CONF-900140--5

UCRL-102639
PREPRINT

UCRL--102639

DE90 006266

Received by OSTI

FEB 05 1990

Absolute Intensity, High Resolution Spectrum of the Vortek Arc Lamp and Its Spectral Match to Nd:YAG Bands

L. E. Zapata
A. J. Pertica

This paper was prepared for submittal to:
SPIE
Los Angeles, CA
January 14-19, 1990

December 28, 1989

Lawrence Livermore National Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Absolute intensity, high resolution spectrum of the Vortek arc lamp and its spectral match to Nd:YAG bands

Luis E. Zapata and Alexander J. Pertica

Lawrence Livermore National Laboratory
P.O. Box 5508
Livermore, California 94550

ABSTRACT

A high resolution (1 Å), absolute intensity spectrum from 300 to 900 nm was obtained for a high average power (100 kWe) argon arc-lamp. The high average power is obtained due to innovative technology that cools the inside surface of the lamp envelope by means of a spiraling water jet. The optical output between 200 and 2000 nm was measured by using a calibrated pyroelectric detector and glass color filters, and accounted for 54% of the electrical input. The argon arc-lamp radiated 35% of the electrical power input in the 400 to 900 nm spectral region when a cerium doped quartz envelope was used; furthermore, 37% of this optical power was emitted as line output between 730 and 830 nm, a region well tuned to Nd^{3+}:YAG absorption bands. Lower resolution spectra and fluorescence/transmission measurements of YAG samples were obtained for mixtures of Ar/Kr and Ar/Xe with up to 14% by volume of the heavier species. When the Ar/14%-Kr mixture was used, increased absorption (115%) and net fluorescence (120%) were measured relative to the pure argon arc-lamp.

1. INTRODUCTION

The Vortek lamp[1] is advertised as the highest average power commercial light source in the world. To make this possible, its innovative technology maintains a vortex stabilized arc and cooling water wall within the lamp envelope. The high average output power makes this lamp an attractive candidate as a pump source for crystal laser amplifiers. To evaluate this choice, a high resolution, absolute intensity spectrum of the Vortek arc lamp was obtained. The spectral data were processed with care to achieve 1 Å resolution, better than 1 Å accuracy on the wavelength scale, and ±1% accuracy on the intensity scale. The result is shown in Fig. 1 for a standard 100-kW_e Vortek argon arc lamp.

Spectra were also obtained at lower resolution (6 Å) for Ar-Kr and Ar-Xe mixtures. The spectra were convolved with the Nd:YAG absorption cross section assuming, YAG crystal thickness of 0.5 cm and doping of 2×10^{20} cm^{-3}. The coincidence of the lamp emission lines and the Nd:YAG absorption lines can lead to high absorption efficiency and high quantum ratio if the proper gas is used in the lamp.

2. EXPERIMENTAL PROCEDURE

2.1. Equipment

The Vortek lamp was operated at up to 114 kW_e electrical input power, the limit of the power supply. The slit (25 μm) of a 28-cm focal length grating spectrometer (1200 grooves/mm) was 7.6 m from the lamp. A 42-cm-long light baffle with a pinhole wheel at the end was used to shield the slit from stray room light. For the absolute intensity measurements, a large aperture permitted the lamp to be in full view of the slit. The spectrometer's optical axis was aimed directly at the lamp, and 13 overlapping spectral ranges (approximately 70 nm wide) were scanned electronically at the focal plane (which contained a 1024-diode Reticon) by an optical multichannel analyzer.

For each spectral range, a penlight spectrum (Ar, Ne, or Hg) was recorded for wavelength calibration, and an NBS-calibrated tungsten standard lamp spectrum was recorded for intensity calibration. The tungsten lamp was cycled on and off between spectral scans. This lamp was mounted on a swivel arm with stops on the optical breadboard to assure accurate positioning of the lamp on-axis. The instrumental resolution of 1.1 Å was determined by measuring the width of the 546.0 nm line of mercury. An appropriate cutoff filter was used to reject second-order diffracted light from each spectral region.

