The Association of Electrical and
Medical Imaging Equipment Manufacturers

Fluorescent Lamp Dimming Ballast Energy Efficiency Methods of Measurement

Dec 2016 Update

ANSI Standards Committee 82 Work Status

- ANSI C82.11 Ad Hoc group worked out a method of measurement draft per the following process:
  - Physics modeling
  - Initial internal testing
  - UL Labs workshop (NVLAP Third party)
  - Power analyzer manufacturers engagement
  - Method formal draft
  - ANSI C82 WG CDC ballot
  - CDC comments resolution
  - ANSI C82 WG CDV

- A rapid start lamp ballast output power has been difficult to determine because rapid start lamps are multiport devices (see Figure 2). Difficulty to calculate the ballast output power impedes calculating ballast efficiency because efficiency calculation requires knowing both the input power and the output power.

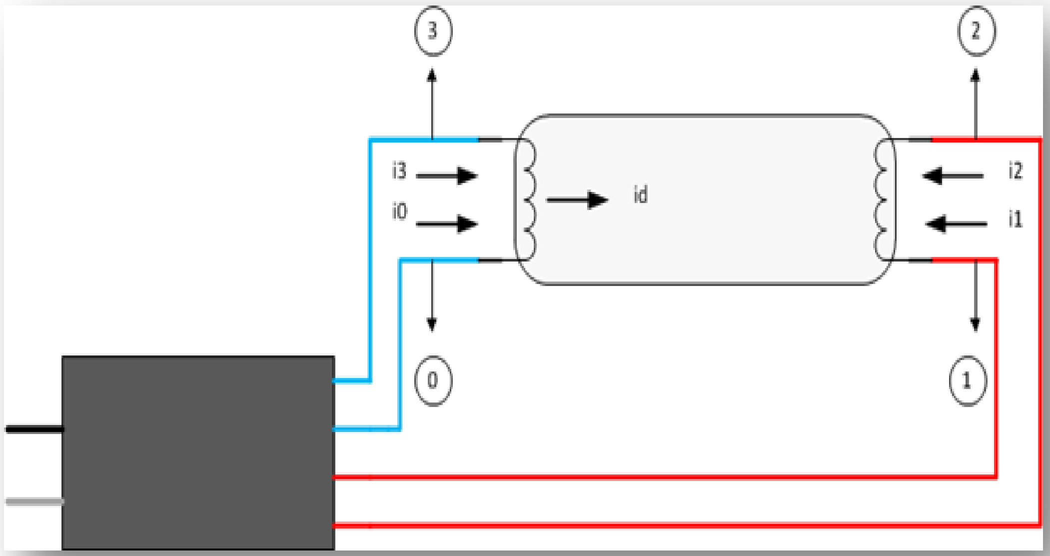


Figure 2. Diagram depicting a dimming ballast as a multiport device.

- It is difficult to estimate rapid start ballast lamp voltage; a different value will be derived from subtracting the voltage from its different alternative ports.
- The lamp voltage calculated from subtracting v_o from v_1 will be different than the lamp voltage calculated from subtracting v_o from v_2.
- A rapid start lamp current is typically measured by means of placing the two ballast lead wires (connected to the same ballast side) through a current transformer. The current transformer frequency response, tolerance, and accuracy are critical for measurement quality.
- Dimming ballasts tend to operate at a higher frequency when dimming; some add a small DC current as a means to mitigate striation.
- Thus, the current transformer needs to have a wide frequency response including DC current sensing. Hall-effect probes are one possible alternative.
- Testing laboratories seeking to determine total lamp power need to consider the electrical phase relationships between the lamp voltage and the lamp current, including a careful de-skewing between the voltage channel and the current channel.

The BLE Approach

- The current Federal Test Procedure (DOE, 10 CFR 430, 2011) mitigates the BEF light output variability by shifting the ballast energy efficiency metric to electrical measurements.
- It defined a new metric, Ballast Luminous Efficiency (BLE), in terms of the lamp arc power to the input power ratio.
- The goal of the new definition of arc power was derived from the need to replace the old light output metric of Ballast Efficacy Factor (BEF) with an equivalent electrical measurement.
- The Federal BLE test method for a rapid or programmed start ballast is described in Appendix Q (DOE, 10 CFR 430 Appendix Q, 2011).
- As described earlier in this workshop, most dimming ballasts operate in a similar way as programmed start ballasts or rapid start ballasts; the following description considers only these types of ballasts.

- The current BLE test method requires connecting the ballast to a stable power supply, and the ballast outputs to a network of two resistors in parallel with the lamp cathodes (see Figure 4).

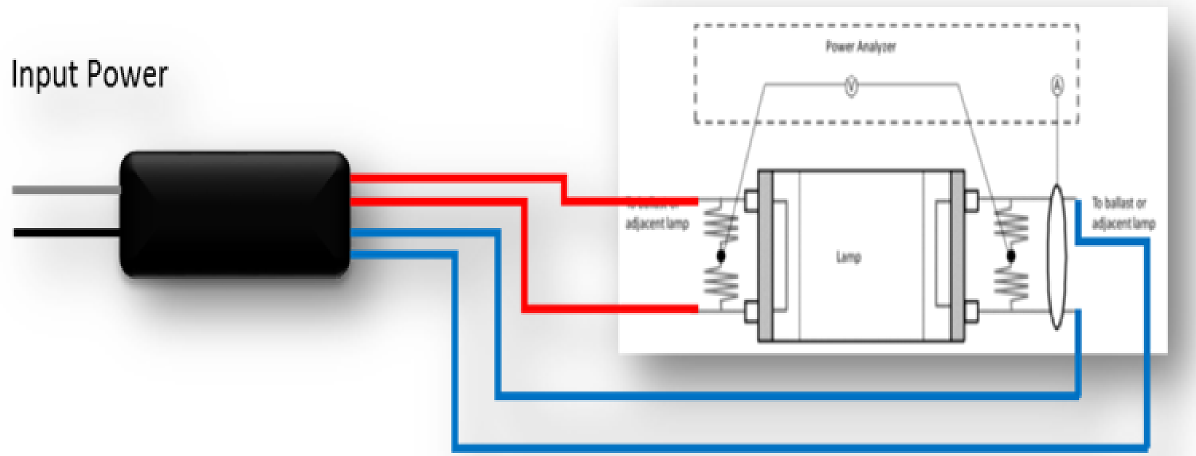


Figure 4. Picture depicting the DOE BLE test method setup.

