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Cesium Vapor Lamps*

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A study of the characteristics of low voltage arc discharges in cesium vapor led to the development of a practical lamp that was used in a successful communication system using infra-red radiation. The radiated energy is confined almost entirely to the cesium resonance lines at 8521 and 8944 angstroms. Data are presented that give structural details, operating characteristics, infra-red output, and efficiencies of several lamps of different sizes. Excellent modulability is attained throughout the audiofrequency range with current modulation up to 100 percent.

A CESIUM vapor lamp development program was undertaken in the engineering and research laboratories of the Westinghouse Lamp Division as a wartime project. The work was sponsored by the Navy Department, Bureau of Ships. The desired end result was a source that had an intensity at least equal to that of a 200-watt projection lamp as measured with a cesium photo-cell through filters that gave equal visual range to the two lamps, was capable of being modulated with audiofrequencies between 200 and 3000 cycles per second, was of such size as to produce a 25° beam when placed in a 15-inch reflector, and had sufficient ruggedness to withstand shipboard use with at least 20 hours useful life. Another objective was to design a lamp of 500 watts power with 360-degree horizontal and 60-degree vertical beam spread.

Exploratory work starting in April, 1944 was done with lamps of various sizes and shapes to investigate factors such as current, voltage, bulb temperature which regulates cesium vapor pressure, kind and amount of gas filling, type and size of electrodes, envelope glass with suitable protective coating to resist chemical attack by the cesium vapor, and infra-red output and life. As quite frequently happens a very simple design was the most practical. Laboratory experimental lamps were burned in Dewar vacuum flasks of small size to conserve heat and generate a sufficiently high pressure of cesium vapor. Commercial lamps were mounted inside an evacuated outer envelope. The infra-red output from these lamps was measured in relative terms with a cesium photo-cell, high sensitivity galvanometer, and suitable filters. This was a simple and quick method to note changes in infra-red output and efficiency with modifications in lamp design. The output in absolute units was measured with a calibrated thermopile and appropriate filters.

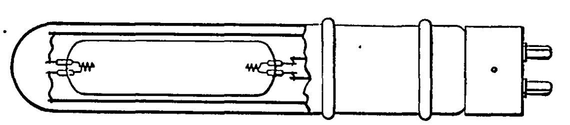

FIG. 1. Cesium vapor lamp.

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TABLE I. Radiant energy from an experimental lamp burned at 5 amperes, mounted in a Dewar flask.

Wave-lengths	Relative intensity
10124A	5.0
10026	3.0
8943	75.0
8521	100.0
8079	1.4
7944	1.2
7609	0.7
6973	2.9
6723	1.9
6215	1.6
4593	1.4
4555	2.0

100-WATT CESIUM VAPOR LAMP

The lamp that was adopted for infra-red communication had a structure shown in Fig. 1. The source of light was a tubular bulb 1.37 inches in diameter about 5 inches long, with a spacing of 3 inches between electrodes. These dimensions gave the required beam spread in a convenient size aluminum reflector. The bulb is coated internally with a special glaze to resist the attack of ionized cesium vapor. It is fitted with two helical tungsten electrodes of small coil dimensions to anchor the arc to the center of the lamp. One or both of these may be coated with barium and strontium oxides. The outer envelope is 2 inches in diameter and has two ridges, the band between them serving to support the lamp and to maintain accurate alignment in relationship to the focal point of the reflector. A four-prong plastic base is cemented to the lamp which fits into a light weight plastic socket. The clamping band is at the center of gravity of this assembly when the lamp is in its normal horizontal position.

A gas filling of 20 to 22 cm of argon produced high efficiency in the cesium resonance lines. Lower gas pressures gave lower infra-red output while higher pressures caused increased visible light and instability. Argon gas was selected for its availability and low cost. Krypton is a heavier gas and increases the useful infra-red about 10 to 15 percent in this size lamp. Several tenths of a gram of pure cesium metal is distilled into the lamp to form the active agent in producing near infra-red radiations.