Low-resolution spectra were also taken with a 150 groove/mm grating. The resolution was reduced to 6 Å, but a full spectrum could be acquired in a single scan. This was useful to monitor the spectrum while changing the composition of the arc-lamp gas by adding small amounts of Kr or Xe (up to 14% by volume in either case) to the argon.

Two small (1 cm per side) samples of YAG were employed to obtain an estimate of the absorption and fluorescence efficiencies as the gas composition was varied. One sample was doped at 1 wt. % Nd^{3+}. The two samples were alternately lowered into a chamber with a 0.1 cm^2 opening directed towards the lamp. The pyroelectric detector measured the transmitted optical power through a clear aperture or through the YAG samples. A silicon photodiode fitted with a narrow band filter centered at 1.064 μm measured the fluorescence emitted at 90° from the sample chamber.

2.2. Wavelength Calibration

The data was transferred to an IBM/AT and calibrated using the wavelength standards. For each spectral region, the penlight data were used for a first-order wavelength calibration. Next, the argon lines were identified and their peak positions were established by a weighted-average (center-of-mass) algorithm. The wavelength axis (as a function of diode number) was fitted to a function describing grating diffraction within the geometry of our Czerny-Turner spectrometer[2]. The function was adapted to the situation of a Reticon array at the focal plane, rather than the standard single slit. In a standard scanning monochromator, the sine dependence in the grating equation is removed by a mechanical "sine drive". For this application, the central wavelength is given by the fundamental grating equation and the wavelength of light falling on each diode was accounted for mathematically by adding to the grating equation the slightly different diffraction angle associated with each diode in the array. Two independent parameters, the central wavelength and the angle between the instrument axis and the incident light, were left in this derivation. The sum of the squares of the errors between the calculated and known wavelengths of the peaks was minimized. Successive iterations converged to values of the independent parameters that typically gave an error of less than 0.5 Å in the wavelength scale.

2.3. Intensity Calibration

The spectrum of the standard tungsten lamp is known absolutely. It is therefore a straightforward task to obtain the instrument response from the recorded spectrum by dividing it point-by-point by the standard spectrum. The instrument response is the product of the grating efficiency, filter transmission, detector sensitivity, and alignment error, and is the same for all spectra taken with the same settings. Because of charge leakage, Reticons exhibit a nonlinear falloff in sensitivity with exposure time; thus, it is important to keep the exposure time constant while collecting the data and the calibration spectra. To accomplish this, the 1 kW_e tungsten lamp was placed 0.8 m from the slit, about ten times closer than the 100 kW_e arc-lamp. Since irradiance depends inversely on the square of the distance to the source, the irradiances of the two lamps were directly comparable at the slit entrance and no correction for exposure time was necessary. The most intense arc-lamp spectral lines were observed, and the exposure time was then selected to keep the diodes below saturation. The tungsten lamp was well within the dynamic range of the diodes (>1000:1). The same exposure time was used for all spectrum pairs (Vortek and calibration lamp spectra for each wavelength region).

The instrument response thus obtained (corrected for the distances to the source and the standard) was applied to the Vortek spectrum for the particular region being processed. This procedure yielded absolute spectral irradiance data for the direct view of the Vortek argon arc-lamp.

2.4. Assembling the Spectral Regions

The final step was to join the adjacent spectral regions. A parabolic spline was fitted to each region, and spectrum values were interpolated at 1 Å intervals. The intensity values at the overlaps agreed to within 1%, and the average value was used in constructing the final spectrum at 1 Å steps from 240 to 900 nm (Fig. 1).