$$\eta = \frac{Arc\ Power}{WInput}$$

- Input power is a straightforward electrical measurement; one need only connect a power analyzer between the voltage source and the ballast lead wires.
- It is impossible to measure the arc voltage directly because there is no access to the lamp's internal parts.
- One could measure the voltage drop between a port from one side to a port from the other side; however, *different combinations of connection will produce different voltage readings*.
- The current BLE test method addresses this difficulty by placing two networks constructed with 1kΩ resistors in parallel with the lamp cathodes, and assumes that the voltage measured between the center of the two networks approximates the arc voltage (see Figure 5).

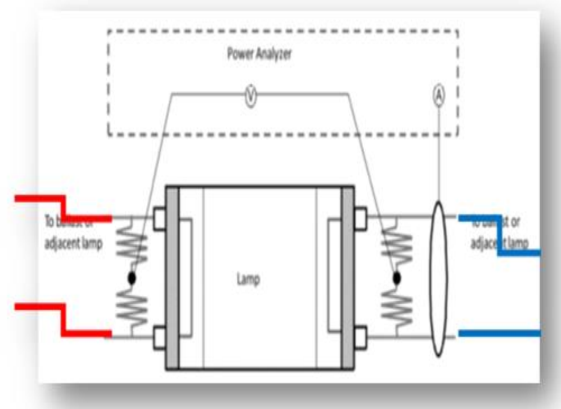


Figure 5. Diagram showing the DOE BLE lamp current, arc voltage, and arc power measurement.

- Then, arc power is calculated by multiplying the arc voltage phasor by the arc current phasor. Arc power is different from the total ballast output power because the ballast also provides the heating cathode power (see Figure 6).

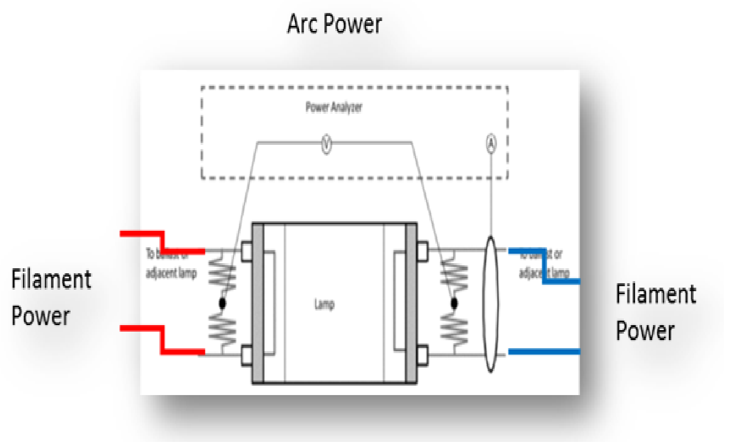


Figure 6. Figure illustrating total lamp power or total ballast output power.

- The BLE test method <u>does not measure filament power; it expresses arc power as the voltage across the voltage dividers multiplied by the lamp current.</u>
- The BLE method produces a highly accurate energy efficiency estimate under the assumption that: either 1) the ballast does not produce any filament power, or 2) the filament power is negligible compared to the arc power.

BLE and Dimming Ballast Energy Efficiency

- Operating the cathode below its thermo-emissive operational point may result in a shortened lamp life and unstable lamp operation.
- Therefore, most dimming ballasts provide additional heating power to the lamp cathode when dimming (reducing the lamp current).
- Thus, the total ballast output power consists of two components: 1) arc power, and 2) filament heating power.
- Table 1 compares BLE to Ballast Efficiency.

ANSI_ANSLG C78.81—2013
Revision of ANSI C78.81-2010

American National Standard

Approved: December, 2013 | Secretariat: American National Standard Lighting Group

for Electric Lamps

Double-Capped Fluorescent Lamps-
Dimensional and Electrical Characteristics

ANSI_ANSLG C78.81—2013
Revision of ANSI C78.81-2010

32-Watt, 48-Inch T8
Fluorescent Lamp
Page 4 of 5

Rapid start requirements
For lamp use with high frequency rapid start ballasts. The following limits are to be observed during the starting period. The requirements of C82.11 section 5.2.3 apply.

Cathode heat requirements
Voltage maximum during operation, V_{rms} 5.3 V

Information for dimming ballast design (Effective January 1, 2015)

For operation at reduced lamp current, the cathode requires supplemental ohmic heating by means of circulating current in the cathode. The following are specifications for the voltage drop, EV, across each cathode in a system of one or more lamps for a range of lamp current, I_D, in dimmed operation.

Maximum heating voltage (V):	$EV_{max} = 5.3$	
Minimum heating voltage (V):	$EV_{min} = 4.0$	for $0.020 \le I_D < 0.050$ (A)
	$EV_{min} = 5.0 - 20{*}I_D$	for $0.050 \le I_D < 0.100$ (A)
	$EV_{min} = 8.45 - 54.5{*}I_D$	for $0.100 \le I_D < 0.155$ (A)
	$EV_{min} = 0$	for $0.155 \le I_D$ (A)

Table 1

Dimming Ballast BLE and Ballast Efficiency Comparison

Dimming Ballast Energy Efficiency Metrics	
BLE method	Ballast Efficiency method
$Arc\_power = \underset{Varc}{\longrightarrow} \cdot \underset{Iarc}{\longrightarrow}$	$Output_{Power} = arc_{power} + Filaments\_Power$
$BLE = \dfrac{arc\_power}{Input\_power}$	$\eta = \dfrac{Output\_power}{Input\_power}$

Recall that the CEC has a different term called Maximum Arc Power

- Two axioms follow from a comparison of the BLE and Ballast Efficiency calculation:
  1. BLE and Ballast Efficiency have the same value in the absence of cathode heating power.
  2. Ballast Efficiency is always higher than BLE when cathode heating power is present.

