integrated over measurement period at 100%, 20% and minimum fraction of light output.	Fraction of rated light output integrated over measurement period at 100%, 20% and minimum fraction of light output.
Amplitude modulation unfiltered	calculated percent amplitude modulation unfiltered for each dimming level (100%, 20% and minimum fraction of light output)
Percent amplitude modulation with 1,000 Hz cut-off	calculated percent amplitude modulation, data filtered with a 1,000 Hz cut-off frequency for each dimming level: (100%, 20%, and minimum fraction of light output)
Percent amplitude modulation with 400 Hz cut-off	calculated percent amplitude modulation, data filtered with a 400 Hz cut-off frequency for each dimming level: (100%, 20%, and minimum fraction of light output)

TABLE JA-10-1. FLICKER DATA TO BE RECORDED AND SUBMITTED TO THE CALIFORNIA ENERGY COMMISSION	
Data	Units/Format
Percent amplitude modulation with 200 Hz cut-off	calculated percent amplitude modulation, data filtered with a 200 Hz cut-off frequency for each dimming level: (100%, 20% and minimum fraction of light output)
Percent amplitude modulation with 90 Hz cut-off	calculated percent amplitude modulation, data filtered with a 90 Hz cut-off frequency for each dimming level: (100%, 20% and minimum fraction of light output)
Percent amplitude modulation with 40 Hz cut-off	calculated percent amplitude modulation, data filtered with a 40 Hz cut-off frequency for each dimming level: (100%, 20% and minimum fraction of light output)

Appendix E: California 2016 Title 24, Part 6 Joint Appendix JA8

The 2016 version of the Title 24 standards (adopted May 2015, effective January 2017) included requirements related to reduced flicker operation. Reduced flicker operation is defined as "percent amplitude modulation (percent flicker) less than 30 percent at frequencies less than 200 Hz."[23] Reference Joint Appendix JA8, "Qualification Requirements for High Efficacy Light Sources," which will apply to most light sources installed in residential new construction, including all screw-based sources. The JA8 standards require light sources to provide reduced flicker operation at 100% and 20% light output. This section is part of the Reference Appendices to the 2016 Title 24, part 6 standards and can be accessed at: http://www.energy.ca.gov/2015publications/CEC-400-2015-038/CEC-400-2015-038-CMF.pdf The text of Joint Appendix JA8 is reprinted here for ease of use.

Appendix JA8 - Qualification Requirements for High Efficacy Light Sources

JA8.1 Purpose and Scope

Joint Appendix JA8 provides the qualification requirements for high efficacy light sources installed to comply with Section 150.0(k). For the purposes of this Section, high efficacy light sources include ballasts or drivers if needed for operation of the light source: light sources shall be certified together with a driver or ballast. If the light source is inseparable from the luminaire the entire luminaire shall meet the requirements of this section. All qualifying light sources shall be certified to the Energy Commission according to all of the requirements in this Appendix.

JA8.2 Certification of Test Labs

The light source under test shall be tested at a testing laboratory participating in the ISO/IEC 17025, by the National Voluntary Laboratory Accreditation Program (NVLAP) or other laboratory accreditation body operating in accordance with ISO/IEC 17011 and produced under an ongoing inspection program carried out by a Type A inspection body in accordance with ISO/IEC 17020.

JA 8.3 Tests to be performed

Compliance with the requirements of this Appendix shall be determined by performance of the following test procedures, as applicable to the type of light source.

Sample size for lamps with ANSI standard bases and that are not recessed downlight retrofits, shall be 10 units per model: 5 units tested base-up and 5 units tested base-down unless the manufacturer restricts specific use or position. If position is restricted, all units shall be tested in restricted position. Test units, including low voltage lamps, shall be operated at rated voltage.

Sample size for all other sources shall be 3 units, tested in accordance with manufacturer's installation instructions for intended orientation.

JA 8.3.1 Efficacy Test

[23] Section JA8.4.6, "Dimming, Reduced Flicker Operation and Audible Noise."