The rating of 5.5 amperes 18 volts was selected for long life with good efficiency and high infra-red output. Life tests showed that these lamps burned about 500 hours at this rating with either a.c. or d.c., and burned equally well in the horizontal or vertical positions. With audiofrequency modulation superimposed upon the normal d.c. current, the increased wattage consumed by the lamp causes a decrease in life. A forced life test with 100 percent current modulation at 1000 cycles with continuous burning gave 50 to 150 hours life. End of life is determined by a sudden decrease of infra-red energy because of loss of cesium vapor that has been absorbed by the glass bulb. The life can be regulated by the amount of cesium introduced into the lamp, the excellence of glaze coating and bulb temperature which is dependent upon the lamp wattage.

A standard inner bulb was mounted in a double wall Dewar flask with a thermocouple junction attached to it with a small amount of kaolin and water glass paste. This should give a rather close approximation to the temperature of the cesium metal at the bottom of the lamp, but will give a value that is somewhat lower than that attained in an evacuated outer housing. For 100 watts power consumption the temperature of the cesium was approximately 300°C which corresponds to a vapor pressure of about 2 mm of mercury.

MEASUREMENT OF INFRA-RED RADIATION

Cesium vapor lamps, when operated under suitable conditions, generate near infra-red radiation with high efficiency. Most of this radiation is confined to the resonance radiation at 8521A and 8944A. Spectrograms taken on infra-red sensitive film show these two lines very strong while the other lines, including the visible, are relatively weak. The spectrograms showed no reversal in the resonance lines at the normal operating current. Measurements with a Beckman spectrophotometer, recorded in Table I, showed that practically all the radiated energy between 10124A and 4555A was confined to the two resonance lines. Krefft[1] measured the intensity of the spectral lines emitted by cesium vapor arcs over a pressure range of 0.1 mm to 28 mm. At 4-mm pressure both resonance lines are strong emission lines while at 20-mm pres-

[1] H. Krefft, Zeits. f. Physik **77**, 752 (1932).

sure these two lines show strong reversal. Mohler[2] and Beutell[3] experimented with low pressure cesium vapor discharges and measured some of their characteristics which indicated that appreciable energy was radiated in the near infra-red region. At relatively high cesium vapor pressures and current densities Mohler[4] calculated high luminous efficiency for the continuous spectrum that was found under those conditions.

The infra-red radiations from a cesium vapor lamp are readily measured with a cesium photo-cell since it has a high response to its own radiations. A Wratten No. 87 filter is satisfactory to eliminate visible radiation from the cesium vapor lamp being measured or from the tungsten filament lamp that might be used as a standard of comparison. A Corning No. 254 glass filter 2.3 mm thick was also used with the standard 500-watt tungsten filament lamp. This filter and lamp combination gave a visual security equal to the Wratten No. 87 filter when used with the cesium lamps. With the particular RCA No. 919 photo-cell used, a normal cesium vapor lamp operating at equilibrium with 5.5 amperes had a rated output of 500 to 700 equivalent watts of tungsten radiation with equal security. This output index was dependent upon the spectral sensitivity of the photo-cell so could not be used for inter-laboratory comparisons, but served very well to detect changes in infra-red output from our experimental lamps as modifications were made in lamp structures.

A thermopile calibrated with a Bureau of Standards standard lamp, a high sensitivity galvanometer and several filters formed a measuring device that gave results in absolute units. The following table of data, Table II, shows the characteristics of an average commercial CL-2 lamp (Westinghouse designation for this lamp as made for the Navy) burned on direct current.

The efficiency of a lamp is dependent upon its arc length and condition of burning as well as purity of gas and other factors inherent in its structure. A lamp similar to the CL-2 lamp but with 4.25 inches arc length burned in double wall Dewar flask at 5.5 amperes 17.5 volts gave 21.4 watts or 22.2 percent of the total wattage supplied to the lamp in the near infra-red. When mounted in an evacuated single wall outer envelope this lamp operated at the same current and voltage but produced 24.1 watts or 25 percent of its applied wattage in the infra-red. The efficiency increased with length of arc stream, other factors remaining the same, since the electrode losses become a smaller part of the total wattage of the lamp.

Lamps 1.66 inches in diameter, with arc lengths of 4, 8, and 12 inches had the same infra-red output per unit of length when burned in a horizontal position at 5.5 amperes and showed an electrode loss of 9 volts and a gradient of 1.25 volts per cm. Using data from 2-inch diameter lamps mounted in vacuum outer jackets an electrode loss of 7 volts and a gradient of 0.97 volt per cm were obtained when the lamps were burned in a vertical position on d.c. These data were for lamps filled with 20-cm argon gas. Changes in gas pressure and kind of inert gas used as well as modifications in lamp structure will change these values.

