High-Intensity Vapor Lamp for Biological Research

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A vapor arc light source has been adapted to the study of the lethal action on bacteria of near-ultraviolet (UV) and visible light. Its use makes possible much shorter exposure times than could be obtained from previously available sources. The output of radiant energy is sufficient to provide a fairly detailed action spectrum for lethality in the long-UV and visible region without the addition of exogenous sensitzers. Populations of cells of *Escherichia coli* WP2 were inactivated through five log cycles with light at 460 nm. Significant inactivation also was obtained with light at 550 and 650 nm.

Lethal effects of near-ultraviolet (UV) (320–390 nm) and visible light (390–750 nm) without the addition of exogenous sensitzers have been studied in a variety of organisms [see reviews by Zelle and Hollander (9), Spikes (6), and Krinsky (4)]. Unless extremely sensitive forms are selected (2), very high radiant flux densities are required for the study of lethal effects of wavelengths longer than 350 nm. Some workers have made use of the greatly increased sensitivity to near-UV and visible light of cells in the frozen state (1) or in the semidried state (3, 8). In our recent studies on inactivation of various strains of *Escherichia coli* by near-UV and visible light (7), radiant flux densities of at least 2,000 ergs per mm² per sec in the near-UV range and 20,000 ergs per mm² per sec in the visible range were required. Radiant energy sources capable of providing these high-dose rates with a half-band width of 20 nm or less are expensive and may offer only a limited number of wavelengths.

Formerly, the most practical visible light source used for inactivation of bacteria was a quartz-iodine lamp utilizing a commercial slide projector optics system. The beam was filtered and focused by two convex lenses into an intense 1.5-cm² spot. Sufficient light was provided to produce meaningful survival curves using the whole visible spectrum (390–750 nm) (7). However, despite various modifications to increase the beam power, the available energy was not sufficient to obtain wavebands narrow enough to produce a detailed action spectrum for the inactivation of bacteria. This report describes a light source that provides more than 10⁶ ergs per mm² per sec (10 w per cm²) over a broad spectral range, an irradiance level adequate for action spectra.

MATERIALS AND METHODS

A commercially available light source and power supply (General Electric Co., Nela Park, Cleveland, Ohio) was adapted for use in biological experiments. The lamp is a 300-w metal vapor arc unit (approximate cost, $35.00), designated Marc 300 (5).

The power supply is especially designed and supplied by the manufacturer for use in standard movie projectors; it is designated as Marc-300/LSU-1 (approximate cost, $260.00). It is intended for installation in an enclosure and does not include mounting and wiring of the fuse panel and control circuits. The completed power supply, shown in Fig. 1, provides electrical safety and adequate ventilation for the power supply components. Figure 2 is a schematic diagram of the control wiring. This circuit includes a series connected fan-lamp switch that ensures operation of the fan before the lamp ignites and continued operation, when the lamp is disconnected, until the temperature in the housing is lowered to a safe level. A resettable running-time meter accumulates the total number of hours each lamp is used.

Because no enclosure is commercially available other than as part of a complete movie projector, we designed a housing for the lamp meeting the manufacturers’ requirements. Figure 1 also illustrates the lamp and condensing-lens mounting and the provisions for an adjustable filter holder assembly.

The image of the metal vapor arc is focused with a two-element air-spaced lens set, including a heat filter (American Science Center, Inc., Chicago, Ill.), providing a combined focal length of approximately 3.5 cm. The diameter of the entrance lens is 6 cm.

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FIG. 1. A high-intensity vapor arc lamp.

FIG. 2. Schematic diagram of the control circuit.

SW₁ POSITIONS: 1 - OFF
                2 - FAN
                3 - FAN AND LAMP

F₁ AND F₂ - 15A 250v EACH

RTM - RUNNING TIME METER
The condenser assembly is adjustable, and the position which provided the brightest, uniform 1-cm² spot was determined.

The center of the sample was located approximately 7 cm from the center of the lens set. Any lens assembly which has similar optical properties and can withstand the heat generated by the lamp can be utilized. An air blower (model no. CC3508, Dynacoool Mfg. Co., Inc., Saugerties, N.Y.), located within the enclosure, directs approximately 4.2 m³ of cool air per min from the inlet upward across the front and rear surfaces of the lamp to ensure efficient lamp operation. An air particle filter made of cheese cloth was mounted in the inlet to minimize contamination by dust of the lamp and condensing lens. Air from this blower circulates over all lens and filter surfaces.

When the light emission of the lamp has declined to approximately 60% of its initial output, after 25 to 50 hr of operation, the lamp is replaced simply by sliding it into a track above the blower. Lamp focus adjustments are never required.