Efficacy at full light output shall be determined by the following test procedures, as applicable to the type of light source:

a) For incandescent and incandescent reflector lamps: 10CFR 430.23(r).
b) For medium base compact fluorescent lamps: 10CFR 430.23(w).
c) For general service fluorescent lamps: 10CFR 430.23(r).
d) For fluorescent lamps that are not Medium base compact fluorescent lamps and general service fluorescent lamps: IES LM-9.
e) For LED light sources, IES LM-79.
f) For high intensity discharge lamps, IES LM-51.
g) For induction lamps, IES LM-66.

The reported value shall be the minimum efficacy of the tested units and be rounded to the nearest tenth.

JA 8.3.2 Power Factor Test

Power factor shall be measured at full light output in accordance with ANSI C82.77, Section 6 and 7.

For lamps, the reported value shall be the average measured values of the tested units rounded to be the nearest tenth.

For all other sources, the reported value shall be the minimum power factor of the tested units rounded to the nearest tenth.

JA 8.3.3 Start Time Test

Start time shall be measured in accordance with the ENERGY STAR Program Requirements Product Specifications for Lamps 1.1: Start Time Test Method, notwithstanding the scope of the test.

For lamps the reported value shall be the average start time of the tested units rounded to the nearest millisecond.

For all other sources the reported value shall be the maximum start time of the tested units rounded to the nearest millisecond.

JA 8.3.4 Color Characteristics Tests

Correlated Color Temperature (CCT), Duv, and Color Rendering Index shall be determined by the following test procedures, as applicable to the type of light source:

a) Incandescent and halogen reflector lamps: IES LM-20.
b) Incandescent non-reflector lamps: IES LM-45.
c) General service fluorescent lamps: 10CFR 430.23(r).
d) Single ended compact fluorescent lamps: IES LM-66.
e) Fluorescent lamps that are not single ended compact fluorescent lamps or general service fluorescent lamps: IES LM-9.
f) Induction lamps: IES LM-66.
g) LED light sources: IES LM 79.
h) High intensity discharge lamps: IES LM-51.
i) Other applicable test procedure approved by the Executive Director

Correlated Color Temperature (CCT) and Duv shall be calculated in accordance with CIE 15 (reference document ANSI C78.377). Color Rendering Index (CRI) shall be calculated in accordance with CIE 13.3.

The reported value shall be the average measured values of units tested rounded to be the nearest whole number for CCT and CRI and to 4 decimal places (closest ten thousandth) for Duv.

JA8.3.5 Ambient Temperature Life Test

The following light sources shall be tested in accordance with the ENERGY STAR Product Specification for Lamps Version 1.1: Ambient Temperature Life Testing, in an ambient temperature condition between 20°C and 35°C and satisfy the lumen maintenance and 6,000 hour survival rate criteria:

a) Omnidirectional lamps < 10 watts, and decorative lamps for which the manufacturer has not performed an elevated temperature life test to show compliance with lumen maintenance requirements in this specification;
b) Omnidirectional lamps labeled “not for use in enclosed fixtures” on the lamp ~~and lamp packaging~~;
c) LED light engines and lamps labeled “not for use in recessed fixtures” on the product ; and
d) Inseparable SSL luminaire: Alternatively inseparable SSL luminaires may reference the in-situ measurement temperature of the LED, IES LM80 test results and TM21 projections for the light source used in the luminaire.

For lamps the reported value shall be the 9th highest measured lumen maintenance value measured (9 out of 10 units must pass life testing).

For all other sources (except those using the IES-LM80 test method and the IES-TM21 calculation method for projecting lumen maintenance) the reported value shall be the minimum measured lumen maintenance value of the 3 samples.

Inseparable SSL luminaires designed to be recessed, shall be ICAT (insulation contact air tight) rated in accordance with Section 150.0(k)1C and tested with sides and top of luminaire in direct contact with insulation in a UL 1598 Test Apparatus.

