Optical Radiation Hazard Analysis

Ultraviolet, Visible and Infrared Optical Sources and Lasers

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Optical Radiation Safety Study
Wildfire VioStorm™ UV-LED VS-120 Projection System

INTRODUCTION

Wildfire has developed the VioStorm™ UV-LED VS-120 projection system, which has twelve 365-nm UV LED emitters (10-W electrical input each) that requires 120 W input power. This “black light” LED fixture is designed to be on par with current high performance long throw UV-A theater spotlights, which currently employ filtered arc discharge lamps. The VioStorm incorporates Wildfire's Trias™ digital intuitive three-button monitoring and control system. The VioStorm is a professional product built for professional use and would not be for consumer use. Each LED emitter has optically clear molded silicone optics that resists degradation or yellowing when exposed to high levels of UV. The VioStorm also offers a unique interchangeable optic system that enables the user to configure beam angles to whatever is required for specific applications. The beam can be dimmed by a pulse-interval modulation to provide “flicker-free,” 16-bit dimming resolution. The unit can be mounted on the floor or on rails and other environments by a fully adjustable, three-position mounting yoke, which includes an integrated floor stand. A high quality truss clamp and safety cable is also supplied with every fixture. User servicing is accomplished by simply removing the top cover and all components become easily accessible. The VioStorm is a professional UV LED black light fixture with the versatility of a long throw. The highest-power model adjusted for long-throw was therefore evaluated in this study. The VioStorm Series also have four preprogrammed variable-speed effects (Strobe 1-60, Flash 1-60, Pules 1-60 and Random Strobe 1-66) that were tested. Figure 1 illustrates the VioStorm.

RADIOMETRIC MEASUREMENTS

Instrumentation

1. The initial radiometric reference measurements of the UV LED sources were made with a Gentec Radiometer, Model Ultra UP Series with a Solo2 readout and detector XLP12-1S-H2-D0. The detector had a circular entrance aperture of 11.3 mm (i.e., an area of 1.0 cm2), to measured irradiance as well as power for large beam sizes, and a spectral range of 190 nm to 11 µm. The manufacturer calibrated the detector on 7 January 2013.

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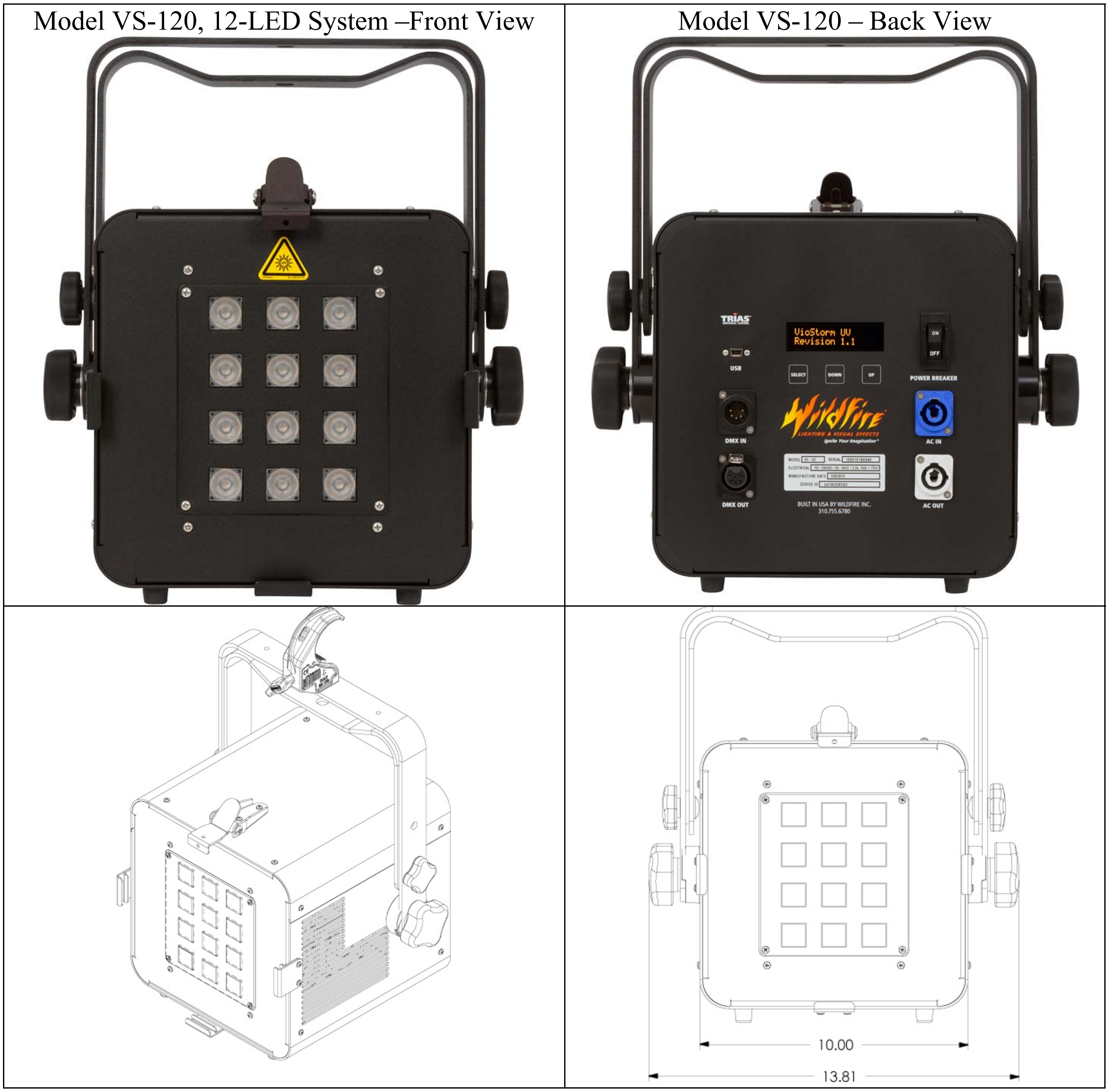

