

20 to 30 kW Xenon Compact Arc Lamps For Searchlights and Solar Simulators

W. E. Thouret, FIES

J. Leyden

H. S. Strauss

G. Shaffer

H. Kee

Xenon compact arc lamps with liquid-cooled electrodes for the 10 to 25 kW input range have come into use in greater numbers during the last years. They have to operate reliably in precise optical equipment under varied environmental conditions. A report is given on the development, production, and practical performance of two types used in solar simulators and searchlights, especially in the 50-unit floodlighting system established for the Apollo spacecraft launchings at Kennedy Space Center. New tungsten anode design and manufacturing methods suitable for extending the power range of such lamps to 30 kW and higher (700 amperes operating current) are described.

XENON COMPACT arc lamps with liquid-cooled electrodes for the 10 to 25 kW input range have been developed since 1964.^{1,2} They have proved to be useful for replacing carbon arc lamps in searchlights and solar simulators, particularly if their performance meets detailed specifications and is reliable and reproducible over a long life.

A basic 20 kW lamp design was described earlier by Thouret, Strauss, Cortorillo, and Kee.¹ The present paper refers to this design and reports on further development work done since it was established. In the course of this work, numerous modifications and additional features had to be introduced in order to meet the diverse requirements of practical use in searchlights and solar simulator systems. It led to the production of hundreds of lamps conforming to such requirements. As an example of their reliability, a report will be given on the performance of a closely supervised 50-unit installation.

As there is a demand for extending the power range of xenon compact arc lamps to 35 kW³ development efforts have been made in this direction. They mainly concern

the anode design and have led to an anode structure that appears to operate satisfactorily at the desired high power levels (up to 700 amperes operating current).

Type XE 20000 C for Searchlights

When the detailed development of this lamp type began, one of its major contemplated applications was in a wheel-mounted general purpose searchlight with a reflector of 30 inches (76 cm) diameter.⁴ In order to assure reliable operation of this searchlight under varied environmental conditions, lamp design and test specifications were drawn up, which to a great extent determined the objectives of the development effort. In the next paragraphs the main contents of these specifications^{5,6} will be described briefly. A report will follow on some problems encountered while attempting to meet the requirements and on the methods that led to their solution.

Required Lamp Supporting, Prefocussing, and Connecting Elements

The lamp had to be supported and located in the fixture by metal rings surrounding the quartz sidearms of the envelope. The support rings had to be fastened by means of room temperature vulcanizing silicone rubber rings cast between them and the sidearms. These rubber

A paper presented at the Annual IES Conference, Tulsa, Okla., July 24-27, 1972. AUTHORS: Duro-Test Corp., North Bergen, N. J.

rings serve also as shock and vibration absorbing support cushions. Proper preparation of the inner metal and outer quartz surfaces has to assure safe adhesion between metal rings, rubber rings, and lamp.

The metal rings and rubber cushions support the lamp in all operating positions, which range from horizontal to vertical with the anode up. While both rings hold the lamp laterally, the ring on the anode sidearm additionally supports and locates the lamp in axial direction by providing the vertical support component required in all positions not exactly horizontal. For this purpose, the anode ring has a spherically curved outer surface. As it has to support the weight of the lamp of approximately 10 lbs (4.5 kg) safely under shock and vibration, the adhesive bond between ring, rubber, and quartz sidearm and the shear strength of the rubber cushion have to withstand a test load of 160 lbs (72.6 kg) applied in direction of the lamp axis. The ring on the cathode sidearm has a cylindrical outer surface and is relatively long in order to allow axial focussing-defocussing movement of the lamp in the searchlight.

The metal support rings also function as lamp prefocusing elements. For this purpose, their outer surfaces have to be adjusted concentrically to each other within 0.010 inches (0.254 mm) and with respect to the cathode tip as center point within 0.020 inches (0.508 mm). For axial location, the inner edge of the anode ring has to be adjusted within ± 0.0313 inches (0.795 mm) axial distance from the cathode tip. The cathode tip represents the location of the "hot spot," the high brightness area of the arc, which remains firmly attached to it under all operating conditions.