For inseparable SSL luminaires referencing the in-situ measurement temperature of the LED, IES -LM80 test results and projecting lumen maintenance using the IES-TM21 calculation method for the light source used in the luminaire, ten samples for each T_S and drive current combination (refer to IES TM-21, section 4.2) must be tested. Each sample set may be composed entirely of one nominal CCT, or may be split between no more than two adjacent nominal CCT values as outlined in ANSI C78.377 (e.g. 2700 and 3000K). The LM-80 test results shall be considered valid for use in the TM-21 calculation of the projected lumen maintenance of the luminaire undergoing the in situ LED temperature measurements if all of the criteria below are met.

1. In the sample luminaire, the in situ TMP_{LED} temperature is less than or equal to the temperature specified in the LM-80 test report for the corresponding or higher drive current, within the manufacturer’s specified operating current range.
2. The drive current measured in the luminaire is less than or equal to the drive current specified in the LM-80 test report at the corresponding temperature or higher.

JA8.3.6 Elevated Temperature Life Test

The following light sources shall be tested in accordance with the ENERGY STAR Product Specification for Lamps Version 1.1: Elevated Temperature Life Testing.

a) Omnidirectional lamps ≥ 10 Watts that are not labeled "not for use in enclosed fixtures" or "not for use in recessed fixtures"; and
b) All other light sources that are not inseparable SSL luminaries, and that are not labeled "not for use in enclosed fixtures" or "not for use in recessed fixtures."

The Option A test method ENERGY STAR Elevated Temperature Life Test shall be modified as follows: Light source shall be tested in an ICAT (insulation contact, air-tight) recessed luminaire of the appropriate size for the source under test. The ICAT luminaire shall be listed for zero

clearance insulation contact (IC) by Underwriters Laboratories or other nationally recognized testing/rating laboratory and have a label that certifies that the luminaire is airtight with air leakage less than 2.0 CFM at 75 Pascals when tested in accordance with ASTM E283. The sides and top of ICAT recessed luminaire shall be in direct contact with insulation in a UL 1598 Test Apparatus..

Light sources tested in accordance with the ENERGY STAR Elevated Temperature Life Test, notwithstanding scope, shall use the modified Option A test method as described above or Option B or C with an operating temperature of:

45degC +/-5degC for omnidirectional sources between 10 and 20 Watts;

45degC +/-5degC for all sources other than omnidirectional not greater than 20 Watts;

55degC +/-5degC for all sources greater than 20 Watts.

If units are tested both base-up and base-down, the average of surviving unit measured values shall be calculated for each orientation and the reported lumen maintenance shall be the lesser of the two averages rounded to the nearest tenth of a percent if the difference between the averages is greater than 3%; if less than 3% difference, then the reported lumen maintenance shall be the average of all surviving units rounded to the nearest tenth percent. If units are tested in one orientation, the reported lumen maintenance value shall be the average of surviving unit measured values rounded to the nearest tenth percent.

For all other sources the reported value shall be the minimum measured lumen maintenance value of the three samples.

JA 8.3.7 Tests for Minimum Dimming Level, Flicker, and Audible Noise

The flicker test is performed for light sources as specified in Joint Appendix JA10 and the audible noise test as specified in the ENERGY STAR Program Requirements Product Specification for Lamps Version 1.1: Noise Recommended Practices, notwithstanding scope.

Minimum dimming level is measured by comparing the stabilized light output of the light source with the dimming control set to full light output with the dimming control being set to the manufacturer's minimum rated output. Full light output and minimum light output is measured after the light output has stabilized according to the test procedures specific to light source type in Section JA 8.3.1.

In addition to the reporting of flicker results as described in Section JA8.6, flicker test data for each combination of light source, ballast or driver (if applicable), transformer type and dimmer type claiming compliance with JA8 shall be submitted to the California Energy Commission in the format as defined in Joint Appendix JA10.

