The Race for TVs with Higher Luminous Efficiency

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Abstract

The major display contenders: LCDs, CRTs, PDPs, projection displays, FEDs, SEDs and OLEDs are each examined in terms of the most critical display characteristic, the luminous efficiency. Each technology has great opportunity for improvement, but which one will win the race?

1. Introduction

These are very exciting times for the display industry. Displays are big business and the world now realizes the critical importance of the man-machine interface.

The development of HDTV has opened up the need for very large screen TVs because the user cannot easily see the high resolution on the smaller screens. This becomes a major limitation for the CRT which, until just a few years ago, was the king of all displays. However the LCDs, PDPs and Projection displays can now all fill the critical need for large screen TVs. New technologies such as FED, SED and OLED are telling their investors that they will be able to beat the leading technologies. But who will be the winner? There are many factors that will determine the outcome and probably manufacturing cost is the most important. However in this paper I would like to examine a display characteristic that is directly related to cost and that is Luminous Efficiency.

The luminous efficiency of a display will alter the design in many ways. Usually manufacturing cost is strongly dependent on luminous efficiency. Higher luminous efficiency means lower power for the same light output and lower power means lower power supply costs, lower packing costs, lighter packages, etc. A design engineer can use higher luminous efficiency to enhance other critical display properties such as luminance, viewing angle or display life.

Displays are fascinating for many reasons. One is the wide array of differing technologies that are used in displays. Virtually every physical, electrical and chemical phenomenon can be found somewhere in the display industry. This keeps displays exciting. But it also makes it very difficult for us to compare the prospects of future display advances. There is frequently such a high degree of individual specialization that an expert in one type of display seldom knows of the exciting advances in the other display types. This results in the common over-statement of the potential of any new technology to compete with existing technology. Unfortunately this frequently produces big losses for the investors that follow the wrong expert.

This paper will cover the prospects for increasing the luminous efficiency of each of the major TV display technologies. It is hoped that this paper will give a balanced picture of the possible advances for all display technologies. The goal is to teach experts of one display technology about the potential improvements in the competitive TV display technologies.

2. Power of Today's TV Displays

Luminous Efficiency is probably one of the most misunderstood and misquoted display characteristics. It is frequently misleading to compare the luminous efficacies of different display technologies. To start, it is important to remember that efficacy is stated in units of lumens per watt, and efficiency is in units of watt per watt, (frequently expressed as a percentage).

What is really important for the customer is not the luminous efficacy but how much power does the TV set take. Figure 1 shows the power of this year's TV sets made from a number of different technologies. The set powers are plotted as a function of the screen area [1]. Each point on Figure 1 is a different TV set product. What is very surprising is that the LCDs, PDPs and HDTV CRTs all fall along the same diagonal line. This shows that for the 2005 models, the LCDs, PDPs, and HDTV CRTs take on the average 580 watts per square meter of display area. This is rather remarkable since everyone expects the LCD to take the least power and the PDP to take the most power.

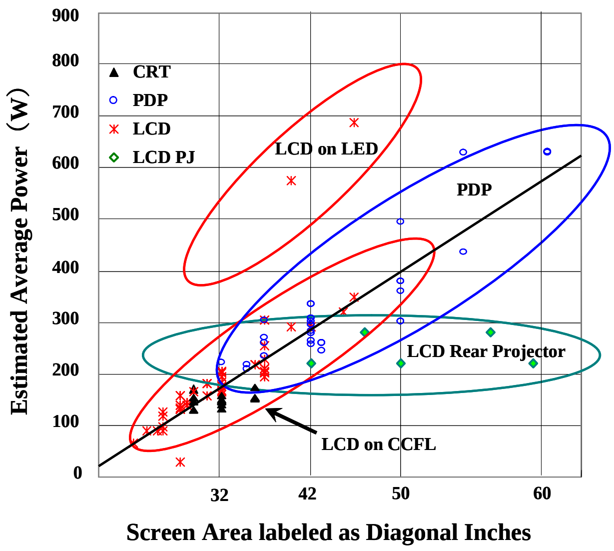

Figure 1. Power for 2005 TV Sets as a function of screen area [1]. Remarkably the LCDs, PDPs and CRTs all fall along same diagonal line. The straight diagonal line corresponds to a power per unit display area of 580 W/m^2.

It is also quite interesting that the projection displays don't follow this trend and they appear to fall along a horizontal line that is independent of screen area. The reason for this will be discussed below in section 7. Also the LED backlit LCDs take roughly twice the power of the CCFL backlit LCDs which is discussed below in section 4.1.