The electrical and cooling fluid connectors are unremovable parts of the lamp; the coolant lines serve also as power connections. The connecting fittings are required to have standard threads and have to be arranged and dimensioned differently for anode and cathode in prescribed manner. A flow of antifreeze coolant at 5 ± 0.5 gallons per minute (19 ± 1.9 liters/min.) through both electrodes in series is specified. This requires an anode inlet pressure of 120 ± 20 psi (8.2 ± 1.4 atm.) and a minimum cathode outlet pressure of 20 psi (1.4 atm.).

Environmental Test Requirements

In order to assure that the lamps can withstand storage, transportation and operation under extreme environmental conditions, randomly selected samples have to survive without damage the following tests.

1. Mechanical shock and vibration tests made on non-operating lamps at room temperature in horizontal position: 24 shocks of 15 g force and six milliseconds duration each; 12 of these shocks applied in direction of the lamp axis and 12 perpendicular to it. Vibration in direction of the lamp axis at an acceleration level of 2.5 g with frequency varying between 15 and 200 cycles per second within 3.5 minutes; the same test in perpendicular direction. Vibration at the same acceleration level at constant frequency of 30 cps for 15 minutes in axial and for 30 minutes in perpendicular direction.

2. Low temperature storage, vibration, ignition, and operation: Storage at -80°F (-62°C) for 24 hours, storage at -65°F (-54°C) for additional four hours; vibration at this temperature at 2.5 g acceleration level at 30

cps for 80 minutes in direction perpendicular to lamp axis; while vibrating in this manner, the lamp is to be ignited five times and operated at 20 kW power level through five cycles consisting of three minutes operation and 12 minutes cooling time each.

3. High temperature storage, ignition, and operation: To be stored in package at 165°F (74°C) for 24 hours, kept in searchlight at 125°F (50°C) for additional four hours, ignited and operated at 20 kW level for two hours cooled to 80°F (27°C) within 30 minutes.

4. High altitude storage and operation: To be stored in a test chamber simulating an altitude of 40,000 ft (12,200 m) for four hours. Ignition and operation at 20 kW level for two hours at simulated altitude of 8000 feet (2440 m).

Optical Electrical, and Life Requirements

The average arc brightness, defined as the average over an area of 2 mm (0.079 inch) diameter around the point on the arc centerline 0.5 mm (0.020 inch) from the cathode tip, has to be 3400 cd/mm² minimum. The minimum peak brightness (value at the center of the defined circular area) is 6000 cd/mm². The minimum initial lumen output at 20 kW input is 800,000 lumens. The electrical data prescribed at the three power levels 10, 15, and 20 kW, and the ignition requirements are contained in Table I. Selected lamps had to pass an electrical overload test consisting of 24 starts bringing the current immediately to 800 amperes and holding it at this level for five seconds each. The holding time was later reduced to one second.

Even if the specified lamp brightness and lumen data are surpassed consistently, the candlepower values obtainable with a searchlight depend strongly upon the optical quality of the lamp bulb. For this reason, a rather sensitive test was prescribed for every individual lamp: The apparent shift of the cathode tip when it is observed through the bulb from all angles under which the searchlight reflector may receive radiation shall lie within a circle of 1.5 millimeter (0.059 inch) radius.

All lamps had to be tested for dimensions, bulb quality, electrical data, and average brightness. Randomly selected test lamps in addition had to survive all environmental tests, the electrical overload tests and to meet initial lumen requirements. After this, they had to be operated at the 20 kW level continuously for 12 hours and intermittently for 400 hours (through 480 cycles: 50 minutes on, 10 minutes off). After attaining this minimum life, the lumen output was required to be at least 70 per cent of the initial value.

Adaptation of Previous Lamp Design to Added Requirements

When the basic 20 kW lamp design was developed,¹ certain requirements of practical use had been expected and met. This refers particularly to the flexibility of operating position and the capability to withstand extreme temperatures and shock and vibration. Therefore, further development efforts seemed to be necessary mainly in the areas of coolant connectors and prefocussing rings.