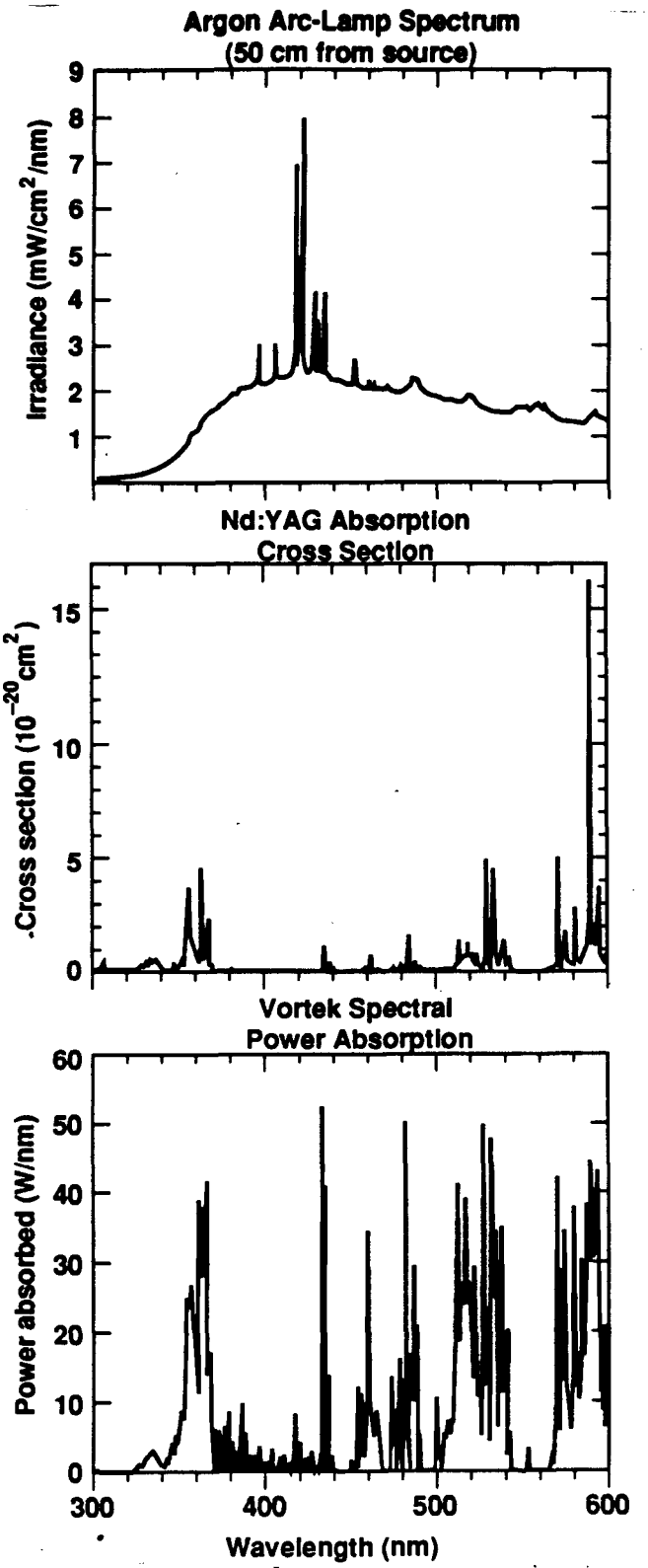

Figure 2. Top: Direct view, Stabicil envelope Argon arc-lamp spectrum. Middle: Nd:YAG absorption cross section. Bottom: Power absorbed by a 0.5-cm thick slab with 2x1020/cm3 doping.