EFFECT OF GAS IMPURITIES

In the course of our investigations it became desirable to learn the effects of small percentages of impurities such as oxygen, nitrogen, and hydrogen in the normally pure rare gas filling. If some or all produced deleterious effects, great effort should be expended in trying to remove them, but if a beneficial effect is produced by their addition, steps should be taken to introduce the optimum amounts. The experimental work consisted in making a number of lamps similar to the commercial CL-2 style and introducing given amounts of gas impurity before the lamps were sealed off exhaust. They were then burned on life test at normal current for time intervals of 300 to 500 hours during which

TABLE II.

Current	Voltage	Watts in near infra-red	Conversion efficiency	Equivalent tungsten watts
4.0 amp.	15.0 volts	12.5 watts	21.0%	400 watts
5.0	15.5	16.3	21.0	525
5.5	16.5	19.6	21.6	630
6.0	17.0	21.2	20.8	675
6.5	17.5	24.1	21.2	755

[2] F. L. Mohler, Bur. Stand. J. Research **9**, 25 and 493 (1932).
[3] M. Beutell, Ann. d. Physik **36**, 533 (1939).
[4] F. L. Mohler, J. Opt. Soc. Am. **29**, 152 (1939).

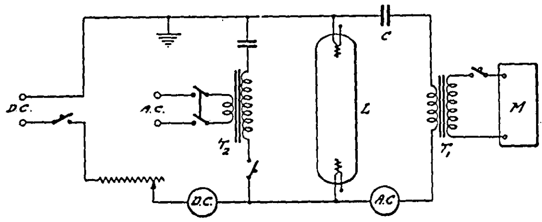

FIG. 2. Wiring diagram for operating cesium lamp. L: cesium lamp, M: modulator, C: modulation condenser of 200 to 500 mf, T_1: modulation transformer, T_2: starting transformer.

time output characteristics were periodically measured.

It was found that oxygen, even in minute amounts, is deleterious and reduces the infra-red output because of its strong quenching action on the resonance radiation of ionized cesium vapor. It should be reduced to the lowest practical limit which can be effected with excellent lamp manufacturing technique aided by the use of a suitable getter as described below.

Small amounts of nitrogen—up to 0.03 percent—gave results equally as good as pure argon gas up to 500 hours life. Lamps with 0.3 percent nitrogen in the argon gas gave only about one-third the normal output.

Carbon dioxide gas caused a reduced infra-red output probably because it dissociated into carbon and free oxygen gas.

Hydrogen gas has a beneficial effect in low concentrations as additions to argon gas. Lamps filled with a mixture of 0.006 percent hydrogen in pure argon showed an increase in the infra-red output of 30 to 50 percent throughout the several hundred hours burning on life test. All lamps burned with approximately the same voltage as the control lamps, hence the efficiency is greatly improved.

It is desirable to have a suitable getter in these lamps to remove the last traces of oxygen in the sealed off lamps. Zirconium or tantalum metal forming part of the electrode structure may increase the infra-red output an appreciable amount—of the order of 10 to 20 percent. These getters, like hydrogen, remove or inactivate small amounts of oxygen from the cesium arc.

STARTING 100-WATT CESIUM VAPOR LAMPS

Cesium vapor lamps have many peculiar characteristics, one of which is the method of starting the lamps. The wiring diagram of Fig. 2 shows the essential connections. The filaments are preheated with separate filament lighting transformers at 6 amperes 2.5 volts for one minute after which a starting current of one ampere from a 300-volt transformer produces an a.c. arc that is allowed to burn for about one minute. Then the d.c. supply voltage is applied to the lamp and the current regulated to its normal value with the control resistance. The high voltage a.c. starting circuit and filament heating circuits are disconnected and the lamp allowed to burn about 15 minutes to attain thermal equilibrium before a.c. modulation is applied.