Fig. 1 shows a type XE 20000C lamp complete with the new external parts. The coolant and power connectors are arranged as specified and have the prescribed configuration. The connectors cannot be removed because the heads of the fastening screws are covered with alumi-

Table I—Main Data of 10 to 32 kW Xenon Compact Arc Lamps for Direct Current

Lamp Designation	Input kW	Lamp Voltage volts	Lamp Current amps.	Electrode Spacing at Room Temperature inches	mm	Initial Peak Brightness cd/mm ²	Initial Average Brightness cd/mm ²	Initial Light Output ^b lumens	Life hours	Maximum Overall Lamp Length inches	cm	Maximum Bulb Diameter inches	cm
XE 20000 C	10	34.8 ± 1.5	288 ± 12	0.532 ± .060	13.5 ± 1.5	—	—	—	1000	24.125 ^b	61.3 ^b	5.375	13.65
	15	39.3 ± 1.7	382 ± 16	" "	" "	—	—	—	750	"	"	"	"
	20	43 ± 1.8	465 ± 20	" "	" "	6370 ^{b,d}	4380 ^{b,d}	877,000 ^e	500	"	"	"	"
XE 20000 D	15	41 ± 1.5	366 ± 13	0.512 ± .040	13 ± 1.0	—	—	—	750	19.156	48.7	5.375	13.65
	20	44 ± 2.0	455 ± 21	" "	" "	6550 ^e	4380 ^e	—	500	"	"	"	"
	25	47 ± 2.5	532 ± 29	" "	" "	8000 ^f	5050 ^f	—	250	"	"	"	"
XE 32000 D	26.5	44 ± 2.0	600	0.500 ± .028	12.7 ± 0.7	9000	5500	—	200	19.156	48.7	5.375	13.65
	29.5	45.5 ± 2.0	650	" "	" "	9800	6000	—	150	"	"	"	"
	32	46.5 ± 2.5	700	" "	" "	10500	6500	—	100	"	"	"	"

NOTES: a Maximum average brightness over a circular area of the arc of 0.25 mm (0.010 inch) diameter.

b Average of values measured on more than 20 lamps during first 10 operating hours.

c Line 0.5 mm (0.020 inch) from cathode tip.

d Measured at 465 amps. test current.

e Measured at 455 amps. test current.

f Measured at 525 amps. test current.

g Light output after 400 operating hours (480 starts): 826,000 lumens (average of 9 lamps).

h Center to Center distance of coolant connector threads: 23.3125 ± 0.1563 inches (59.2 ± 0.4 cm).

SAFETY: Because of their high internal pressure the lamps must be operated at all times in enclosures that exclude any hazard to persons. In addition, protection from the intensive ultraviolet and the developing ozone has to be provided. The lamps are supplied within protective cases. Housings and reflectors should be designed to allow removal of these cases after lamp installation.

IGNITION: The lamps achieve a fully sustained arc within 2 seconds after actuation of an ignition circuit with these data^a: Ignition pulse voltage 45,000 volts, pulse repetition rate 1,600 per second, energy per pulse 0.1 wattsecond, integrated pulse energy 160 watts, auxiliary voltage 95 volts d.c. open circuit with 100 watts energy.

COOLING REQUIREMENTS: Continuous flow of distilled (deionized) water or antifreeze coolant No. 63616 from Bel-Ray Co., Farmingdale, N. J., or equivalent. For XE 20000 C, XE 20000 D: 4.5 to 5.5 gallons/min. (17–21 liter/min.) through both electrodes in series. Required inlet pressure: 140 psi (9.5 atm.), outlet pressure: 20 psi (1.4 atm.). The cathode can be cooled separately at 3 gallons/min (11.4 liters/min.). For XE 32000 D: Minimum flow rate through lamp electrodes 5 gallons/min (19 liters/min.). This minimum flow rate shall be obtained at a minimum inlet pressure of 150 psi (10.2 atm.) and a minimum outlet pressure of 30 psi (2.05 atm.).