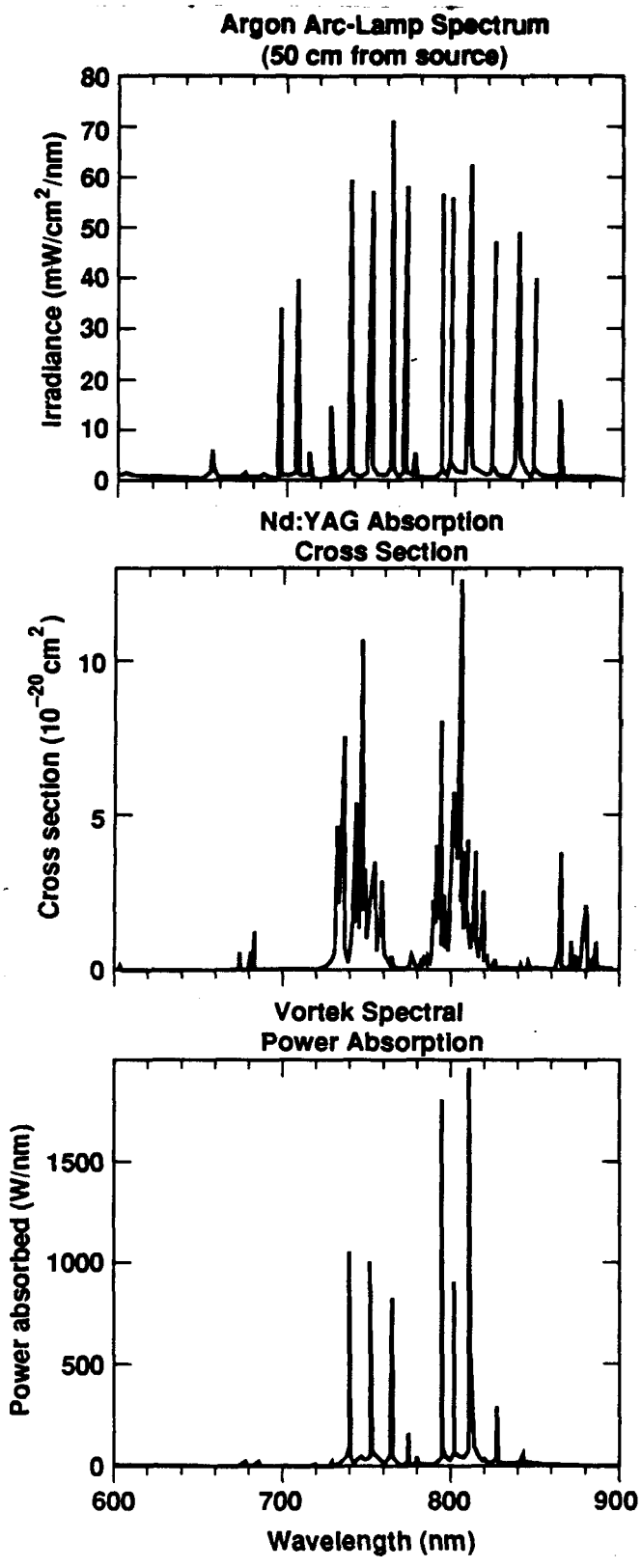

Figure 3. Continuation of Fig. 2, but at higher wavelengths. Note the change of vertical scales for the top and bottom graphs.

Figures 4 and 5 show an improvement in spectral overlap in an Ar-Kr mixture and a decrease in overlap in an Ar-Xe mixture, both with respect to the standard pure Ar arc-lamp. The addition of 14% xenon to the argon resulted in increased overall output. The absorption and fluorescence measurements showed that the net fluorescence stayed at the same level (within the experimental error of ±5%) as in the pure argon case, but the relative absorption decreased to 80% of the absorption level measured with the pure argon arc lamp. The addition of 14% krypton did not seem to improve the overall output significantly. However, it improved the net fluorescence to 120% and the relative absorption to 115% as compared to the pure argon case. The fortuitous overlap with the Nd:YAG absorption spectrum of a greater number of lines in the Ar-Kr mixtures, shown in the figures, accounts for the increases in absorption and fluorescence yield.