- A multi-lamp ballast energy efficiency can be calculated by the sum of each lamp arc power plus its cathode's heating power (total output power), divided by the input power.

$$\eta = \frac{\sum_i^n (arc\_power_i + cathode\_R\_power_i + cathode\_L\_power_i)}{Input\_power}$$

Where

n = number of lamps

arc_power_i = each lamp arc power

$cathode\_R\_power_i$ = each lamp right side cathode heating power

$cathode\_L\_power_i$ = each lamp left side cathode heating power

Input_power = ballast input power

Table 2, Analysis

Parameter	Full Light Output	Dimmed Output
Input Power	62 W	44 W
Lamp1 arc power	28 W	14 W
Lamp 1 right cathode heating power	0 W	2.5 W
Lamp 2 left cathode heating power	0 W	2.5 W
Lamp 2 arc power	28 W	14 W
Lamp 2 right cathode heating power	0 W	2.5 W
Lamp 2 left cathode heating power	0 W	2.5 W
Total arc power	56 W	28 W
Total output power	56 W	38 W
BLE	0.90	0.64
Ballast Efficiency	0.90	0.86

Ballast efficiency includes Filament Power

- BLE is a metric based on electrical measurements to replace the old BEF metric based on light output measurements, and it appears to report a similar number as the ballast efficiency at full light output.
- Consideration is needed for using BLE for other dimming operational points because the BLE metric underrepresents the ballast efficiency.
  - This is because it does not account for the cathode heating, even at 100% light output
  - The ballast provides cathode heating power because the lamp needs to keep the cathodes heated to operate correctly
- A dimming ballast’s total output encompasses both the arc power and the cathode heating power. The following section discusses how to consider the full ballast output power in dimming.

Evaluating Ballast Efficiency in the Dimmed State

Multiport Test Method

- Consider a multiport device like the one described below in Figure 7. Let's assume that the device is not accumulating charge; the power delivered to any port is expressed by the following relationship (Millman & Halkias, 2001):

$$P_j = \frac{1}{T}\int_0^T v(t)_j * i(t)_j * dt$$

Where j identifies a specific terminal or port

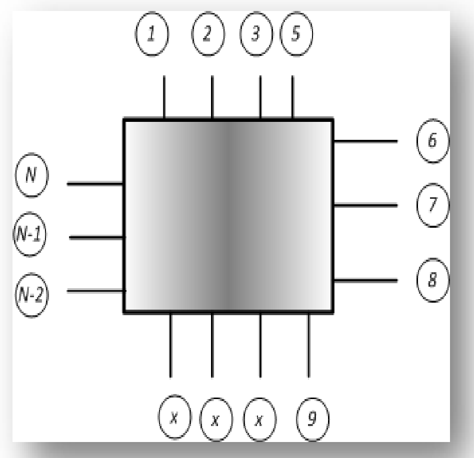


Figure 7

Diagram illustrating the multiport device.

- The total power to the system is the aggregation of the individual ports' power (Millman & Halkias, 2001):

$$P = \sum_{j=1}^{N} \frac{1}{T} \int_0^T v(t)_j * i(t)_j * dt$$

- Since the sum of integrals is equal to the integrals of the sums, the above equation may be rewritten as:

$$P = \frac{1}{T} \int_0^T \sum_{j=1}^{N} v(t)_j * i(t)_j * dt$$

- Thus, the power of a multiport device is equal to the sum of the individual ports' power.

- Since we have assumed that the device is not accumulating charge, following Kirchoff's current law (Millman & Halkias, 2001), we can write the net total current into the device as zero.

$$\sum_{j=1}^{N} i(t)_j = 0$$

- The last term may be moved to the other side of the equation and rewritten as:

$$\sum_{j=1}^{N-1} i(t)_j = -i(t)_N$$

- The total power into the device may also be rewritten as:

$$P = \frac{1}{T}\int_0^T \left\{ \left(\sum_{j=1}^{N-1} v(t)_j * i(t)_j \right) + v(t)_N * i(t)_N \right\} * dt$$

- Using the previous equation to replace the last term:

$$P = \frac{1}{T}\int_0^T \left\{\left(\sum_{j=1}^{N-1} v(t)_j * i(t)_j\right) - v(t)_N * \sum_{j=1}^{N-1} i(t)_j\right\} * dt$$

- Which reduces to:

$$P = \frac{1}{T}\int_0^T \left\{\sum_{j=1}^{N-1} \left[v(t)_j - v(t)_N\right] * i(t)_j\right\} * dt$$

- By considering the axiom that the integral of a summation is equal to the summation of the integrals once more, the total power equation takes the form of:

$$P = \sum_{j=1}^{N-1} \frac{1}{T}\int_0^T \left[v(t)_j - v(t)_N\right] * i(t)_j * dt$$

- In practical terms, the total power delivered to a multiport device may be found by adding the N-1 two terminal power measurements where the Nth terminal is used as the common reference for all measurements.
- This technique has been used by previous researches to measure rapid start ballast total power output (Roberts, 1981; Rudolph, Oliver, & Francis, 1985).

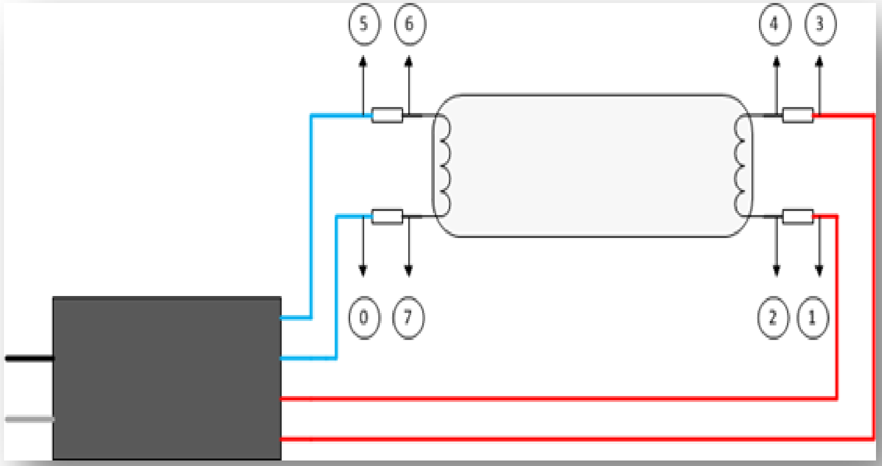


Figure 8. Illustration shows a one-lamp ballast as a multiport system.