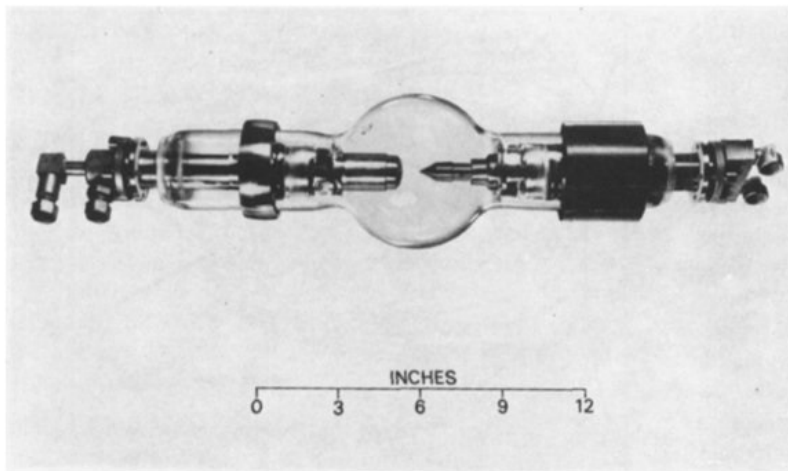


Figure 1. 20 kW xenon compact arc lamp with liquid-cooled electrodes for searchlights (type XE 20000 C).

num and, therefore, inaccessible. However, in the laboratory, the connectors with the attached coolant injector tubes can be taken off by cutting the screws. Thus, the internal electrode surfaces, especially the critical inner front surface of the anode, can be inspected and cleaned without destroying the lamp. The advantages of this arrangement will become clear in the next paragraph.

The first lamps equipped with the new connectors and support rings passed most of the prescribed optical, environmental and reliability tests. However, when standard antifreeze coolant (ethylene glycol—water mixture) was used during the life test, the performance of the anode indicated a problem area. Anode design and coolant properties required improvements as described in the next paragraph.

Anode Design and Coolant Problems

The anode tube of the earlier described 20 kW lamp design¹ consisted of a 1.250 inch (3.17 cm) diameter molybdenum rod hollowed out to a flat front surface approximately 0.200 inch (0.51 cm) thick. To this front surface was brazed with platinum the actual anode, a massive tungsten cylinder of nearly the same diameter as the molybdenum tube, 0.750 inch (1.9 cm) long with curved front surface. At the 20 kW input level, with currents of 445 to 485 amperes, the tungsten anode body assumed temperatures from approximately 900°C at the rear surface to about 2700°C at the front in contact with the arc discharge. It reached this high temperature range because of the relatively poor heat conduction to the coolant through the platinum braze and the molybdenum front surface of the anode tube.

The high operating temperature indicated that the anode was only partly cooled by the flow of liquid and partly also by radiation. This had the advantage that the anode was insensitive to accidental overloads and to temporary reductions of the coolant flow. In such cases, a surface layer of tungsten at the center of the front surface would melt temporarily, but no serious damage would result if the overload was of short duration. However, two disadvantages of this anode structure became gradually apparent:

At the high operating temperature in the front region the tungsten evaporation led to bulb blackening and occasionally destructive cracks developed after longer op-

erating hours. Also, it was not possible to regularly obtain the required full surface coverage of the platinum braze between tungsten and molybdenum.

For these reasons, a modified anode design was developed that proved to be largely free of the explained problems. Fig. 2A shows the new anode structure in cross section. The bottom of the molybdenum tube has been removed, the tungsten block is platinum-brazed only to the front edge of the open tube. The molybdenum tube bottom is replaced by a meniscus-shaped layer of copper. This copper layer is produced by a casting process under vacuum; it is, therefore, vacuum-tight and in direct thermal contact with the tungsten block safely over the entire surface.

In this arrangement, only the thin layer of copper separates the cooling liquid from the tungsten anode body. This is cooled effectively and the operating temperature of its front region is lowered to approximately 1900°C. While it is difficult to determine the anode front temperature directly, essential changes in this temperature