3. Efficacy Comparison Pitfalls

Comparing luminous efficacies of one technology with another is very risky. Each of the major TV technologies works on completely different physical principles and so great care must be taken in comparisons. There are two major pitfalls that occur because of the differences in these technologies. The safest way to avoid these pitfalls is to measure the TV set efficacies using broadcast TV signals.

3.1 Front Filter Pitfall

Emissive displays such as CRTs, PDPs, FEDs and SEDs obtain light from powder phosphors. These phosphors generally reflect white light and so a light absorbing filter is usually placed in front of these displays to improve the bright room contrast ratio. A typical transmission for this filter is 50%. Since the amount of filter transmission is a variable of the final system design, the efficacies of these displays technologies are traditionally quoted assuming that this filter does not exist. The LCD and projection technologies do not have this filter because they do not have visible white powder phosphors. When comparing efficacy numbers between LCDs or projectors and one of the emissive displays it is necessary to properly correct for the transmission of the front filter used with the emissive displays.

3.2 Power-on-Demand Pitfall

Most LCDs and projection displays take a fixed amount of power that is independent of the input signal. However the emissive technologies such as the PDP, FED, SED and OLED have a "power-on-demand" characteristic. For these technologies the major energy dissipation comes from lighting the pixels. This means that for a dark image the set will dissipate a small amount of power and for a bright image the set will dissipate a large amount of power. The power required by these displays depends strongly on the TV signal.

A quantity called the Average Picture Level (APL) can be used to determine the typical power usage. The APL of TV images, as measured after the inverse gamma correction circuit of these sets, is typically 20% or less. When comparing the efficacy of a power-on-demand TV display technology to one with constant power, this 20% translates to a factor of 5 that must be considered. For example, an LCD TV with an efficacy of 2.5 lm/W may take the same power as a PDP TV with 0.5 lm/W because the PDP is power-on-demand. This is why the LCD TVs and PDP TVs fall along the same power per unit screen area line in figure 1. Failure to consider this power-on-demand factor of 5 frequently leads to the mistaken conclusion that PDP TVs take more power than LCD TVs.

4. LCD Efficiency Improvements

Virtually all of the power in the LCD TV is dissipated by the backlight. Almost all LCDs on the market today use the cold cathode fluorescent lamp (CCFL) as the backlight because it is a low cost and high efficiency solution. These have a luminous efficacy of 60 to 80 lm/W. LCD TV backlights typically have a very high luminance on the order of 10,000 cd/m^2. When the LCD shutter is completely open it transmits approximately 5% so the full white luminance of today's LCD TVs is typically 500 cd/m^2. The low 5% transmission is due to the many optical systems and layers that the light must pass though in going from the backlight to the front surface of the display. Major components of loss are the RGB color filters which only transmit 30% of the white light from the backlight. When losses in the power supply are included, the overall efficacy of the LCD TV is typically 2.5 lm/W.

4.1 LCD Backlight Improvements

The CCFL is a very mature technology and so only relatively small improvements are possible in the future. It may be possible to ultimately achieve fluorescent lamp backlight efficacy of 100 lm/W since the best fluorescent lamps for lighting can achieve this today. Work is going on with External Electrode Fluorescent Lamps (EEFL) which can increase efficacy by 10%. Also Hot Cathode Fluorescent Lamps (HCFL) are a possibility [2]. Flat fluorescent lamps are attracting attention since they would eliminate the diffuser and light guide which account for a significant amount of light loss [3].

There is great excitement for developing LED backlights for LCDs [4]. The LEDs have demonstrated very nice color gamut improvement over the phosphors of the CCFL. LEDs will not immediately replace CCFLs because the white efficacy of today's LEDs is only 30 lm/W and the LED cost is considerably greater than the CCFL cost. The lower efficacy of the LED compared to the CCFL shows up very clearly on Figure 1. The LED backlight TVs take twice the power of the CCFL TVs. This is also clear from the massive heat sink found on the back of the current LED backlight LCD TV products.

The good news is that LED backlights are continuing to improve and in a few years they may have comparable or higher efficacy than the CCFL. There are great efforts to improve LED efficacy for lighting purposes and these improvements will help for LED backlights. The big challenge for the LED will be to compete with the very low cost of the CCFL.