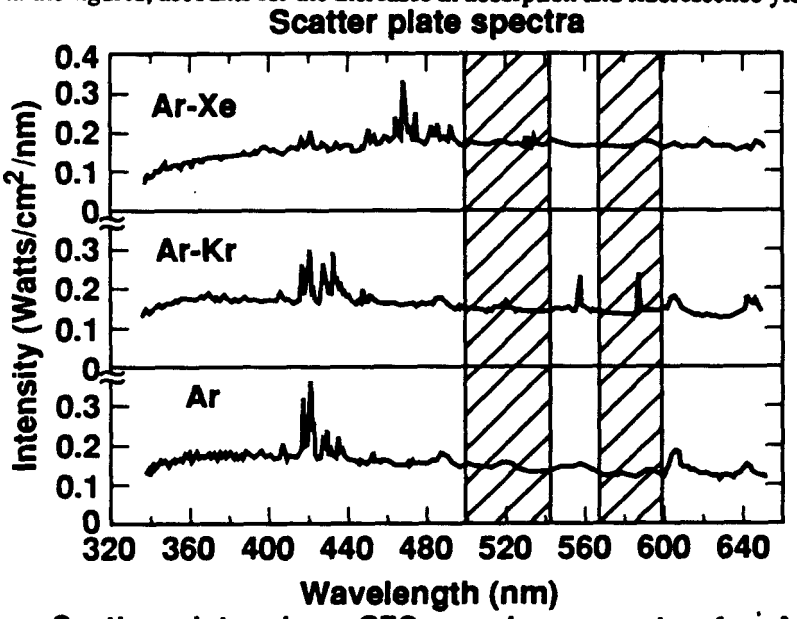

Figure 4. Scatter plate view, CFQ envelope spectra for Ar-Xe, Ar-Kr and pure Ar lamps. The shaded regions indicate the spectral regions useful for pumping the upper laser level in Nd:YAG.

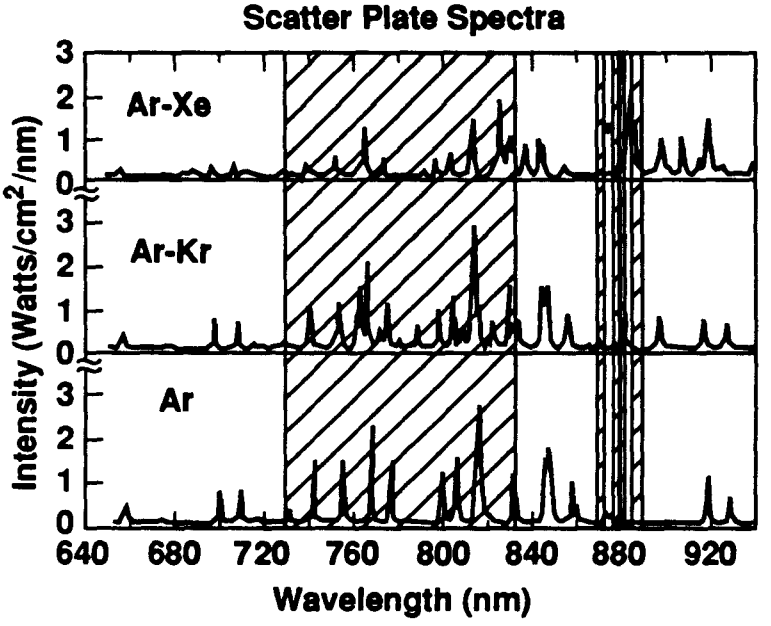

Figure 5. Continuation of Fig. 4, but at higher wavelengths. Note the change of vertical scales.

The electrical efficiency of the lamp, between 200 and 2000 nm was 54% with pure Ar and 59% with the Ar-Xe mixture. (Electrical efficiency data on Ar-Kr are not available because of erroneous positioning of the pyroelectric detector.) Owing to its intrinsically higher emissivity, the addition of xenon enriched the gray-body content of the lamp spectrum; however, argon emission lines within the most important Nd:YAG absorption band (730 to 830 nm) were quenched, shifting the power output into longer-wavelength xenon lines. If the laser material were a broadband absorber such as Cr:Nd:GSGG or Nd:glass, it would be more advantageous to use Ar-Xe lamps; for Nd:YAG, however, the best coupling is obtained from an Ar-Kr mixture.

In Table 1, the direct-view, Stabicil-envelope spectrum and the scattering plate, CFQ-envelope spectra are convolved with the absorption spectrum of the laser slab described above. All the calculations were done in the spectral region from 400 to 900 nm, where the difference in lamp envelopes is not significant (Stabicil is cerium doped and absorbs in the UV). Because the spectral range used in these calculations is different, the results are slightly different from those summarized above for the Stabicil-envelope, high-resolution spectrum.