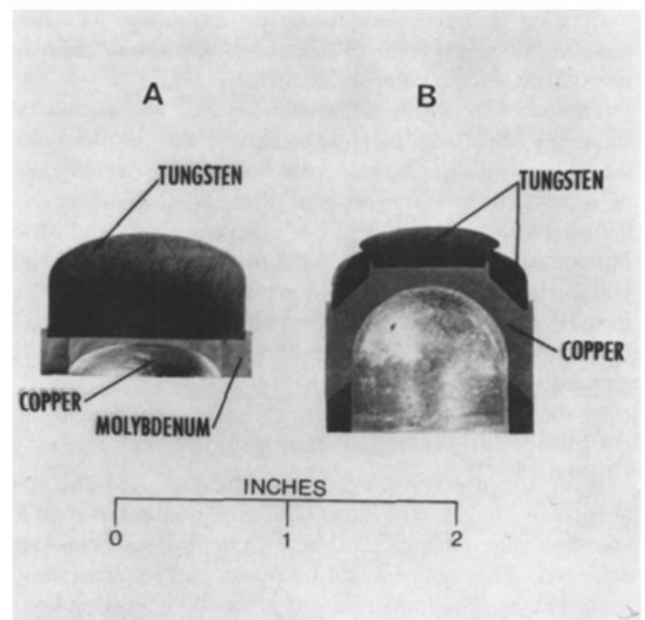


Figure 2. Cross sections of anodes for high power xenon compact arc lamps. A: Anode of 10 to 25 kW lamp types. B: Anode of 700-ampere lamp.

can be recognized easily through measuring the time from an instantaneous power interruption to the moment when the visible incandescence of the anode disappears. This "anode cooling time" was about four seconds for the earlier anode design and about 1.7 seconds for the new anode. In order to pass the 800-ampere five-second overload test the anode thickness was later reduced by 0.125 inch (3.18 mm). This lowered the front temperature further by 250 to 300°C and shortened the cooling time to approximately one second.⁷

The new anode structure has proved to be of great advantage both from the point of view of reproducible manufacture and concerning occurrence of cracks. Because of the lower operating temperature the latter have become rare even after long hours and repeated temporary overloading. However, the lower front temperature, accompanied by the use of the low melting copper as vacuum-tightening layer, has made the anode structure more sensitive to irregularities in the coolant flow. It is much more dependent upon undisturbed heat transfer between coolant and inner front surface than the earlier anode design.

The new anode operated without damage well beyond the required 400 hours life with deionized water as coolant. However, difficulties appeared when tap water or standard ethylene glycol—water antifreeze mixture were used. The anode operating temperature, clearly measurable through the cooling time, increased relatively fast, indicating reduced heat transfer between coolant and internal copper front surface. Access to this surface for examination is fortunately possible without destruction of the lamp. A relatively thick layer of foreign, apparently heat transfer impeding material was discovered both when tap water and when ethylene glycol—water mixture was used. Analysis of the material deposited by the antifreeze coolant proved it to be predominantly metallic, consisting of nearly all metals occurring in the coolant circulation system. It is assumed that the ethylene glycol, through its contact with the hot anode and other effects, undergoes changes that result in dissolution of small amounts of metal from the cooling system and their deposition on the hot inner anode surface.

The problem of internal anode deposits was serious because the use of an antifreeze coolant is essential for many lamp applications. It was solved through development of a new proprietary coolant, designated Bel-Ray No. 63616. This consists basically of ethylene glycol and water but contains additives with foam depressing, anti-oxidant, and surfactant properties, which effectively prevent the formation of internal anode deposits, at least over periods of 200 to 400 hours. It is usually feasible to renew the recirculating coolant within such intervals.

Achieved Lamp Characteristics

With the described anode modification and the new antifreeze coolant the lamps have consistently met all specified requirements. Table I gives in detail the data achieved. They considerably surpass the required minimum values. The lumen output after 400 operating hours (480 starts) has been measured on nine lamps, resulting in an average of 822,000 lumens. This means that the average drop in lumen output after 400 hours was only 6.3 per cent of the initial value.