- A one-lamp ballast has been connected according to its label diagram; small impedance (0.5 ohms) current sensors have been introduced in series with each (port) lamp terminal.
- The port marked 0 has been chosen as the reference port.
- According to the previous section, the total ballast output power may be found by aggregating the power of all ports.
- Each port's power may be measured by; 1) connecting to the power analyzer voltage probe with one side to the reference port and the other side to the port to be measured, and 2) connecting the current probe to the port to be measured (Figure 9).

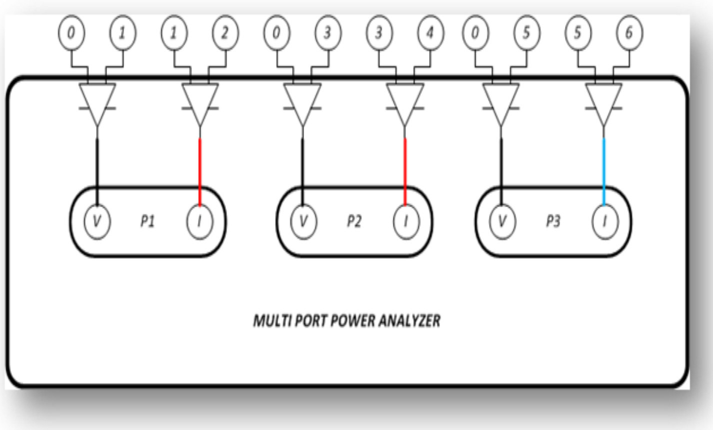


Figure 9. Diagram showing the dimming ballast output power ports measurement.

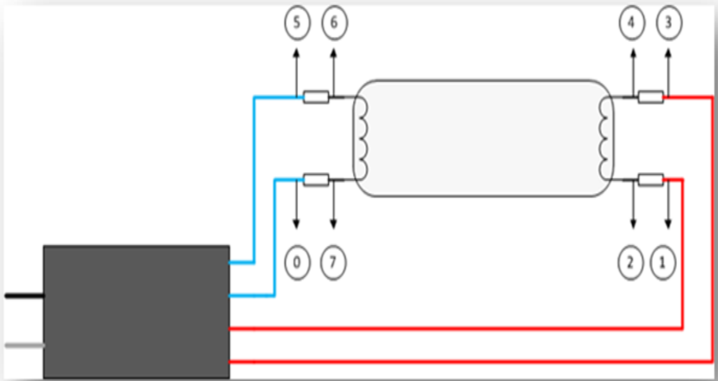


Figure 8. Illustration shows a one-lamp ballast as a multiport system.

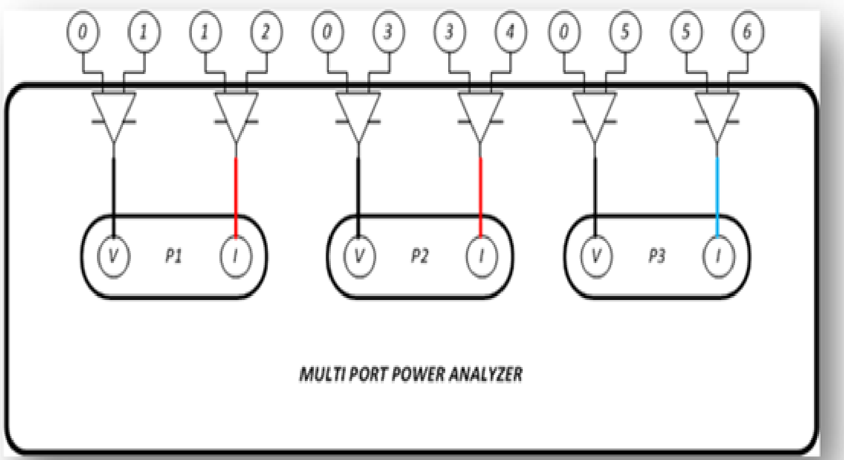


Figure 9. Diagram showing the dimming ballast output power ports measurement.