Testing for minimum dimming level, flicker, and audible noise is required for each combination of light source, ballast or driver (if applicable), transformer type and dimmer type as follows:

1. Low voltage light sources shall be tested with a representative transformer for each transformer type that the light source is claiming compatibility.
2. Light sources claimed as compatible with forward phase-cut dimmers shall be tested in combination with a NEMA SSL 7A compliant dimmer.
3. Light sources claimed as compatible with dimmers other than forward phase-cut dimmers, dimmability, low noise and low flicker operation shall be tested for each ballast or driver combination (if applicable) with at least one representative dimmer for each dimmer type for which compatibility is claimed.

JA 8.4 Qualification Requirements

The following qualification requirements must be met for the light source to be considered High Efficacy as specified in Section 150(k) and Table 150.0-A.

JA8.4.1 Luminous Efficacy

The light source shall meet the following requirements when measured in accordance with the test method of Section JA8.3.1:

The luminous efficacy of the light source shall be equal to or greater than 45 lumens/Watt when tested at its full light output.

JA8.4.2 Power Factor

The light source shall meet the following requirements when measured in accordance with the test method of Section JA8.3.2:

The light source shall have a power factor equal to or greater than 0.90 when tested at its full light output.

JA8.4.3 Start Time

The light source shall meet the following requirements when measured in accordance with the test method of Section JA8.3.3:

The light source shall have a start time no greater than 0.5 seconds.

JA8.4.4 Color Characteristics

The light source shall meet the following CCT, Duv, and color rendering requirements when measured in accordance with the test method of Section JA8.3.4:

(a) Inseparable SSL luminaires, LED light engines, and GU24-based LED lamps shall be capable of providing a nominal Correlated Color Temperature (CCT) that is 4000 Kelvin or less and within 0.0033 Duv of the black body locus in the 1976 CIE color space.

(b) All other light sources shall be capable of providing a nominal Correlated Color Temperature (CCT) that is 3000 Kelvin or less and within 0.0033 Duv of the black body locus in the 1976 CIE color space.

(c) All light sources shall provide a Color Rendering Index (CRI) of 90 or higher and color rendering R9 value of 50 or higher when measured at a correlated color temperature and Duv value that comply with Section JA8.4.4.

JA8.4.5 Lumen Maintenance, Rated Life and Survival Rate

The light source shall meet the lumen maintenance, rated life, and survival rate criteria when measured in accordance with the test method of Section JA8.3.5 and JA8.3.6.

(a) Lumen Maintenance: The percentage of initial light output after the 6,000 hour test must be equal to or greater than 86.7 percent. For inseparable SSL luminaires referencing the in-situ measurement temperature of the LED, complying products shall have IES LM-80 test results that produce an IES TM-21 projected L70 of at least 25,000 hours.

(b) Rated Life: The light source shall have a minimum rated lifetime of 15,000 hours.

(c) Survival Rate: 90 percent of tested units shall be operational at the completion of the 6,000 hour life test.

Exception to Section JA8.4.6(c): Inseparable SSL luminaires referencing the in-situ measurement temperature of the LED.

JA8.4.6 Dimming, Reduced Flicker Operation and Audible Noise

The light source shall meet the following dimming, reduced flicker operation, and audible noise requirements when measured in accordance with the test method of Section JA8.3.7:

(a) The light source shall be dimmable down to 10 percent light output where 100 percent full light output is defined as operating the light source at the maximum setting provided by the control.

(b) LED-based light sources shall meet the requirements of NEMA standard SSL 7A as Type 1 or Type 2 products.

EXCEPTION to JA8.4.6(b): LED based light sources designed to be dimmed by controls other than forward phase cut dimmers.

(a) Light source in combination with specified control shall provide "reduced flicker operation" when tested at 100 percent and 20 percent of full light output, where reduced flicker operation is defined as having percent amplitude modulation (percent flicker) less than 30 percent at frequencies less than 200Hz, tested according to the requirements in Joint Appendix JA-10.