Figure 1. VioStorm UV LED Projection Systems. Top views are photographs of VS-120, 12-LED system and bottom panels show line drawings of the VS-120 system (inch dimensions).

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2. International Light Technologies, ILT-950 Spectroradiometer #1007094u1 with W2 receptor, calibrated on 7 January 2015.

3. Recalibrated (using Wildfire LEDs) International Light Technologies, IL1700 readout #1373 with SED038 detector #2200, UVA filter #9322, and window W #5083. Spectral data analysis from the ILT-950 yielded a calibration factor of 6.50E-3 $A \cdot W^{-1} \cdot cm^2$.

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4. Oriel ND1 reflecting quartz type filter model 50700 (SN 455) with density of 0.94 at 350 nm and 0.96 at 400 nm. At 368 nm the interpolated transmission for this filter was calculated as 11.3%. Oriel ND3 and ND4 absorbing glass filters models 51000 (SN513) and 51010 (SN248).

5. A Canon G-1 Pro Series digital camera with 2x2 inch filter tray and macro lens set was employed to obtain ultraviolet digital intrabeam images of the source. Oriel ND3 and ND4 absorbing glass filters were employed to reduce the exposure level to the camera image.

Measured Irradiance Values

Rather than measure all six models, we chose to measure in detail the VS-120 narrower-beam model, since that would represent the worst-case compared to any of the other models. Some very preliminary measurements were: 675 $mW \cdot cm^{-2}$ at contact, 96 $mW \cdot cm^{-2}$ at 20 cm and 12.5 $mW \cdot cm^{-2}$ at 100 cm using the GenTec broad-band thermal radiometer, which was also sensitive to the infrared radiant heat from the product. The spectroradiometric measurements (Figure 2) then permitted the determination of total ultraviolet irradiance, as provided in Table 1 below and are plotted later in Figure 3.

Table 1. Unweighted UV irradiance from 300 nm to 400 nm with distance from the front face.

Distance (cm)	VS-120, 12 – LEDs ($mW \cdot cm^{-2}$)	Single LED package ($mW \cdot cm^{-2}$)
1	603	524
5	168	164
10	117.4	52.4
20	85.6	15.9
40	38.6	4.15
70	16.4	1.55
100	9.38	0.711
150	4.44	0.317
200	2.56	0.194
300	1.17	0.0905
400	0.67	0.0518
500	0.438	0.0340
600	0.324	0.0254

The irradiance data in Table 1 were obtained with an International Light Technologies IL1700 Research Radiometer set with a UV-A receptor that was recalibrated using an ILT950 Spectroradiometer with spectral irradiance data summed from 300 nm to 400 nm. Several baffles were constructed to select LEDs individually or as a group. Figure 2 shows a typical spectral scan of the source.

Effective UV Irradiance

The actinic UV was also measured and weighted spectrally with the UV hazard function $S(\lambda)$ using a computer spreadsheet. Because stray-light can cause significant errors, spreadsheet analysis was terminated for wavelengths shorter than 310 nm. The effective actinic UV irradiance was determined as 8.45 $\mu W \cdot cm^{-2}$ at 20 cm.