4.2 Increasing LCD Efficacy

4.2.1Dynamic Backlight

The current LCD designs with a fixed intensity backlight do not have the power-on-demand advantage discussed in section 3.2. There is an opportunity for LCDs to get some of this possible factor of 5 advantage by reducing the backlight intensity dependent on the TV signal. The LCD is a light shutter and so the pixel luminance is determined by the product of the backlight luminance and the LCD transmission. Let's assume that the brightest pixel in a given TV frame is only at 50% of peak luminance. Then there are two ways that an LCD can display 50% luminance:

1. Backlight = 100%, LCD Transmission = 50%
2. Backlight = 50%, LCD Transmission = 100%

Obviously the second method takes half of the power even though both methods give the same pixel luminance.

The amount of power that can be saved is strongly dependent on the TV signal. The luminance of the backlight should never be reduced below the level needed for the brightest pixel in the frame. This rule should be followed in order to emit the proper luminance level for the brightest pixel when the LCD shutter is fully open. For TV signals, dynamic backlights may result in a 25% or more savings in power which is quite significant [5], [6]. Further savings can be had by independently controlling each individual CCFL lamp for an intensity dependent on the brightest pixel illuminated by a given lamp [7].

4.2.2 Field Sequential Color

The RGB color filters found in LCDs transmit only 30% and so field sequential color offers a way to eliminate these filters and increase efficacy by a factor of three, in theory. This will require that the backlight be rapidly flashed sequentially with one of the RGB colors at a time and also that the LCD be fast enough to cleanly switch to the gray level of each color field. A single color field might have a period of about 5 ms for 180 color fields per second. The LED backlights are a natural choice for this since the individual R, G and B LEDs can be turned on and off in microseconds. The decay times of the R and G phosphors in the CCFL are currently too long to work properly for field sequential color.

The LCDs for field sequential need a very fast switching mode in order to meet the 180 color field per second requirement. This probably requires worst case switching to a stable gray level of 2 milliseconds or less. This is very hard for the LCD modes used in current LCD TVs, but the Optically Compensated Birefringent (OCB) mode of LCDs can achieve this [8]. Fortunately the necessary compensating film for OCB mode has recently become commercially available and so OCB products can now be practical [9]. This fast switching is also possible with ferroelectric LCDs.

Field sequential color offers a large opportunity for LCD luminous efficiency improvement. Its success will depend on the expected future increase in efficacy of the LED backlights. The higher cost of the LEDs may be offset by the savings from eliminating the color filters. The color breakup problem or "rainbow effect" must be satisfactorily resolved.

5. CRT Efficiency Improvements

Cathodoluminescence is reasonably efficient at near 30 lm/W for 30 kV electrons. However as shown in Figure 2, the shadow mask of the CRT cuts this efficiency by a factor of 5 [10]. If we assume a 50% transmission glass faceplate filter, as discussed in section 3.1, then another factor of 2 is lost and so the CRT tube runs at about 2.5 lm/W.

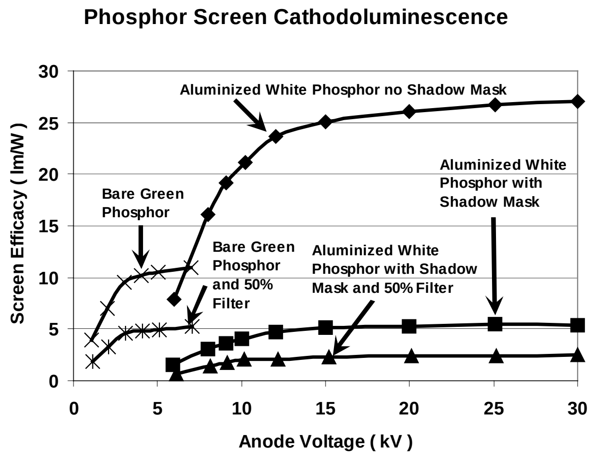

Figure 2. Luminous efficacies of cathodoluminescent phosphor screens [10].

However most of the CRT power is not dissipated in the tube. The biggest power loss is in the magnetic deflection circuits. Because of the higher frequencies and wider deflection angles of HDTV, this deflection circuit loss can be much greater than the losses from standard definition TV. So shadow mask CRTs will have a TV set efficacy that is a small fraction of the 2.5 lm/W efficacy of the tube. This is why the HDTV CRT sets fall along the same power per unit display area line as the LCDs and PDPs in figure 1.