Table 3 One Lamp Ballast Multiport Testing Example

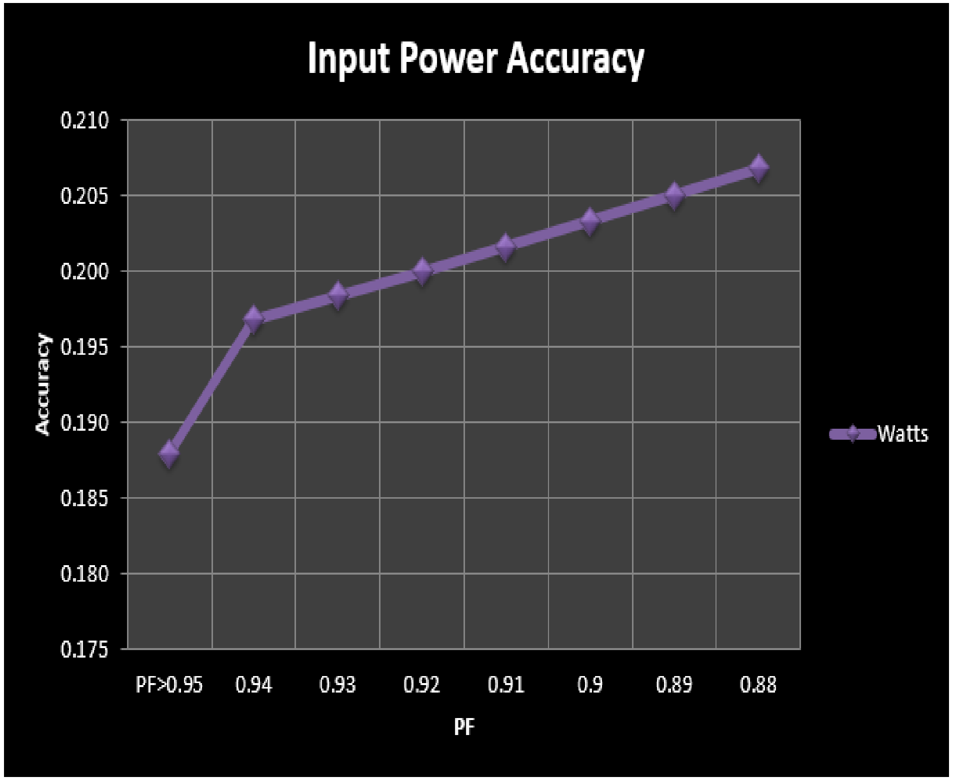
One F32T8 32W lamp dimming ballast total output power, BLE, and efficiency		
Parameter	Full Light Output	50% Output
Input Voltage (Vrms)	119.6	119.7
Input Current (Arms)	0.3	0.2
Input Power (W)	32.8	20.7
Arc Power (W)	28.1	14.0
BLE	0.86	0.68
Port B1Power (W)	0.1	1.7
Port R1 Power (W)	6.4	-44.1
Port R2 Power (W)	22.7	59.3
Total Output Power (W)	29.2	16.9
Efficiency with Cathode Heat	0.89	0.81

Test Method Accuracy

Dimming Ballast Efficiency Measurement Accuracy

Input power measurement accuracy

INPUT POWER ACCURACY in WATTS								
Power	PF>0.95	0.94	0.93	0.92	0.91	0.9	0.89	0.88
69	0.188	0.197	0.198	0.200	0.202	0.203	0.205	0.207