Table 1

Absorption characteristics in the 400-900 nm spectral range of a 0.5-cm-thick, 2x 10^{20} ions/cm^3 Nd:YAG slab for the direct-view, high-resolution Ar spectrum and the scattering-plate view of several Vortek lamp mixtures

	Absorbed fraction of emitted power (%)	Fraction of power emitted at 730-830 nm (%)	Fraction of emitted power absorbed at 730-830 nm (%)	Quantum ratio
Direct view:				
Ar	27.6	37.3	21.9	0.697
Scattering plate:				
Ar	27.0	35.8	21.0	0.697
Kr	27.7	37.8	21.4	0.702
Xe	22.4	27.2	14.1	0.684

For the Ar and Ar-Kr spectra, 57 to 59% of the energy available in the 730-830 nm band is absorbed by the slab in a single pass. For Ar-Xe, this quantity is 52%. For the Ar and Ar-Kr spectra, 82 to 85% of the upper laser level pumping power is derived from this band, as against 68% for the Ar-Xe lamp; therefore, even if the Ar or Ar-Kr arc-lamp spectra were filtered (anywhere below 730 nm) to prevent solarization of a Nd:GGG laser slab, only a modest penalty in laser efficiency would be incurred.

3.3. Pulsed Operation

For-pulsed power operation of the Vortek lamp (in which the lamp power during the pulse may be higher than reported here) experiments will be required to determine the optimum gas mixture. It is expected that the higher currents will increase the gray-body output of the lamp and thus decrease the coupling.

Pulsed operation can significantly increase the instantaneous gain and reduce the upper-level decay loss. According to G. Albach of Vortek Industries, the lamp has operated with current fluctuations between 70 and 750 Amps. at 360 Hz.[4] Shorter pulses are desirable from the lifetime and gain viewpoint; however, both the spectral shift towards the UV and the higher gray-body power at increased current densities increase the value of χ, the heat load parameter.

3.4. Lamp Tube Filtering

Doped quartz lamp tubes may be used in place of clear ones in order to filter out undesirable portions of the emission spectrum. Even with the cerium-doped (Stabicil) lamp envelope, 25% of the output spectrum is below 500 nm. Substantially more output below 500 nm (38%) was measured when the lamp envelope was clear fused quartz. This portion of the spectral power would have to be filtered for use with solarization prone laser materials such as Nd:GGG.

3.5 Data Accuracy

There was good agreement between the irradiances obtained with a calibrated pyroelectric detector and a calibrated thermopile and by integration of the spectrum tied to the NBS-calibrated tungsten filament lamp. A significant experimental difference was the envelope being cerium doped for the spectral measurement and clear fused quartz for the pyroelectric- and thermopile-detector measurements. The pyroelectric-detector irradiance readings were compared with those of the thermopile detector (provided by Vortek) which was placed next to it, and the difference was never more than 5% as a series of filters was placed in front of both detectors; however, the thermopile readings were consistently higher. The filter transmissions were calculated digitally using the NBS standard-lamp-based spectrum of Fig. 1. The irradiance values for several spectral bands were then compared with the pyroelectric detector and found to agree within 1% when the spectral band chosen did not overlap the absorption edge of the Stabicil envelope.

3.6. Lamp Electrical Efficiency

The spectrally resolved data were combined with the (spectrally filtered) pyroelectric detector data to produce a running total for the irradiance 50 cm from the lamp. This is shown in Fig. 6, where the irradiance integrated up to each wavelength is plotted. The radiant power below 400 nm can be markedly reduced (to one-third of the value in Fig. 6) by use of the stabicil envelope . A substantial portion of the power output is found above 900 nm. The figure shows this as a broken line rising to the maximum, unfiltered pyroelectric-detector irradiance measurement at the limit of water transmission of 2 μm.