5.1 Increasing CRT Efficacy

Figure 2 shows that the efficacy of the phosphor saturates at a little under 30 lm/W. While there may be hope to increase this to 35 lm/W at 30 kV, this is a fundamental limit because these very high energy electrons create Auger electrons which will not contribute to the luminance. At 35 lm/W, the deflection circuit losses would still be the same and would completely overwhelm the energy lost in the CRT tube. So the major hope for increasing efficacy in CRTs is to eliminate the deflection circuits and also eliminate the shadow mask. This is the strategy being used by the FED and SED devices that will be covered below in section 8. It is the increased efficacy of these new CRT technologies which is one of their main selling points over the LCDs and PDPs.

6 PDP Efficiency Improvements

The highest white luminous efficacy of a PDP product is 1.8 lm/W. This is just the device efficacy without the filter discussed in section 3.1. A 50% filter will reduce this to 0.9 lm/W. Additional circuit overheads will reduce this even further but the reduction percentage depends strongly on the TV signal. With such low efficacies, how is it that the PDP TV sets take the same power per display area as the CRT and LCD as shown in Figure 1? The PDP is a power-on-demand technology as described in section 3.2. This gives it a factor of 5 multiplier when it is used to display TV signals. A plasma TV set that is running 0.5 lm/W will dissipate the same power as a LCD TV set running 2.5 lm/W with a fixed intensity backlight.

6.1 Increasing PDP Efficacy

Most of the PDP power goes toward supplying energy to the gas discharge. The 1.8 lm/W is a very low number for gas discharge light sources. The common fluorescent lamp that we use for everyday lighting can achieve white efficacies of 80 lm/W or more. The CCFL used for LCD backlights can also do 80 lm/W. The PDP is really a million little fluorescent lamps. So why does the PDP have 50 times less efficacy?

One reason is that the gas discharge in the PDP has very large losses to ions that simply heat the gas instead of producing light. There are two fundamental regions of a gas discharge: the positive column and the negative glow. The positive column is very efficient at generating UV light and it is responsible for the high efficacies of the fluorescent lamps. The negative glow is two orders of magnitude less efficient since it has a high population of ions compared to electrons and the energy put into ions mostly heats the gas. On the other hand the positive column is a true plasma and it has an equal number of ions and electrons. Since the electrons have a 100 times greater mobility than the ions, 99% of the energy dissipated in the positive column goes into the electrons. The electrons can then efficiently excite atoms and create UV light. This UV can strike the phosphors and generate the RGB colors for the TV display.

The problem with today's plasma displays is that they put too much energy into the inefficient negative glow and not enough into the very efficient positive column. There is no fundamental reason why this has to be so. A number of prototypes have recently appeared that have increased the PDP efficacy to 5 lm/W [11], [12]. These results are achieved by placing more energy in the positive column and by using a greater percentage of xenon gas.

While PDPs may not achieve the 80 lm/W of the fluorescent lamp, there is no fundamental reason why they will not achieve 20 lm/W or more. The big question is when? The factor of 50 difference between the current PDP products and the fluorescent lamp is simply too large for there not to be some creative solutions. This is very much like the situation faced by LEDs a few years ago when the best devices gave only a few lumens per watt. LEDs now have more than an order of magnitude higher efficacy and they continue to improve. There is no reason why PDPs can't follow a similar efficacy learning curve.

7. Projection Display Efficiency Improvements

There are many types of projection TV displays including the CRT projector and the light valve projectors: AMLCD, DLP, LCOS. Most of the TV light valve projectors use an arc lamp and the arc lamp represents the vast majority of the power dissipation in the set. Projection displays have made tremendous recent progress at increasing the luminous efficacy. The best projectors today achieve 10 lm/W. This is high compared to the LCDs, PDPs and CRTs. The arc lamp is on constantly and does not have the factor of 5 power-on-demand advantage of the emissive technologies such as the PDP, FED, SED and OLED as described in section 3.2.

For home TV projectors, a great deal of this improvement is attributable to a new lamp technology called the UHP (Ultra High Pressure, also marketed as Ultra High Performance). This lamp uses a very small 1 mm long mercury arc that operates at 200 atmospheres pressure of mercury gas. These lamps are widely available in the 100 to 200 W range and they achieve typically 60 lm/W. The big advantage of the UHP lamps is the very small 1 mm arc. All projectors face the engineering challenge of getting as much light as possible from the lamp to the screen. The smaller the lamp spot size, the easier is the engineering job to maximize that screen light. In general the light valves such as the AMLCD, DLP or LCOS have a relatively small panel size in order to keep costs down. Small panels of course have a small aperture that can limit the amount of light that passes to the screen. The small 1 mm spot size of the UHP lamp allows the small light valve panels to be used and still achieve a high efficacy system.