MODULATION EXPERIMENTS

The infra-red output of our experimental lamps measured in our laboratory with a thermopile and suitable filters or with a cesium photocell showed that the required total infra-red energy was satisfactory. Permission was received to have Dr. Phillips Thomas at the Westinghouse Research Laboratories in East Pittsburgh make measurements on the frequency response throughout the audio-range. He had suitable equipment that was already set up, and in a few hours on August 4, 1944 measurements were made on three lamps using 800-cycle key signals, voice, phonograph record transmissions, and audio-frequencies of 200 to 10,000 cycles per second from an oscillator. The sound transmitted by the invisible infra-red radiations was of excellent quality. The frequency response throughout the audible range showed that high quality transmission with good efficiency could be expected up to 100 percent current modulation. Distortion appears above 100 percent current modulation due to harmonics, but the lamp will not be extinguished with overmodulation.

The circuit shown in Fig. 3 can be used to

TABLE III.

Frequency	Modulation Westinghouse	Modulation Michigan
200	75	90
500	73	80
1000	72	70
2000	65	60
3000	58	35
5000	45	25

measure both the d.c. and a.c. component of light emitted by the lamp while it is being modulated. The lamps were burned in a Dewar flask with 100 percent current modulation, and all gave comparable results. The accompanying Table III gives data showing the modulation factor for selected frequencies as determined at the Westinghouse Laboratories and also at the University of Michigan 10 days later by Dr. J. G. Black by an entirely different set of apparatus and a different method. Modulation factor is taken as the percentage light modulation for 100 percent current modulation.

These data show that high modulation factors are obtained even with our early experimental lamps. An ordinary 60-watt tungsten filament lamp can be burned on d.c. and readily modulated with audiofrequencies to 6000 cycles per second, but the modulation efficiency is very low because of heat capacity and thermal inertia of the tungsten filament. At 1000 cycles the cesium vapor lamp is about 1000 times as efficient as the tungsten filament lamp.

Two lamps of the 100-watt size can be burned in series or in parallel and modulated with the same power unit. While series operation has little to recommend it since longer lamps of higher wattage can be made quite easily, parallel operation will provide for greater reliability and insurance against failure without any mechanical difficulties of synchronization.

500-WATT LAMPS

Research on the 100-watt cesium vapor lamps was later expanded to include 500-watt and 50-watt sizes. The lamps are essentially similar in structure to the 100-watt size but have their own peculiarities. The 500-watt size was made for use without a reflector and must be burned in a vertical position. The arc stream is 2 inches in diameter, 17 inches long, and requires 10 amperes at 50 volts. Because of its length the lamp is more efficient than the 100-watt size as

TABLE IV. Characteristics of 500-watt cesium vapor lamp.

Current (amperes)	10.0	9.0	8.0
Voltage (volts)	49.5	47.5	46.5
Total infra-red watts	172	149	121
Efficiency	34.8%	35.0%	35.3%
"Equivalent" watts	5800	4750	4150

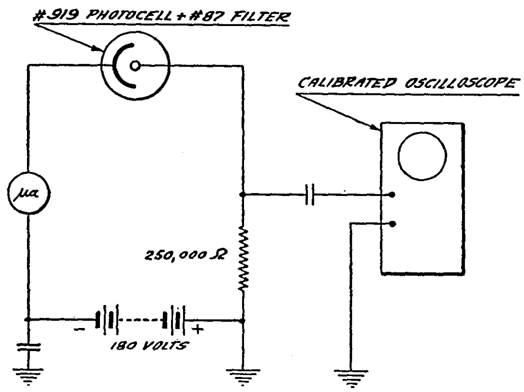

FIG. 3. Circuit used to measure d.c. and a.c. components of infra-red radiation from cesium vapor lamps.

the data in Table IV indicate. The lamp is fitted with a base at each end of the lamp to avoid arc displacement to the side of bulb because of the magnetic effect of the current passing through a conductor near the inner envelope. This problem was not important in the smaller lamps but becomes serious in lamps carrying 10 to 20 amperes arc current. Lamps greater than 3 inches in diameter tend to become unstable even with special electrodes that were designed to keep the arc stable.