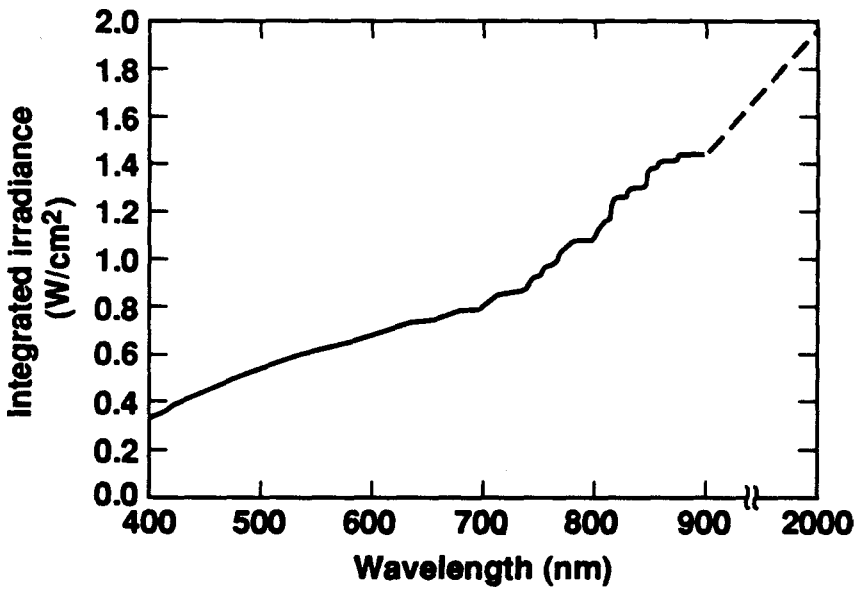

Figure 6. Irradiance 50 cm from an argon arc-lamp presented as a running total (i.e., integrated from 0 to l). The figure is a composite of pyroelectric (filtered) data and the spectrum f Fig. 1. Below 400 nm and above 900 nm, the pyroelectric detector data were used. Between 400 and 900 nm, the spectrally resolved data agreed with the pyroelectric detector data to within 1%.

The lamp efficiency can be estimated based on the basis of the data of Fig. 6, but it will depend on the choice of spectral range. The net irradiance in the chosen spectral band is multiplied by $4\pi(50)^2$ cm^2 and divided by the electrical input power (114 kW_e). The pyroelectric irradiance limit indicates a total emission efficiency (light output between 200 and 2000 nm divided by electrical input) of 54%, while the net efficiency up to 900 nm is 40%. If the Stabicil envelope is used, the net efficiency is 35% (which represents the spectral power contained in Fig. 1).

The efficiency estimate computed in this way will always be low, because the angle dependence of the radiation field was not measured or taken into account. The sample spectra here were obtained at a distance of 7.6 m, with a viewing angle perpendicular to the lamp; thus, a very restricted range of plasma depths irradiated the detectors. We hoped that the angle dependence of the spectrum could be extracted from the scattering plate spectra, but there were no significant relative differences between the low-resolution data taken viewing the lamp directly or indirectly (via the scatter plate). It was expected that the gray-body intensity of the scattered light would rise relative to the line peaks because of averaging of plasma depths, but this was not observed, perhaps because the plasma was optically thin in spectral regions away from the lines. (The maximum angle subtended between the lamp plasma and the scattering plate vertical was 70°.)

4. CONCLUSIONS

The Vortek lamp characteristics are fairly well established by the data given here. Based on these data, the calculated results assuming a baseline Nd:YAG laser slab show a promising outlook for Vortek-lamp pumping of crystal laser slabs. Pulsing of the lamp should be possible and may provide further improvements in laser operation because of more intense pumping of the upper laser level, and lower decay losses, which would provide higher instantaneous gain at extraction time.

5. ACKNOWLEDGEMENTS

Work performed jointly under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48, for the U.S. Army Strategic Defense Command in support of SDIO/SDC-ATC MIPR No. W31RPD-7-D4041.

6. REFERENCES

1. Manufactured by Vortek Industries, Vancouver, B.C., Canada.
2. F. E. Jenkins and H. E. White, *Fundamental of Optics*, 4th edition, McGraw Hill Book Co., New York, 1976.
3. H. Griem, *Plasma Spectroscopy*, McGraw Hill, New York, 1964.
4. Gary Albach, Vortek Industries, personal communication.