Figure 1 shows the interesting result that the projection TV set power does not depend on screen area. The projection sets all fall along a horizontal line that is constant and averages 250 watts. Does this mean that the larger screens are more efficient? No, the constant power is really an indication of the lamp technology and not the efficiency. The UHP lamps are not available in powers larger than 300 watts and UHP lamps in the 120 to 200 watt range are much more common. Arc lamps are of course available for thousands of watts but the arc sizes are very much larger than the 1 mm of the UHP lamps. Such a larger spot size means that most of the light will be lost by being blocked by the small aperture of the light valve. So the optimal solution is still the small arc size of the UHP lamp. The end result is that most of the projection products shown in Figure 1 are using the very practical 200 watt UHP lamp. Both the large diagonal and the small diagonal projectors are using this same UHP lamp and so all screen sizes emit roughly the same number of lumens. The larger screens have either a reduced luminance or use a screen with a higher gain. Of course use of a higher gain screen has the price of further limiting the viewing angle.

7.1 Increasing Projector Efficacy

The UHP lamp is a remarkable development but it is pushing the limits of physics. It is not very likely that the efficacy will improve much beyond 60 lm/W or that the arc size will go much below 1 mm. The 200 atmosphere mercury pressure, the electrode current densities of 10 kA/cm^2 and electrode heat densities of 100 kW/cm^2 puts the electrode tip temperature very near the melting point of tungsten which defines the limit of the materials technology [13]. The major area where there will be future projector efficacy gains is by allowing more of the light to get from the lamp to the screen. This will require larger light valve panel sizes. The challenge will be to hold down the manufacturing cost of these larger panels so that the set prices will be acceptable to the market.

There is also considerable effort to use LED light sources for TV projectors. This is a challenge because of two factors. First the 30 lm/W efficacy of today's LEDs is still a factor of two less than for the UHP lamp. Of course the LEDs will likely overcome this disadvantage in the next few years. The second and bigger issue is the available light output of the LED. Today's brightest commercial LEDs put out only 200 lumens [14]. This is 60 times less than the 12,000 lumens of the 200 watt UHP lamp. This is a very big factor to overcome. LEDs may find applications in small screen projection displays for mobile business applications but they have a large challenge for use in big screen TVs that compete with the UHP lamp projectors. The LEDs can be used in a dynamic power-on-demand mode to further reduce power as described in section 3.2. However like the dynamic LCD backlights described above in section 4.2.1 they will not enjoy the advantage of the full factor of 5 for TV signals as do the PDPs, FEDs, SEDs and OLEDs.

8. FED and SED Efficiency Improvements

Interest in FEDs is renewed based on use of carbon nano-tube (CNT) cathodes. The SED has received a lot of recent press attention and demonstrated a 36 inch diagonal display prototype in 2004 that took half the power of comparable LCD and PDP [15] products. The SED is simply a FED with a unique type of cathode. The efficacy for a SED will be equivalent to a FED and so the remainder of this efficiency analysis will treat the FED and the SED as the same. For brevity I will use the term FED to refer to both technologies.

The major reason for interest in FEDs is the increased luminous efficacy over the other TV technologies. An FED can have all of the excellent visual performance advantages of the emissive phosphor based CRTs and PDPs TVs and so an increased efficacy FED TV product would compete well with these more established technologies. Figure 2 shows the reason why some investors are excited about FEDs. The FED does not have a shadow mask like the CRT and so they can avoid the factor of 5 loss of efficacy due to loss of electrons in the shadow mask. This allows the FED to have significantly higher efficacies than the shadow mask CRT.

A disadvantage of the FED is that it cannot operate at the 30 kV voltages of the CRT and so it is not possible to achieve the 30 lm/W efficacy of the phosphor. There are two reasons for this limitation. First the faceplate of the FED is very thin and it will not stop the strong X-rays. FEDs could use a thick faceplate like the CRT to accomplish this but that would make it much heaver than the competing LCDs and PDPs. The X-ray limitation restricts the FED voltages to less than 10 kV. The second reason restricting the FED to relatively low anode voltages is the potential for destructive arcs. The separation between the anode and cathode of a FED is on the order of a millimeter or two. If the voltage is too high, the arcs will occur and these usually destroy the pixel. There is not a simple solution for this problem since increasing the anode-cathode spacing beyond the millimeter range will cause defocusing of the pixels.