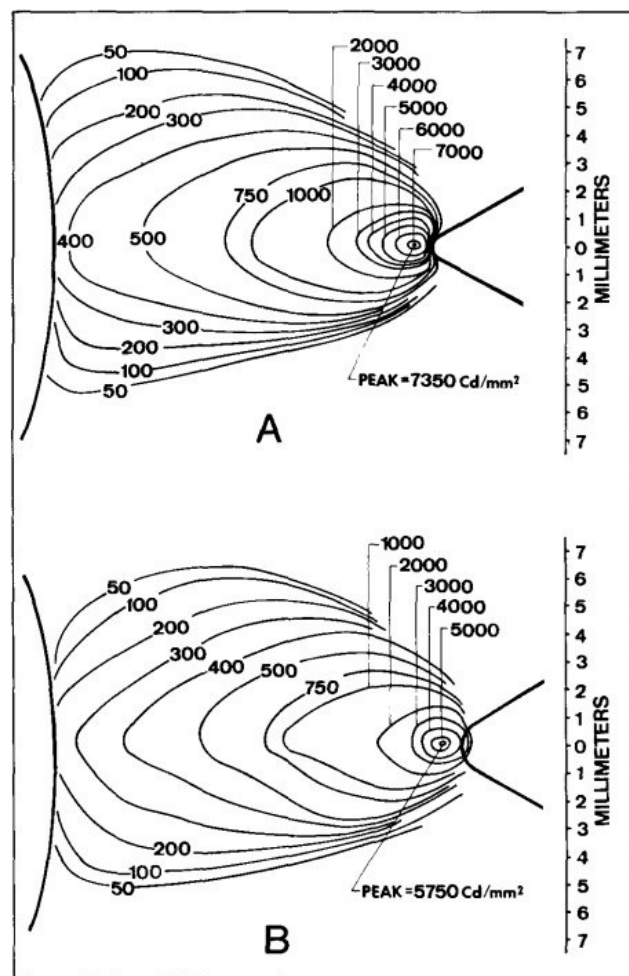


Figure 3. Luminance distributions of 20 kW xenon compact arc lamp XE 20000 C. A: From lamp with less than 10 operating hours at 465 amperes (measured at 45.2 volts, 21 kW, 13.3 mm operating arc gap). B: From lamp with 400 operating hours (480 starts) at 465 amps (measured at 44.6 volts, 465 amps, 20.7 kW, 14.2 operating arc gap).

These lumen outputs appear relatively low when compared to values published elsewhere. The lumen data reported here have been obtained in a five-foot (1.52 m) diameter sphere photometer calibrated with a 2000-watt incandescent projection lamp lumen standard operated at 2870K color temperature from the National Bureau of Standards. No other more suitable standard seems to be available. The authors are under the impression that discrepancies in the results of lumen output measurements on high-wattage xenon lamps can easily be caused by the method of photometer calibration. It is unlikely that the luminous efficacy of arc discharges in pure xenon could be increased or decreased as long as operating pressure, electrode configuration, and electrical conditions remain the same.

Fig. 3 shows luminance distributions. They have been measured on single randomly selected lamps and do not represent averages. Fig. 3A is the luminance distribution of a new lamp while Fig. 3B gives the luminance contour diagram of a lamp with 400 operating hours (480 starts).

Approximately 600 lamps of the type XE 20000C have so far been produced. 85 of these lamps were used in a particular, well supervised installation. Their perform-

ance can be judged on the basis of available reports summarized further below in this paper.

Type XE 20000 D for Solar Simulators

This lamp type is equal to the XE 20000C in basic design and internal construction. The connecting and supporting parts are different because they have been adapted to the requirements of solar simulator systems. Efforts have been made to meet with this lamp the tentative specifications drawn up as "Joint Industry/Government Standard (JIS) for 20 kW Xenon Compact Arc Lamp" on January 17, 1968 by the leading builders and users of solar simulators.

Lamp Dimensions, Supporting, Prefocussing, and Connecting Elements

Fig. 4 gives the appearance of the XE 20000D lamp. Its main burning position is vertical with anode up but it can be tilted by an angle down to horizontal position. The lamp is considerably shorter than the XE 20000C type. The circular end plates have a diameter of 2.750 inches (6.98 cm); they are designed and dimensioned according to the Joint Industry/Government Standard and serve as combined electrical and coolant connectors. The cathode end plate also serves as main lamp support and as prefocussing element. Shock and vibration absorbing cushioned supports seem to be unnecessary in solar simulators because they are stationary installations. The cathode tip is adjusted to 9.250 ± 0.040 inches (23.5 ± 0.10 cm) axial distance from the cathode end plate and is centered with respect to this end plate within 0.020 inch (0.508 mm) maximum deviation. If the lamp is fastened rigidly in the equipment by the cathode end plate, the anode end plate has to be supported with sufficient flexibility to avoid thermal and mechanical stresses in the lamp both under non-operating and under operating conditions. The cooling requirements are stated in Table I.

Electrical and Optical Lamp Data

The main electrical and brightness data are listed in Table I. The lamp can be operated with steady arc at any input between 10 and 25 kW. Its expected life is 500 hours when operated up to 20 kW, 250 hours when operated at higher wattage.