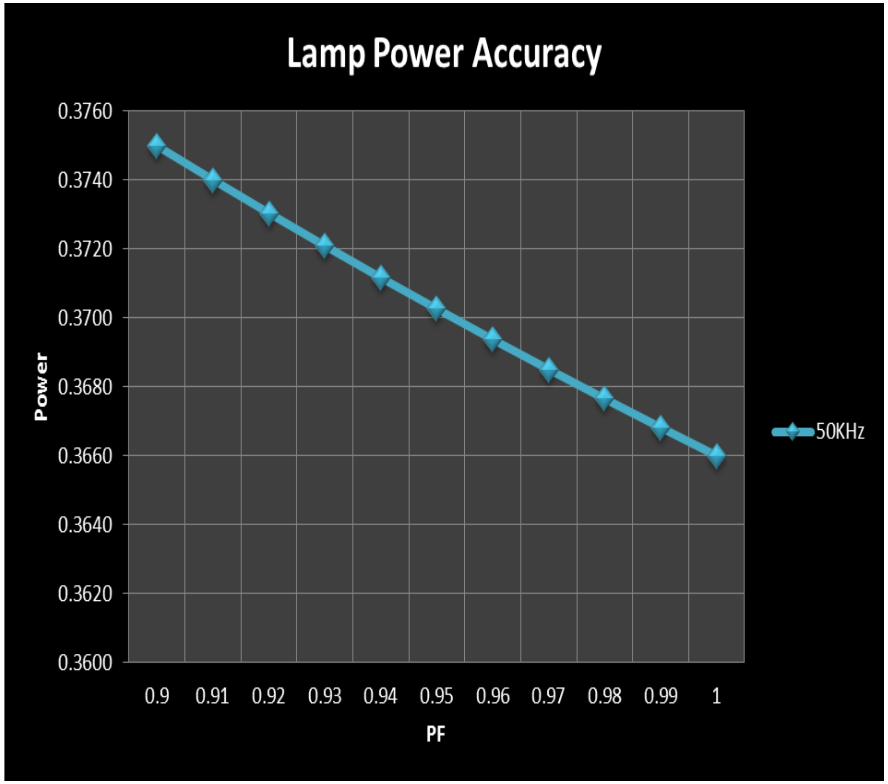


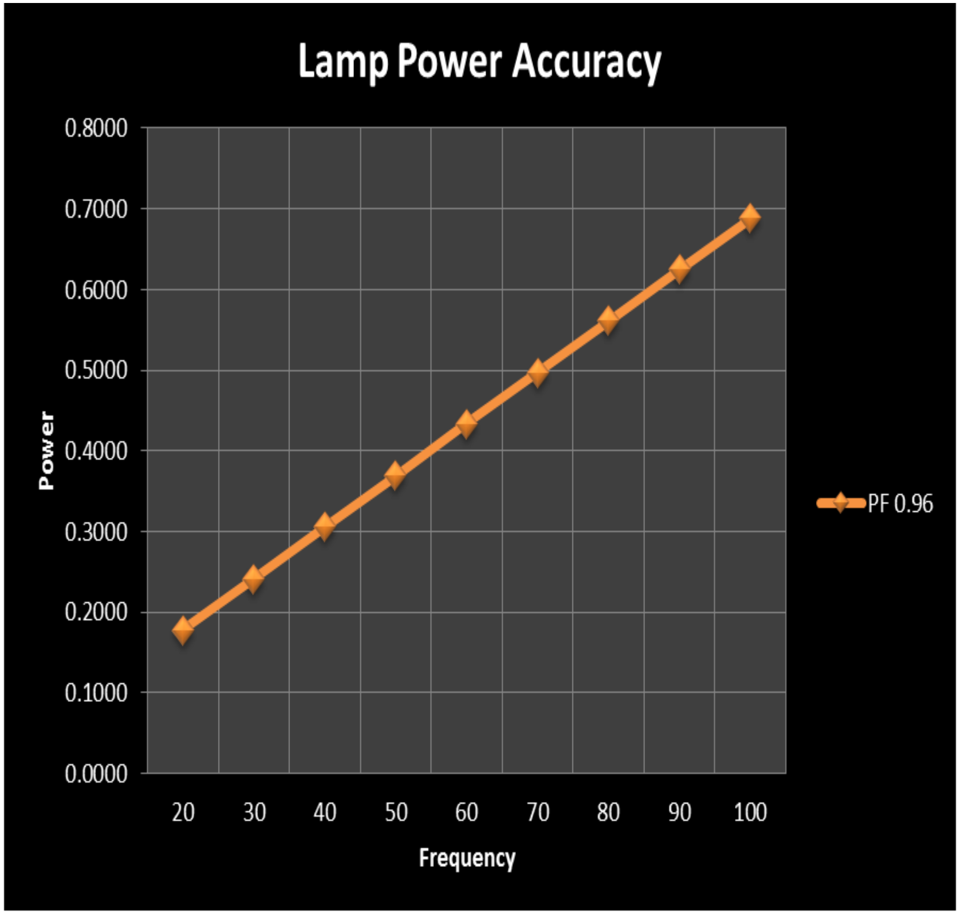
Lamp power measurement accuracy

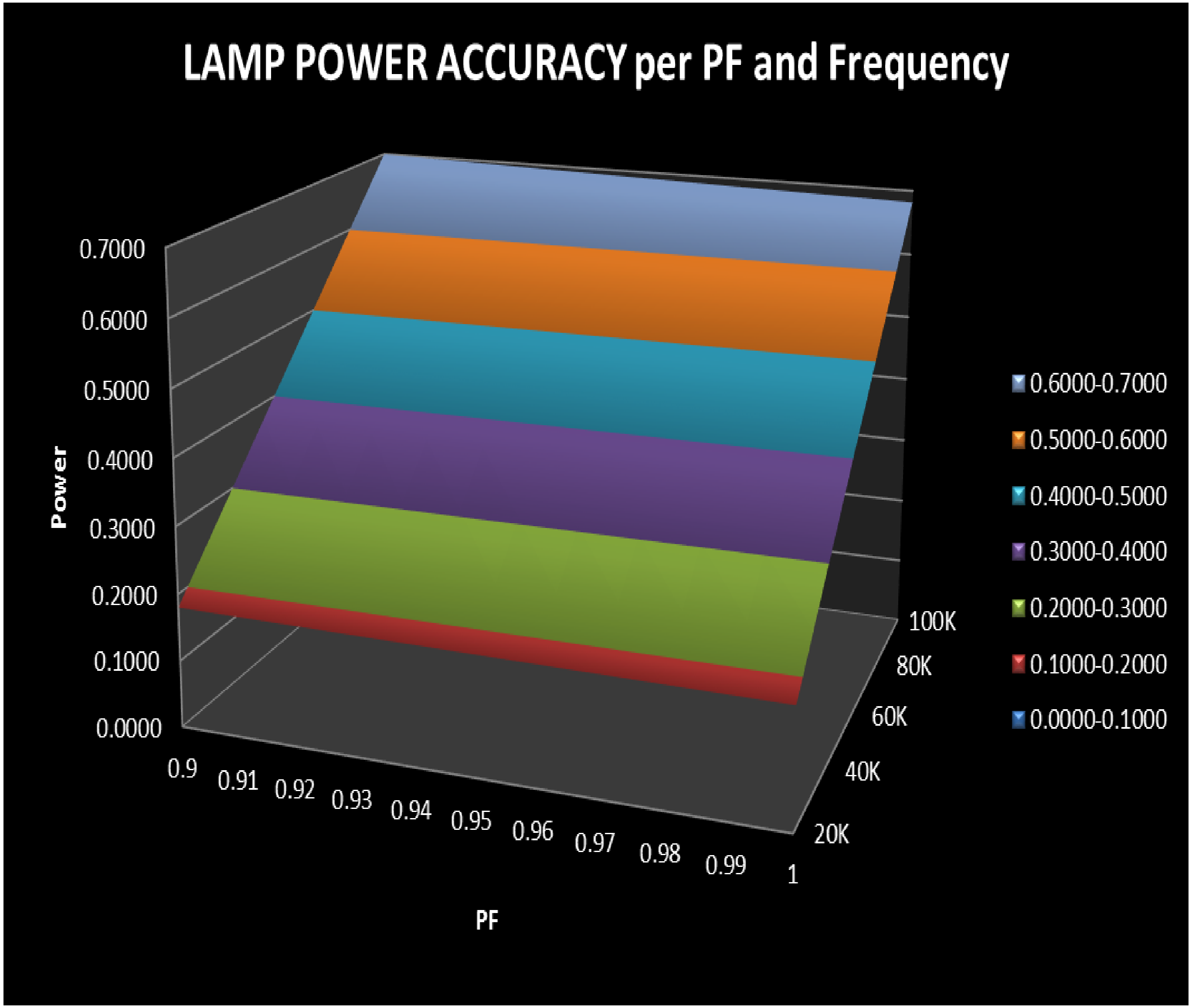
Modern Power Analyzer Output Power Measurement Accuracy Exemplary

POWER	PF										
54	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
Frequency	ACCURACY IN WATTS										
20	0.1800	0.1796	0.1792	0.1788	0.1785	0.1781	0.1778	0.1774	0.1771	0.1767	0.1764
30	0.2450	0.2444	0.2438	0.2433	0.2427	0.2422	0.2416	0.2411	0.2406	0.2401	0.2396
40	0.3100	0.3092	0.3084	0.3077	0.3069	0.3062	0.3055	0.3048	0.3041	0.3035	0.3028
50	0.3750	0.3740	0.3730	0.3721	0.3712	0.3703	0.3694	0.3685	0.3677	0.3668	0.3660
60	0.4400	0.4388	0.4377	0.4365	0.4354	0.4343	0.4333	0.4322	0.4312	0.4302	0.4292
70	0.5050	0.5036	0.5023	0.5009	0.4996	0.4984	0.4971	0.4959	0.4947	0.4935	0.4924
80	0.5700	0.5684	0.5669	0.5654	0.5639	0.5624	0.5610	0.5596	0.5582	0.5569	0.5556
90	0.6350	0.6332	0.6315	0.6298	0.6281	0.6265	0.6249	0.6233	0.6218	0.6203	0.6188
100	0.7000	0.6980	0.6961	0.6942	0.6923	0.6905	0.6888	0.6870	0.6853	0.6836	0.6820