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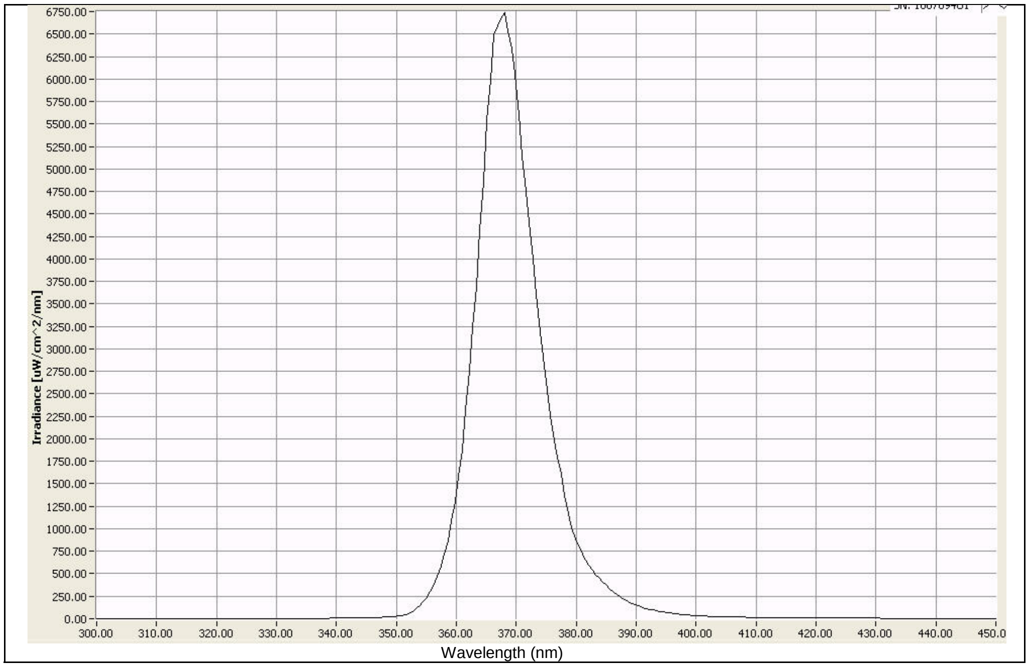

Figure 2. Spectral irradiance at 20 cm from the VS-120, twelve-LED system. The peak irradiance occurred at ~368 nm with 50% peak-irradiance-points at 362.7 nm and 373.9 nm for a full-width-half-maximum bandwidth of 11.2 nm.