Interference filters are inserted in direct line with the condensed light beam. The holder is adjustable to position rigidly one or several filters (2 by 2 inches) in combinations chosen by the user. Only heat-resistant interference filters should be used with any absorbing layer on the filter positioned away from the lamp and directly in the path of a stream of cooling air. Considerable care is taken in all cases to exclude infrared radiation by the use of blocked interference filters (Baird-Atomic), separate blocking filters (Optics-Technology), and the heat filter in the condenser set.

The object to be irradiated, (for example, a bacterial suspension), is placed in the path of the condensed and filtered light beam. Temperature of the irradiation vessel is maintained to within 5 C of ambient by cool air from a blower (model no. 2500S, Pamotor Inc., San Francisco, Calif.) positioned about 50 cm away. This arrangement provides additional cooling for the filters. Ambient temperature was controlled at 22 to 23 C in the experiments reported here.

Survival curves were obtained with stationary state E. coli WP2 from the surface of nutrient agar (Difco) slants that had been incubated for 2 to 4 days at 37 C. Suspensions were prepared for irradiation by mixing a small loop of surface growth in a phosphate minimal salts buffer (M9), pH 7, and diluting in the same buffer to give a final concentration of approximately 10⁷ cells per ml. The irradiation vessel was a Pyrex tube with an inside diameter of 1 cm. Air saturated with water vapor was passed through a capillary tube affixed to the bottom of the vessel to provide aeration and stirring. Survival was measured by plating appropriately diluted samples on the surface of nutrient agar and counting the visible colonies after 48 hr of incubation at 37 C in the dark. Control nonirradiated suspensions were treated in the same manner when irradiations exceeded 3 hr, and, if significant control inactivation occurred, these values were used in calculating the surviving fractions. In no case did control inactivation exceed 20%.

RESULTS AND DISCUSSION

The visible output of the lamp (greater than 10⁴ ergs per mm² per sec in a small spot) is higher by a factor of 10 than the maximal output we have obtained from a quartz-iodine light source. Figure 3 compares the output of the vapor arc lamp with a quartz-iodine lamp and direct sunlight over the wavelength range of 350 to 750 nm. The sunlight measurements were made with a Schwarz vacuum thermopile (standardized against a lamp from the National Bureau of Standards) and a Keithley model 150B microvolt ammeter. The measurements on both lamps were made on a 1-cm² spot with a YSI-Kettering model 65 radiometer (standardized against the Schwarz thermopile). Ample energy is available from the vapor arc source to allow the use of interference filters with a relatively narrow band width at half peak (20 nm). For example, an irradiance of 7 × 10⁴ ergs per mm² per sec was obtained through an interference filter having a peak transmission of 55% at 490 nm and a band width at half-peak transmission of 20 nm. The filters used were Baird-Atomic type.
B3 for 350 to 510 nm and Optics Technology “Varipass” (set 60) for 600 to 750 nm, with a peak transmission that varied from 35% at 350 nm to 65% at 650 nm. Much of the energy from the lamp is available in the long-UV and blue-visible range. The conventional quartz-iodine lamp has diminishing output in this region.

An example of a microbiological application is shown in Fig. 4, where the light from the vapor arc lamp is used to inactivate liquid suspensions of E. coli WP2 (a strain relatively resistant to far-UV) at wavelengths throughout the visible spectrum. Figure 4 reveals that the band of visible light between 450 and 470 nm (referred to as 460 nm) is considerably more efficient in killing E. coli than the bands of visible light between 510 and 590 nm (550 nm) and 610 and 690 nm (650 nm). The curve at 460 nm shows a broad shoulder which is larger than that of the 254 nm survival curve typical of this strain. The curves centered at 550 and 650 nm indicate a surviving fraction of approximately 0.1 at 1.9 x 10^4 ergs per mm^2 and 2.2 ergs per mm^2, respectively. Although significant inactivation was produced at 550 and 650 nm, even larger doses will be required to determine the shapes of the survival curves.

We infer from these data that killing by 460-nm radiation is not simply due to thermal effects produced by the very high irradiance employed (5 x 10^4 ergs per mm^2 per sec). Thermal effects should be at least as great at the higher irradiances used at 550 nm (16 x 10^4 ergs per mm^2 per sec) and 650 nm (9 x 10^4 ergs per mm^2 per sec); however, the sensitivities of the cells were much less than that observed at 460 nm.

The radiant flux density obtainable from this metallic arc system is 10 times greater than that from any source known to us at anywhere near its construction cost. In addition to the versatility and high useful output provided at a small fraction of the price of a comparable, commercially available system, the lamp, power supply and housing assembly are simple and hence convenient to operate and maintain.

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