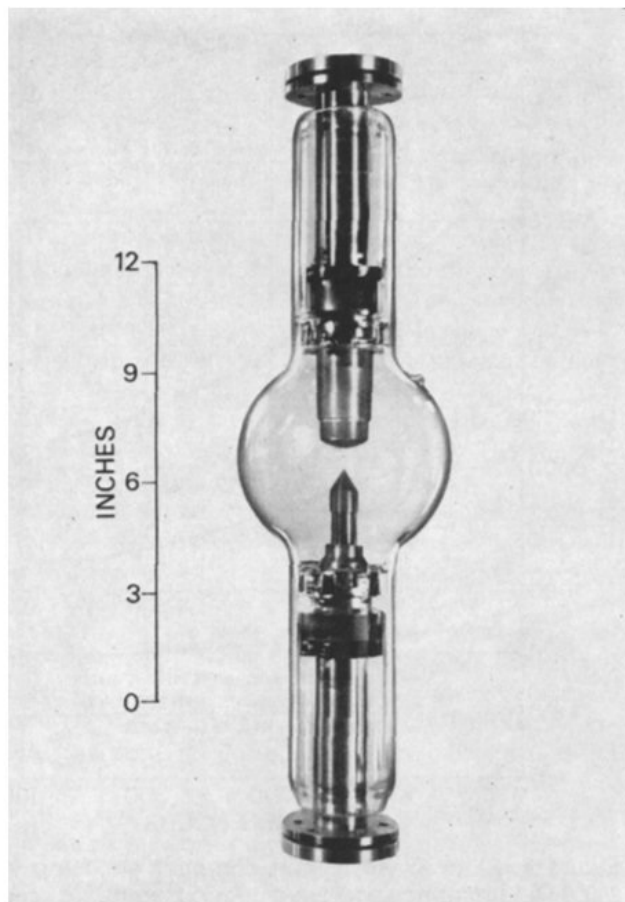


Figure 4. 20 kW xenon compact arc lamp with liquid-cooled electrodes for solar simulators (type XE 20000 D).

All XE 20000D lamps undergo the tests for optical bulb quality described for the XE 20000C. Fig. 5 supplies brightness distribution contour diagrams of a randomly selected lamp. Fig. 5A gives the values obtained at 20 kW input, Fig. 5B those measured at 25 kW. Fig. 6 shows the maintenance of arc luminance over lamp life at an input power of approximately 24 kW. The luminance values are given as averages over three different arc areas in front of the cathode. Fig. 7 shows the polar distribution of the radiation output in watts per steradian averaged from six lamps measured at 18 kW input.

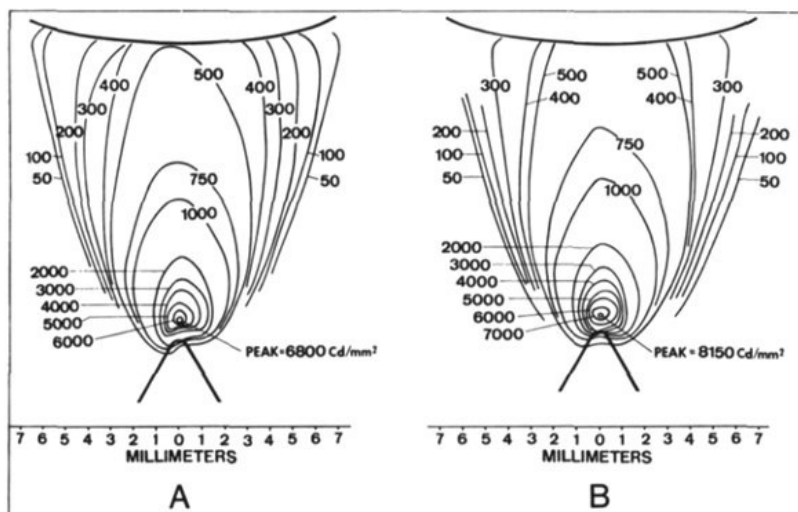


Figure 5. Luminance distributions of 20 kW xenon compact arc lamp XE 20000 D. A: From lamp with less than 10 operating hours at 20 kW (measured at 44 volts, 455 amps, 20 kW, 12.6 mm operating arc gap. B: From the same lamp at 25 kW (47.5 volts, 525 amps, 12.4 mm operating arc gap).