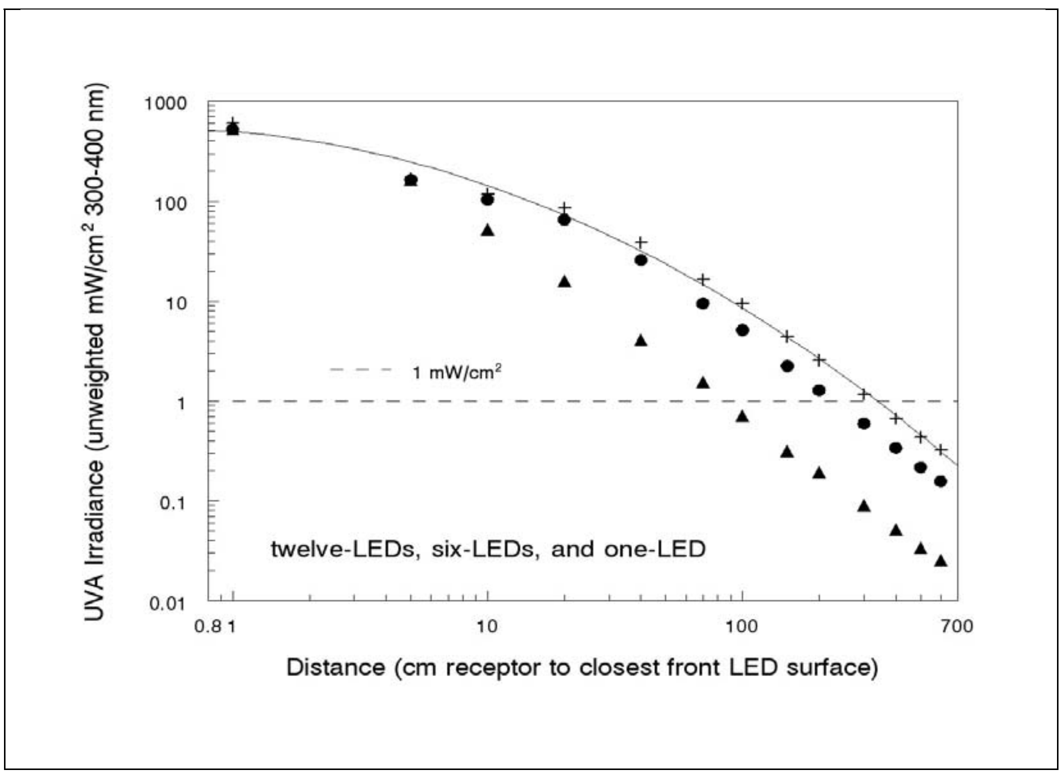

Figure 3. Unweighted UV-A irradiance from 300 nm to 400 nm with distance from the front face obtained with the ILT-950 spectroradiometer and IL1700 UVA radiometer. The top curve (+) is for the full, twelve-LED emission and the bottom curve (▲) is for one-LED.

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Radiance Measurements

UV digital imaging and direct radiance measurement were made using the aperture technique. Figure 4 shows the appearance of the full array of LEDs, a sub-group and the appearance of a single-LED projector element.