KHz


Lamp Power Accuracy
Power
0.3760
0.3740
0.3720
0.3700
0.3680
0.3660
0.3640
0.3620
0.3600
0.9
0.91
0.92
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1
PF
50KHz


Lamp Power Accuracy
Power
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
20
30
40
50
60
70
80
90
100
Frequency
PF 0.96


LAMP POWER ACCURACY per PF and Frequency
Power
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
0.9
0.91
0.92
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1
PF
100K
80K
60K
40K
20K
0.6000-0.7000
0.5000-0.6000
0.4000-0.5000
0.3000-0.4000
0.2000-0.3000
0.1000-0.2000
0.0000-0.1000

- Ballast efficiency measurement accuracy
- $A = A_{input\_power} + A_{output\_power}$

POWER	PF										
100	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
Frequency	UNITARY EFFICIENCY ACCURACY IN WATTS										
20	0.5289	0.5257	0.5226	0.5196	0.5166	0.5032	0.5025	0.5019	0.5012	0.5006	0.5000
30	0.6322	0.6287	0.6252	0.6218	0.6185	0.6047	0.6038	0.6028	0.6018	0.6009	0.6000
40	0.7356	0.7316	0.7278	0.7241	0.7204	0.7063	0.7050	0.7037	0.7024	0.7012	0.7000
50	0.8389	0.8346	0.8304	0.8263	0.8223	0.8079	0.8063	0.8046	0.8031	0.8015	0.8000
60	0.9422	0.9376	0.9330	0.9286	0.9243	0.9095	0.9075	0.9056	0.9037	0.9018	0.9000
70	1.0456	1.0405	1.0357	1.0309	1.0262	1.0111	1.0088	1.0065	1.0043	1.0021	1.0000
80	1.1489	1.1435	1.1383	1.1331	1.1281	1.1126	1.1100	1.1074	1.1049	1.1024	1.1000
90	1.2522	1.2465	1.2409	1.2354	1.2300	1.2142	1.2113	1.2084	1.2055	1.2027	1.2000
100	1.3556	1.3495	1.3435	1.3376	1.3319	1.3158	1.3125	1.3093	1.3061	1.3030	1.3000

Efficiency Accuracy Full Power

Modern Power Analyzer Efficiency Measurement Accuracy Exemplary

POWER	PF										
59	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
Frequency	Unitary Efficiency Accuracy in Percent										
20	0.626%	0.623%	0.620%	0.617%	0.614%	0.600%	0.600%	0.599%	0.599%	0.598%	0.597%
30	0.743%	0.740%	0.736%	0.733%	0.730%	0.716%	0.715%	0.714%	0.713%	0.712%	0.711%
40	0.861%	0.857%	0.853%	0.849%	0.846%	0.831%	0.830%	0.829%	0.828%	0.826%	0.825%
50	0.978%	0.974%	0.969%	0.965%	0.961%	0.947%	0.945%	0.944%	0.942%	0.940%	0.939%
60	1.095%	1.090%	1.086%	1.081%	1.077%	1.062%	1.060%	1.058%	1.057%	1.055%	1.053%
70	1.212%	1.207%	1.202%	1.198%	1.193%	1.178%	1.176%	1.173%	1.171%	1.169%	1.167%
80	1.330%	1.324%	1.319%	1.314%	1.309%	1.293%	1.291%	1.288%	1.286%	1.283%	1.281%
90	1.447%	1.441%	1.435%	1.430%	1.425%	1.409%	1.406%	1.403%	1.400%	1.397%	1.395%
100	1.564%	1.558%	1.552%	1.546%	1.540%	1.524%	1.521%	1.518%	1.515%	1.512%	1.508%