(b) Light source shall not emit audible noise above 24dBA measured at 1 meter from the light source when tested at 100 percent and 20 percent of full light output.

JA8.5 Marking

Light sources meeting the requirements of this Appendix shall be marked with "JA8-2016" to indicate their compliance with the criteria of this Appendix. Light sources that have passed the Elevated Temperature Life Test shall instead be marked with "JA8-2016-E", to indicate that they comply with this Appendix and may additionally be installed in elevated temperature applications such as enclosed fixtures. Light sources that do not comply with this Appendix shall not be marked with "JA8-2016" or "JA8-2016-E".

JA8.6 Data Reporting

The following test data shall be submitted to the California Energy Commission in the format specified in Table JA-8. The entity submitting the filing shall keep all test data and documentation required for compliance for at least two years from the date of certification and shall provide copies of this documentation to the Energy Commission within 10 days of written request received from the Energy Commission.

TABLE JA-8. DATA TO BE RECORDED AND SUBMITTED TO THE CALIFORNIA ENERGY COMMISSION

Required Information	Permissible Answers	Compliance Threshold
Manufacturer, Model number, Description		
Light Source Type	LED, OLED, Fluorescent, HID, Incandescent, Other	
Product type	Omnidirectional lamp, Directional lamp, Decorative lamp, LED light engine, inseparable SSL luminaire, other	
Lab accredited by NVLAP or accreditation body operating in accordance with ISO/IEC 17011?	Yes/No	Yes
Initial Efficacy	Value (lumens/Watt)	≥ 45 lumens/Watt
Power Factor at Full Rated Power	0 – 1 Fraction	≥ 0.90
Start time	Value (seconds)	≤ 0.5 sec
Correlated Color Temperature (CCT)	Number Kelvin	For inseparable SSL luminaires, LED light engines and GU24 LED lamps, ≤4000 Kelvin. For all other sources,≤ 3000 Kelvin.
Duv	Number Duv	≥-0.0033 and ≤ +0.0033
Color Rendering Index (CRI)	0-100	≥ 90
Color Rendering R9 (red)	0-100 or below 0	≥ 50
Ambient or elevated temperature test for rated life, lumen maintenance, and survival rate	Ambient or Elevated	"Ambient" allowed only for omnidirectional lamps <10W, and decorative lamps, or labeled "not for use in enclosed fixtures", lamps and light engines that are labeled "not for use in recessed fixtures" and "inseparable SSL luminaires". All others must report "Elevated".
6,000 hour lumen maintenance	Value (percent), N/A	≥ 86.7% or NA for integral luminaires providing TM-21 L70 projections based on light source LM80 data

Required Information	Permissible Answers	Compliance Threshold
LM-80 and TM-21 Projected Time to L70	Value (hours), N/A	≥ 25,000 hours, or N/A for light sources providing 6,000 hour lumen maintenance testing
Rated life	Value (hours)	≥ 15,000 hours
6,000 hour survival rate	Value (percent)	≥ 90% or NA for integral luminaires whose lumen maintenance/rated life is evaluated using light source LM-80 data.
Minimum dimming level	Value (percent)	≤ 10%
Dimming control compatibility	Forward Phase cut control, reverse phase cut, powerline carrier, digital, 0-10 VDC, other.	At least one type must be listed
NEMA SSL 7A compatible?	Yes/No	If compatible with forward phase cut dimmer control, “Yes”. If not, “No”.
Flicker:		
See JA10 Table 10-1 for flicker data requirements and permissible answers		≤ 30% <30% for frequencies of 200 Hz or below, at 100% and 20% light output
Audible Noise		
100% light output: Audible Noise	Value (dBA)	≤ 24 dBA
20% light output: Audible Noise	Value (dBA)	≤ 24 dBA
Marking		
Marked in accordance with JA8.5	Yes/No	Yes. “No” allowed only for lamps and LED light engines with diameter less than 1.0” and decorative lamps with a diameter less than 2.0”