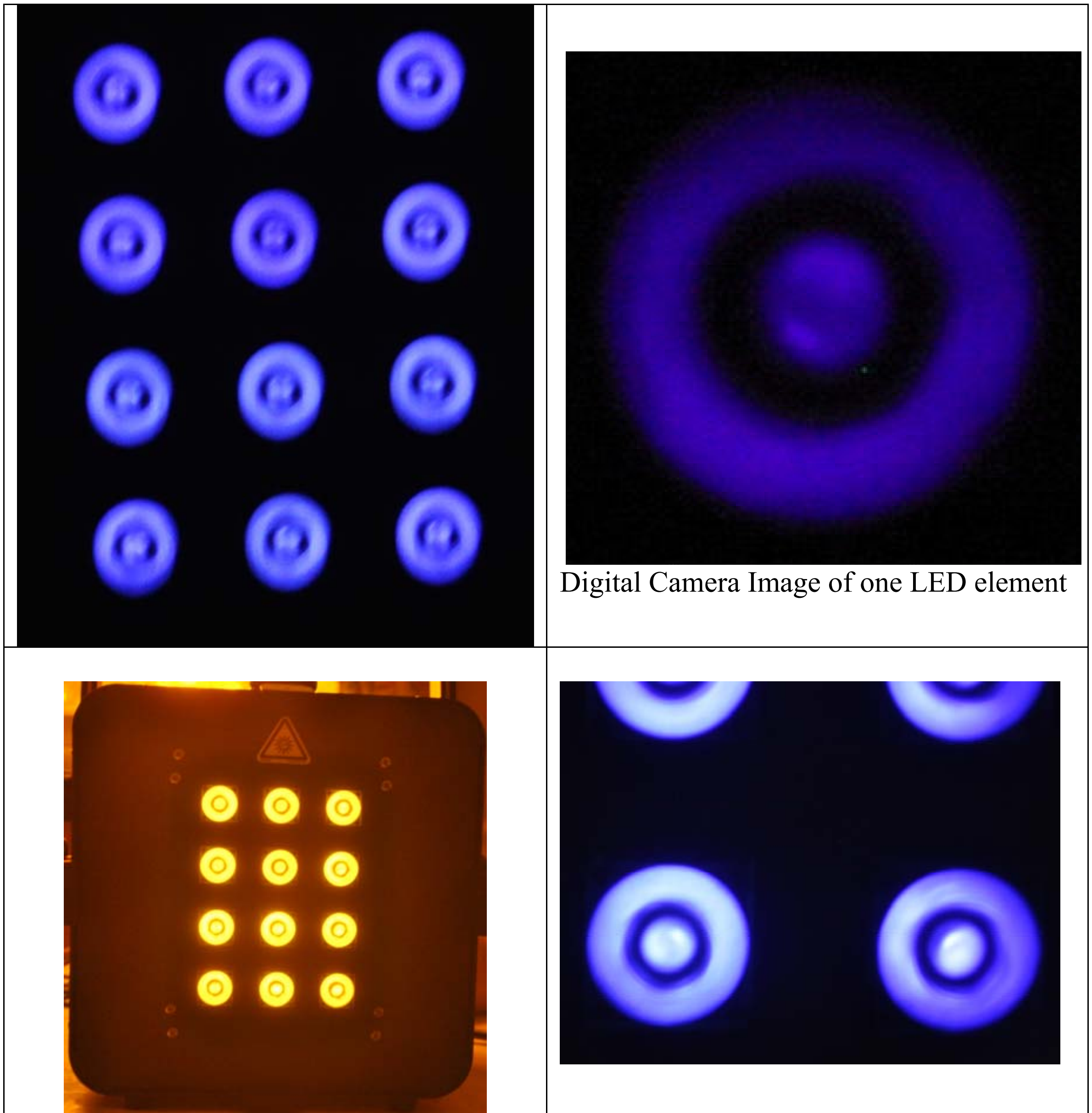

Figure 4. Intrabeam digital photographs of sources operating in the UVA. The upper-left panel shows full array at 40 cm and lower-left shows full array at 100 cm through a yellow filter will all sources flashed. The sources appear indigo-violet in the photo as the camera sensor has very little sensitivity to shorter wavelengths. The upper-right image shows a single LED emitter whereas the lower-right photo shows appearance at 20 cm where each element is not fully flashed.

The effective blue-light radiance was computed with a spectral spreadsheet that showed that the effective blue-light fraction was 1.4% of the total irradiance. To directly measure radiance (brightness) of any LED, the ILT-950 spectroradiometer was positioned at 20 cm from the source with a 2.2 mm aperture placed over the brightest spot of an LED, and then a spectral

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weighting spreadsheet was used to determine the effective blue-light radiance. This was 0.065 $W \cdot cm^{-2} \cdot sr^{-1}$ from 300 nm to 700 nm. The 2.2 mm aperture was scanned across several operating LEDs with a special test fixture employing micrometer adjustors.

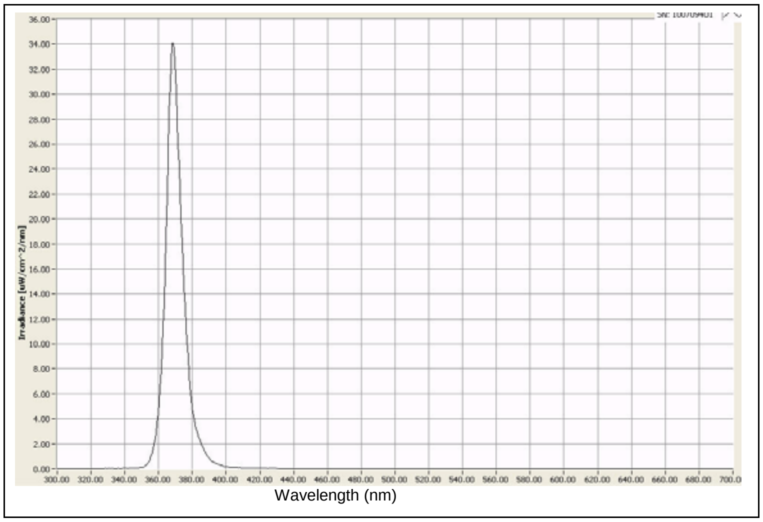

Figure 5. Peak values of spectral radiance from 300 nm to 700 nm observed for an 11 mrad circular aperture (2.2 mm at 20 cm). The spectral irradiance was weighted against the blue-light hazard function and summed then divided by 95 μsr to yield an effective blue-light radiance of 0.065 $W \cdot cm^{-2} \cdot sr^{-1}$.

Measurements in the Pulsed Modes

The VS-120 was also operated in several in strobe modes, but all measurements of peak power output indicated that the emissions were little above a gated CWoperation. Figure 6 shows an oscilloscope trace with there two sets of pulses at intervals of 2.7 ms with large pulses separated from small pulses at ~1.3 ms. The large pulses lasted ~11.5 μs and the smaller pulses lasted ~12 μs. In Strobe1, the CW gated pulses lasted ~16 ms with 440 ms between repeated pulses. Inside each pulse were 5 large pulses and 6 small pulses. Although the peak pulse power could be slightly above the CW power, but basically the output was almost the same as gated CW. This lead to the conclusion that the hazard assessment was most severe if the device is treated as CW or as gated CW at the same amplitude.