Even with the restrictions to low voltage, the FED has substantial efficacy advantages over the CRT. Figure 2 shows that FED phosphors without an aluminizing layer (bare) can be operated below 7 kV and still achieve 10 lm/W with a green phosphor. This will correspond to about 5 lm/W for RGB phosphors. If a standard CRT aluminized phosphor screen is used and the voltage can be raised into the more risky arc prone range of 9 or 10 kV, an efficacy of 15 to 20 lm/W may be achievable for RGB. This would translate to 7 to 10 lm/W with a 50 % transmission filter.

Another important efficacy advantage of the FED over the CRT is the lack of power dissipation in the deflection system. Most of the power dissipated in CRT TV sets shown in Figure 1 is from deflection. This is a substantial advantage. Also the FED is a power-on-demand technology just like the PDP as discussed in section 3.2. This gives the FED TVs another factor of 5 improvement over technologies that have fixed power. Of course the FED will also have some power overhead associated with the drive electronics.

In spite of the potential luminous efficacy advantages, the FED has a challenging road ahead. A general rule of the display industry is that any new display technology, without established manufacturing capacity, needs to be overwhelmingly better than an existing well established technology in order to overcome the established display technology. The SED TV prototype that was demonstrated in 2004 was only 2 times more efficient than the LCD and PDP products. This is not yet overwhelming. The LCD and PDP TVs are very likely to increase their luminous efficiencies by more than a factor of two before any FED product will be able to establish a competitive infrastructure and manufacturing plant capacity. This is not to say that FEDs cannot win the race; they are simply behind and not now running as fast as the other established technologies.

9. OLED Efficiency

OLEDs are making dramatic progress. This year we have already seen the first 40 inch diagonal OLED TV prototypes. One was a small molecule OLED and the other was a polymer OLED. Both devices were built on a-Si active matrix backplanes.

OLEDs are at an early stage of maturity and so it is too soon to tell the efficacies of the practical devices that will be capable of TV products, however great progress has been made. White efficacies of 10 lm/W at 1000 cd/m^2 appear practical [16]. There are reports of record efficacies of 80 lm/W in green at 100 cd/m2 and 100 lm/W at probably lower luminance [17]. The efficacy of OLEDs typically goes down as luminance increases and so any efficacy specification needs to be accompanied by a luminance value.

The big question for OLEDs is display lifetime. The life progress for OLEDs has been good but TV displays require a very stable life characteristic since TV customers are very sensitive to the differential image burn-in issues. A good minimum target value for TV is 60,000 hours of operation to half luminance with TV signals.

One strategic advantage of OLEDs is that they can use the silicon based thin-film-transistor active matrix technology that was developed for LCDs. This means that OLEDs can easily exploit the very strong infrastructure developed for the AMLCD.

There is still debate in the OLED industry on which of two active matrix approaches to take. The OLED takes substantially more current than the LCD and so some proponents feel that the high conductivity of poly-silicon is needed. However, very large active matrix backplane manufacturing plants are available for amorphous silicon and so there is considerable effort to use these for OLED TVs.

The OLED takes 4 or more transistors per sub-pixel because of the required very tight control of the current. The LCD typically takes two transistors. The OLED active matrix will cost more than the LCD active matrix. It is the hope of the OLED proponents that this cost will be offset by not needing a backlight.

OLEDs are a power-on-demand technology and so they will enjoy the factor of 5 advantage discussed in section 3.2. OLEDs have good potential for a high luminous efficiency TV display. However, they must first mature by solving many practical problems.

10. Conclusion

The luminous efficiencies of all of the major TV display technologies have great potential for improvement. LCDs can improve by using dynamic backlights and also by using field sequential color with LED backlights. CRTs can improve by converting to the FEDs or SEDs since these technologies do not have the very large losses of the shadow mask and the deflection system. PDPs can improve by directing the input power from the cathode glow and toward the very efficient positive column. Projection displays can improve by using larger light valve panel sizes so that more of the light from the UHP lamp can get to the screen. OLED displays must solve the life issue in order to make practical high efficiency displays.

Which technology will win the efficiency race? The answer is that all of the major technologies will win since they each have clear paths toward increasing luminous efficiency. The TV consumer will win with lower power, lower cost and higher performance products. And we, the display engineers and scientists, will win with the many opportunities to develop the new technologies needed to keep each of our technologies running as fast as our competitors.

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