The nominal rating of this size lamp is 10 amperes 50 volts d.c. with 100 percent a.c. modulation for code signal transmission. With modulation current superimposed upon the steady d.c., the lamp voltage is 7 to 8 volts less as measured on a d.c. meter. There is about a 20 percent increase in wattage with 100 percent current modulation which increases the visible light and long wave infra-red, since the near infra-red as measured both with a thermopile and cesium photo-cell remains constant. The visible light increases from about 500 lumens when the lamp is operating with 9.5 amperes d.c. to 750 lumens when the lamp is operating with 100 percent 800-cycle modulation current superimposed upon the d.c. current. This represents the difference in light output between a 40-watt and a 60-watt household incandescent lamp. The greatest part of the increase in energy is converted to long wave-length infra-red that raises the bulb temperature 15° to 20°C.

A "standby" current of 5 amperes may be used to keep the lamp warm, but it cannot be operated at full output for about 10 minutes

TABLE V.

Current (amp.)	4.0	3.5
Voltage (volts)	12.5	12.0
Infra-red watts	9.3	7.6
Efficiency (percent of input)	18.6	18.2
"Equivalent" watts	308	254

after normal power is supplied to the lamp. At 5 amperes the infra-red output is about 30 percent of the normal equilibrium value but 80 percent of rated output is attained in three to four minutes.

Even though a security filter may not be necessary, it is highly desirable to surround these lamps with a transparent glass cylinder to form a protecting shield from cold weather and high winds since the radiation from the outer jacket helps to maintain high cesium vapor pressure in the lamp. This condition is not encountered in the smaller lamps that are used within a reflector housing.

50-WATT LAMPS

A small size 50-watt lamp was developed for the Army Air Corps. This lamp had an arc length of only two inches with an over-all length of 6.5 inches including the base pins. The inner bulb was one inch in diameter and the outer bulb 1.5 inches in diameter. The lamp can be modulated with a.c. throughout the audio-range, and can be burned in any position. These lamps can be conveniently burned on a 24-volt d.c. supply line, but the starting cycle is a little longer than when used on a 120-volt d.c. supply. A lamp was burned on life test with 3.5 amperes d.c., 2.45 amperes 1500-cycle a.c. modulation for over 200 hours with constant output. With 4.0 amperes d.c. and 2.8 amperes 1500-cycle a.c., lamps have burned over 100 hours with approximately constant output. In these lamps a slight change in bulb shape to approximate an isothermal surface will increase the infra-red output and efficiency an appreciable amount. Table V gives data on the characteristics of the 50-watt lamps.

Immediately after the tests at the University of Michigan on August 15, 1944 several lamps were sent to Northwestern University where for some time a group of men under the direction of Dr. W. S. Huxford had been developing a communication system under an NDRC contract using a different type of lamp that did not meet all of the Navy's requirements. Our experimental lamps of 5.5 amperes current rating matched their power supply and searchlight reflector, and in a few days an operable field unit demonstrated that this system formed a practical means of communication. Two-way ship to shore voice and code communication by invisible infra-red light beam was demonstrated on the Atlantic Ocean, October 18 and 19, 1944 with equipment built at Northwestern University.

The advantage of using an invisible light beam as a carrier wave of modulated a.c. currents is that such a system can be made into a secret system that cannot be detected or jammed like radio. It is limited to horizon distances and the light can be used like a searchlight beam if desired. These lamps may be adapted to ship to shore use in crowded harbors where radio might be objectionable, and in convoy work.

ACKNOWLEDGMENTS

This project extended from April, 1944 to October, 1945 and required the assistance of men in our own organization as well as those in other laboratories mentioned above. The problem was suggested to us by Mr. Joseph Ballam at the Bureau of Ships who coordinated lamp development at the Westinghouse Lamp Division and equipment development at Northwestern University. Experimental work involved in conducting field tests at the Navy's test station and at the Naval Research Laboratory was done largely by Mr. E. Goldstein.

After field tests demonstrated the feasibility of using our 100-watt cesium vapor lamps in a secret communication system, an order was taken to make them on a commercial scale. Adapting the experimental lamps to factory production methods was assigned to Mr. T. C. Retzer, who had to make a new product rapidly, on existing equipment, in reasonable quantity and with excellent quality. Engineering development on the 500-watt size lamp occupied the full time of Mr. C. M. Rively throughout the cesium lamp project. Much of the work involved in making experimental lamps was done by Mr. A. J. Oszy.