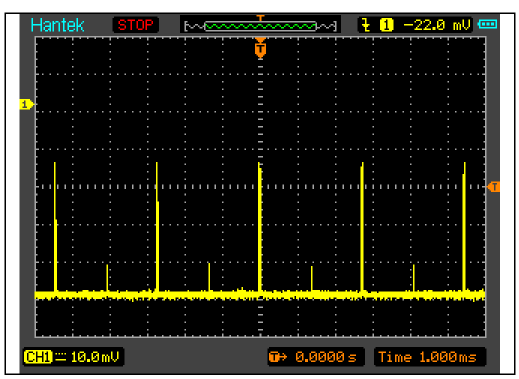

Figure 6. Oscilloscope trace of one pulse mode.

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POTENTIAL HAZARDS

The eye is well adapted to protect itself against optical radiation (ultraviolet, visible and infrared radiant energy) from the natural environment and mankind has learned to use protective measures, such as hats and eye-protectors to shield against the harmful effects upon the eye from very intense ultraviolet radiation (UVR) present in sunlight over snow or sand. The eye is also protected against bright light by the natural aversion response to viewing bright light sources. The aversion response normally protects the eye against injury from viewing bright light sources such as the sun, arc lamps and welding arcs, since this aversion limits the duration of exposure to a fraction of a second (about 0.25 s) if substantial visible light is present. Because of the strong fluorescence of the crystalline lens (Zuclich, 2005), some aversion to viewing exists because of the annoyance.

However, the protective benefits of the aversion response are not at play during surgical procedures. There are at least five separate types of hazards to the eye from optical sources, which are recognized and are evaluated for any device (Sliney and Wolbarsht, 1980):

(a) Ultraviolet photochemical injury to the cornea (photokeratitis) and lens (cataract) of the eye (180 nm to 400 nm). Two exposure limits apply.

(b) Thermal injury to the retina of the eye (400 nm to 1400 nm).

(c) Blue-light photochemical injury to the retina of the eye (principally 400 nm to 550 nm; unless aphakic, 310 to 550 nm).

(d) Near-infrared thermal hazards to the lens (approximately 800 nm to 3000 nm).

(e) Thermal injury (burns) of the cornea of the eye (approximately 1400 nm to 1 mm).

For the 360-370 nm ultraviolet UV-A LEDs used in the Wildfire projector, only aspect (a) is clearly relevant, and perhaps aspect (c) although little UV-A reaches the retina. And since thermal retinal injury requires much higher radiances, aspect (b) is not possible from LEDs. Aspects (d) and (e) apply only to infrared sources and are therefore not of concern. However, potential thermal hazards to the skin, which normally requires irradiances in the hundreds-of-milliwatts-to-watt range, require analysis. Therefore, this report focuses on the potential *photochemical* effects at the cornea and lens from UV-A. Although the ultraviolet LEDs emit very little energy in the visible and would not be expected to approach limits to protect the eye against aspect (c), these emissions will be analyzed.

UV RADIATION EXPOSURE LIMITS

Ultraviolet radiation exposure criteria have evolved over the last several decades based upon biomedical laboratory research, human epidemiological studies, and clinical experience. These human exposure criteria are presented in regulations, standards and guidelines for product safety and for occupational health. Government agencies issues regulations based on enabling laws passed by legislative bodies. Local, national, or international standardization bodies issue standards. Standards may be developed either through a consensus process, where virtual unanimity exists, or they may be based only on a majority opinion. Guidelines are generally

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prepared by professional societies as recommendations based upon scientific and medical knowledge. The current UV guidelines are nearly identical internationally for exposure durations less than 1000 seconds.

A number of national and international groups have recommended occupational or public exposure limits (ELs) for UVR. The ultraviolet guidelines of the International Commission for Non-Ionizing Radiation Protection (ICNIRP, 2004) and the American Conference of Governmental Hygienists (ACGIH, 2015) are by far the widest known. Both groups have recommended essentially the same limit based in large part on ocular injury data from animal studies and human accidental injury studies. The primary guideline to protect the skin and the eye is an S(λ) weighted daily (8-hour) exposure H_{eff} of 3 $mJ \cdot cm^{-2}$ or 30 $J \cdot m^{-2}$ referenced to 270 nm, which corresponds to 27 $J \cdot cm^{-2}$ at 365 nm. In addition to the primary S(λ)-weighted limit, a second limit that is not spectrally weighted is provided to protect the lens from excessive exposure to the UV-A: it is a 1 $J \cdot cm^{-2}$ limit applying to all radiant energy between 315 and 400 nm. ACGIH applies this only to exposures less than 1,000 seconds, and recommends a dose-rate limit of 1 $mW \cdot cm^{-2}$ for longer exposures. However, ICNIRP applies the 1 $J \cdot cm^{-2}$ limit to a full-day (30,000 s) exposure. It is the latter limit that is most restrictive for 360-370 nm. This is a limit that considers chronic outdoor solar exposure over a lifetime, and appears excessively conservative to apply in the context of the relatively brief exposures to the direct beam of the UV-A projector. To place the exposure in perspective, it is useful to consider environmental exposure to the UV in sunlight (Sliney, 2004).