Efficiency Accuracy 50% Power

Modern Power Analyzer Efficiency Measurement Accuracy Exemplary

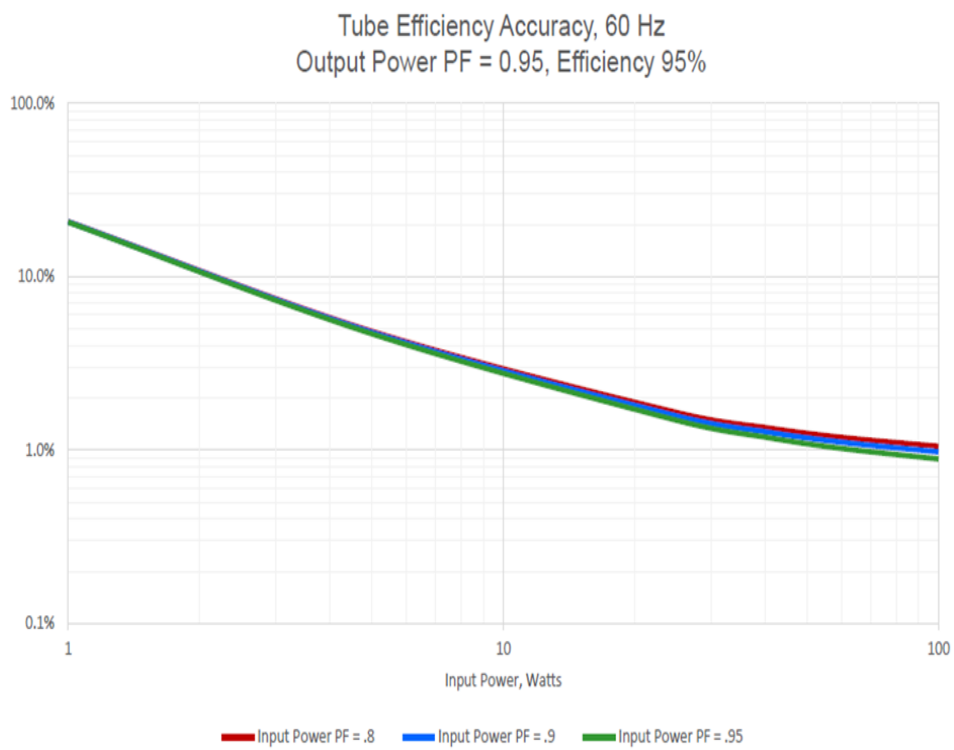
POWER	PF										
29	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
Frequency	Unitary Efficiency Accuracy in Percent										
20	0.872%	0.868%	0.865%	0.862%	0.859%	0.846%	0.845%	0.845%	0.844%	0.843%	0.843%
30	1.024%	1.020%	1.017%	1.014%	1.010%	0.996%	0.995%	0.995%	0.994%	0.993%	0.992%
40	1.176%	1.172%	1.169%	1.165%	1.161%	1.147%	1.146%	1.144%	1.143%	1.142%	1.141%
50	1.329%	1.324%	1.320%	1.316%	1.312%	1.298%	1.296%	1.294%	1.293%	1.291%	1.290%
60	1.481%	1.476%	1.472%	1.467%	1.463%	1.448%	1.446%	1.444%	1.442%	1.440%	1.439%
70	1.633%	1.628%	1.623%	1.618%	1.614%	1.599%	1.596%	1.594%	1.592%	1.590%	1.588%
80	1.785%	1.780%	1.775%	1.770%	1.765%	1.749%	1.747%	1.744%	1.741%	1.739%	1.737%
90	1.938%	1.932%	1.926%	1.921%	1.916%	1.900%	1.897%	1.894%	1.891%	1.888%	1.886%
100	2.090%	2.084%	2.078%	2.072%	2.066%	2.050%	2.047%	2.044%	2.041%	2.038%	2.034%

○ Efficiency Accuracy 50% Power

Modern Power Analyzer Efficiency Measurement Accuracy Exemplary

POWER	PF										
10	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
Frequency	Unitary Efficiency Accuracy in Percent										
20	1.789%	1.786%	1.783%	1.780%	1.777%	1.763%	1.763%	1.762%	1.761%	1.761%	1.760%
30	2.072%	2.069%	2.065%	2.062%	2.059%	2.045%	2.044%	2.043%	2.042%	2.041%	2.040%
40	2.356%	2.352%	2.348%	2.344%	2.340%	2.326%	2.325%	2.324%	2.322%	2.321%	2.320%
50	2.639%	2.635%	2.630%	2.626%	2.622%	2.608%	2.606%	2.605%	2.603%	2.602%	2.600%
60	2.922%	2.918%	2.913%	2.909%	2.904%	2.889%	2.888%	2.886%	2.884%	2.882%	2.880%
70	3.206%	3.201%	3.196%	3.191%	3.186%	3.171%	3.169%	3.166%	3.164%	3.162%	3.160%
80	3.489%	3.484%	3.478%	3.473%	3.468%	3.453%	3.450%	3.447%	3.445%	3.442%	3.440%
90	3.772%	3.766%	3.761%	3.755%	3.750%	3.734%	3.731%	3.728%	3.726%	3.723%	3.720%
100	4.056%	4.049%	4.043%	4.038%	4.032%	4.016%	4.013%	4.009%	4.006%	4.003%	4.000%

○ One Power Analyzer Efficiency Accuracy Example



Input Power (W)	Input Power PF = .8	Input Power PF = .9	Input Power PF = .95
1	20.7%	20.7%	20.6%
5	4.83%	4.76%	4.67%
25	1.65%	1.57%	1.49%
40	1.35%	1.27%	1.19%
60	1.18%	1.11%	1.02%
100	1.05%	0.976%	0.888%

Assumes a 40 KHz Lamp operation

Efficiency Measurement Dispersion

- Ballast efficiency reporting may vary by 1.69% (92.40-90.71) at full power, and in a range of 2.82% (92.04-89.22) at 50% Dimming.

2X32WT8RS BALLAST

	Min	Nominal	Max
Acc	-0.25%		0.25%
Input	57.855	58.000	58.145
Acc	-0.67%		0.67%
Output	52.744	53.100	53.456
Efficiency	**90.71%**	**91.55%**	**92.40%**

Output @ 40 KHz

2X32WT8RS BALLAST

	Min	Nominal	Max
Acc	-0.36%		0.36%
Input	31.885	32.000	32.115
Acc	-1.20%		1.20%
Output	28.652	29.000	29.348
Efficiency	**89.22%**	**90.63%**	**92.04%**

Output @ 70 KHz

Alternative Method

- Multiport power analyzers are not as common as two port (regular) power analyzers.
- Accuracy may be increased by reducing wiring connections and port measurements.
- An alternative method supported in the same BLE setup may help laboratories to maximize the use of the existing setups, reduce the number of measurements, and reduce accuracy errors by reducing parasitic effects.
- ANSI is to consider an alternative test method that will estimate the total output power as the addition of the arc power plus a predetermined minimum energy. This would ensure proper lamp filament heating, and therefore comply with the applicable lamp and ballast ANSI standards.
- $\eta = \frac{arc\ power + filament\ power}{input\ power}$ will be replaced by
- $\eta = \frac{arc\ power + compensating\ factor(s)}{input\ power}$

Conclusions

- Fluorescent lamps require additional cathode heating to operate correctly in dimming conditions as described in the proper ANSI standards
- Therefore the total ballast output power encompass two elements; arc power and filament power
- Congruently, ballast efficiency is calculated as

$$\eta = \frac{arc\ power + filament\ power}{Input\ Power}$$

- Most ballast increase their operational frequency under dimming conditions
- Measuring high frequency low power is challenging. The current instrumentation technology is pushed to its limit
- ANSI has developed a dimming ballast test method. Additional works are ongoing to develop an alternative test method to improve accuracy, and to re use the BLE test setups