APPLYING THE ICNIRP/ACGIH LIMITS

Ultraviolet Exposure Limits

Two limits apply—a spectrally weighted limit to protect the cornea [Eqn. 1] and an un-weighted UV-A limit [Eqn. 2] :

$$E_{UV} \cdot t = \Sigma E_{\lambda} \cdot S(\lambda) \cdot t \cdot \Delta\lambda = 3 \text{ mJ} \cdot \text{cm}^{-2} \text{ effective (i. e., 28,000 mJ} \cdot \text{cm}^{-2} \text{ at 368 nm)} \qquad [1]$$

Which applies to any duration up to one full day; and, to protect the lens and retina:

$$H_{UV\text{-}A} < 1.0 \text{ J} \cdot \text{cm}^{-2} \quad \text{for } t < 1{,}000 \text{ s} \qquad [2a]$$

and:

$$E_{UV\text{-}A} < 1.0 \text{ mW} \cdot \text{cm}^{-2} \quad \text{for } t > 1{,}000 \text{ s} \qquad [2b]$$

To calculate the maximum direct viewing duration when either [1] or [2] is not satisfied, the maximum "stare time," t_{max}, is found by inverting Eqn. [1] or [2a] for a CW source with a weighted or un-weighted irradiance.

$$t_{max} = 3 \text{ mJ} \cdot \text{cm}^{-2}/E_{UV} \quad \text{for the S}(\lambda)\text{-weighted value} \qquad [3a]$$

$$t_{max} = 1.0 \text{ J} \cdot \text{cm}^{-2} /E_{UV\text{-}A} \quad \text{for the UV-A} \qquad [3b]$$

For example, at a distance of 1 m, the total irradiance from the VS 120 was 9.38 $mW \cdot cm^{-2}$, hence the t_{max} from Eqn. [3b] would be: 1.0 $J \cdot cm^{-2}$ /(0.00938 $W \cdot cm^{-2}$) = 107 s. And at only 20

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cm, because a small amount of UV-B (280 – 315 nm) radiation was measured, the effective irradiance from [3a] was 8.45 $\mu W \cdot cm^{-2}$ at 20 cm, and the permissible exposure duration t_{max} would be 355 s. Hence the limiting case will be the limit of [3b]. Indeed, the permissible exposure duration at 20 cm from [3b] would be only $(1.0\ J/cm^{-2})/(0.085\ W \cdot cm^{-2}) = 11.7$ s. At that irradiance the temperature rise in the skin would limit the exposure faster.

Blue-Light Photochemical Retinal Hazard

The ACGIH TLV (ACGIH, 2010) and ICNIRP guidelines (ICNIRP, 2004) are identical for large sources and are designed to protect the human retina against photoretinitis, "the blue-light hazard" is an effective blue-light radiance L_B spectrally weighted against the Blue-Light Hazard action spectrum $B(\lambda)$ and integrated for t s of $100\ J \cdot cm^{-2} \cdot sr^{-1}$, for $t < 10{,}000$ s, i.e.,

$$L_B \cdot t = \Sigma L_\lambda \cdot B(\lambda) \cdot t \cdot \Delta\lambda \leq 100\ J \cdot cm^{-2} \cdot sr^{-1} \text{ effective} \qquad [4]$$

and for $t > 10{,}000$ s (2.8 hrs.):

$$L_B \leq 10\ mW \cdot cm^{-2} \cdot sr^{-1} \qquad \text{for } t > 10{,}000 \text{ s} \qquad [5]$$

To calculate the maximum direct viewing duration when [5] is not satisfied, this maximum "stare time," t-max, is found by inverting Eqn. [4] for a CW source with a weighted radiance of L_B:

$$t_{max} = (100\ J \cdot cm^{-2} \cdot sr^{-1}) / L_B \qquad [6]$$

The radiance values are averaged over a field of view which is not less than 11 mrad = 0.011 rad. The blue light hazard is evaluated by mathematically weighting the spectral irradiance, E_λ, against the blue-light hazard function to obtain E_B: however, because the 370 nm radiation is largely absorbed at the lens, less than 1% reaches the retina, and the spectral weighting function value of $B(\lambda)$ is 0.01. Hence the limit would be $1.0\ W \cdot cm^{-2} \cdot sr^{-1}$ for $t > 10{,}000$ s, which was exceeded by the maximum radiance of the source. The measured effective blue-light radiance was $0.065\ W \cdot cm^{-2} \cdot sr^{-1}$ from 300 nm to 700 nm as measured at 20 cm. Although unlikely, an accidental exposure at a 20-cm viewing distance would only be momentary. The duration t_{max} for staring at the source can be calculated from Eqn. [6], and would be $L_A = (100\ J \cdot cm^{-2} \cdot sr^{-1}) / (0.065\ W \cdot cm^{-2} \cdot sr^{-1}) = 1540$ s = 25.6 minutes. This would stare time - which is not reasonably foreseeable because of glare and lens fluorescence – would be for the normal (phakic) eye. Certainly the maximal worst-case exposure to the operator from reflections from many hours of operation a day could not exceed any of the applicable limits. However, in the very rare instance of an aphakic person viewing the direct source, the weighting factor shifts from $B(\lambda)$ to $A(\lambda)$ and the spectral weighting factor for 368 nm becomes 4.0 and the effective aphakic radiance L_A becomes $4.0(6.5\ W \cdot cm^{-2} \cdot sr^{-1}) = 26\ W \cdot cm^{-2} \cdot sr^{-1}$. This means that the stare-time would be reduced to only ~ 4 s. However, an aphakic person would see a very strongly bright source, and the actual exposure would be reduced to the standardized 0.25 s aversion response to bright light.

The above exposure guidelines apply to the awake, task-oriented eye and incorporate an underlying assumption that the eye constricts with bright light, that the aversion response limits exposure duration, and that eye-movements are not restricted.

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HAZARD ANALYSIS

The VS-120 emits irradiance values well in excess of lengthy UV-A exposure limits however, the units can be safely used – as their arc-lamp predecessors – by properly mounting the units away from accessible occupied areas for the first 3.5 m (see Table 1) of the throw to remain below the continuous UV exposure limit of 1 $mW \cdot cm^{-2}$.

Assessment Distance and Risk Group

ANSI/IESNA RP27.3 specifies a measurement distance of 20 cm for bare lamps, but with an assessment distance where the illuminance reaches 500 lx for general light service (GLS) lamps. However, no assessment distance was provided for some specialized applications such as searchlights or UV spotlights. Assessment distances were not provided for other types of non-GLS lamp products, although this was intended to be provided in vertical (application-specific) standards. IEC standard 62471 follows the ANSI/IESNA RP27.3 emission limits and the default measurement distance of 20 cm; however, IEC 62471-5 is a vertical standard for image projectors, and specifies an assessment distance of 1 m. Some suggested assessment distances for searchlights have been 2-3 m or even greater distances. But, using a very conservative, 1-m assessment distance, the irradiance of the VS-120 is 9.38 $mW \cdot cm^{-2}$, which just places it in Risk Group RG-2. The RG-2 Emission Limit is E_{UV} = 3 $\mu W \cdot cm^{-2}$ for Actinic UV effective irradiance, and 400 $W \cdot cm^{-2} \cdot sr^{-1}$ for L_B. The measured actinic E_{UV} at 20 cm was 8.45 $mW \cdot cm^{-2}$, which if extrapolated to 100 cm would be 0.93 $\mu W \cdot cm^{-2}$, which is well below the limit of 3 $\mu W \cdot cm^{-2}$. Continuous skin and eye exposure for many hours at 100 cm is not assumed likely for RG-2 products. Actually, a more realistic assessment distance for a professional theatrical spotlight or specialty projection system like the VS-120, is more likely to be set at no less than 200 cm, where the irradiance falls to 2.6 $mW \cdot cm^{-2}$; which is below the 3.3-$mW \cdot cm^{-2}$ RG-1 (very low risk) category for UV-A. A caution distance (sometimes referred to as a "hazard distance," even if not RG-3) exists to a distance of 1 m (100 cm ~ 3.3 feet). Finally, the distance to 1 $mW \cdot cm^{-2}$ for continuous stareing into the beam would be 3.3 m, or 11 feet.

CONCLUSION AND RECOMMENDATIONS

The VSS-120 poses no significant hazard beyond 1 meter, and momentary exposures within that distance are not hazardous. However, persons should be warned not to stand in the beam within 1 meter, and not to continuously stare directly into the source within 3.3 m (11 feet), even though it is highly unlikely that anyone would. A warning label should so indicate

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