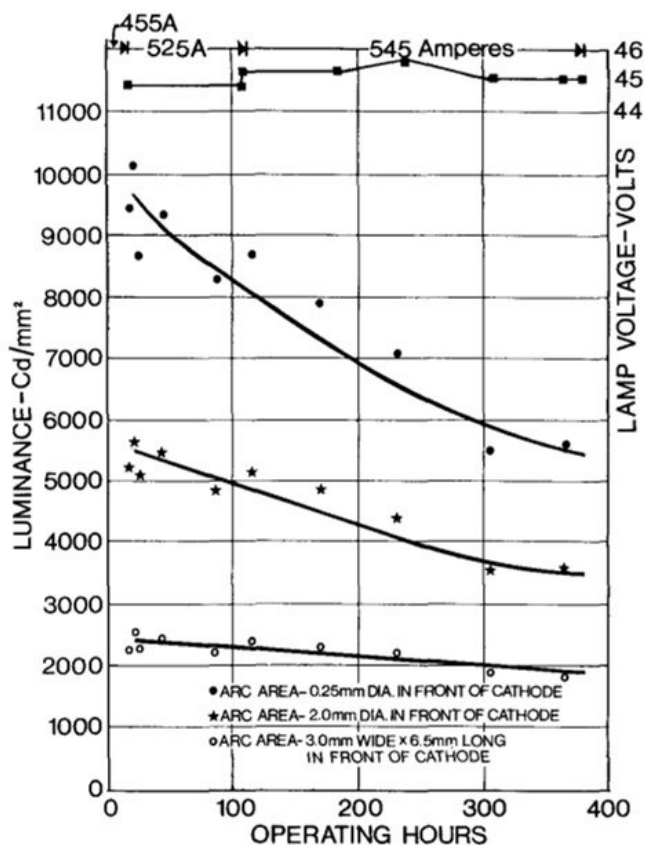


Figure 6. 20 to 25 kW xenon compact arc lamp XE 20000 D. Luminance averaged over different arc areas at cathode as a function of lamp life; operating arc gap: 11.8 mm (.466 inches); burning position vertical anode up.

50 Searchlights for Floodlighting at Kennedy Space Center

The usefulness of a light source largely depends upon the reliability of its practical performance. New lamp types in small and medium wattages usually come into production in relatively great numbers and statistical data on their reliability can be obtained at reasonable expense both in the laboratory and in field use. For an intricate high powered unit like the XE 20000C xenon compact arc lamp, it is much more difficult and costly to obtain statistically conclusive performance data. For-

tunately, a relatively large number of these lamps have come into use in a well supervised installation, and reports on their performance over three years have been made available.⁸

Fifty wheel-mounted general purpose searchlights with 30-inch (76 cm) diameter reflector, equipped with 20 kW xenon lamps are at Kennedy Space Center, Florida, for launch vehicle and launch pad illumination.⁴ They were first used in 1968 during launch preparations for the Apollo 8 moon flight.^{9,10} At the Saturn V launch complex the searchlights are located in five different arrays approximately 1000 feet (305 m) from the launch pad; Fig. 8 shows them in operation. They provide an illumination level of 125 to 175 footcandles (1350 to 1880 lx) over the entire surface of the launch vehicle and 90 to 140 footcandles (970 to 1500 lx) on the launch tower swing arms and the fuel lines in the back of the tower. This illumination is required for television and photographic coverage during nighttime test and fueling operations. The system had to operate continuously over longer periods up to a maximum of 77 hours.

Eighty-five lamps of the XE 20000C type were used until September 17, 1971. Thirty-one of these are still operational in searchlights. They have accumulated an average of 418 operating hours per lamp without any apparent reduction of searchlight beam candlepower. The remaining 54 lamps had to be replaced for the following reasons:

Thirty lamps have begun to emit radio frequency interference signals after an average of 503 operating hours per lamp; they are still operational and meet the specified requirements but cannot be used at Kennedy Space Center because radio interference is not acceptable there.

Four lamps do not ignite after an average of 688 operating hours; 10 lamps have developed leaks after an average of 463 operating hours; four of the failures were at under 400 hours.

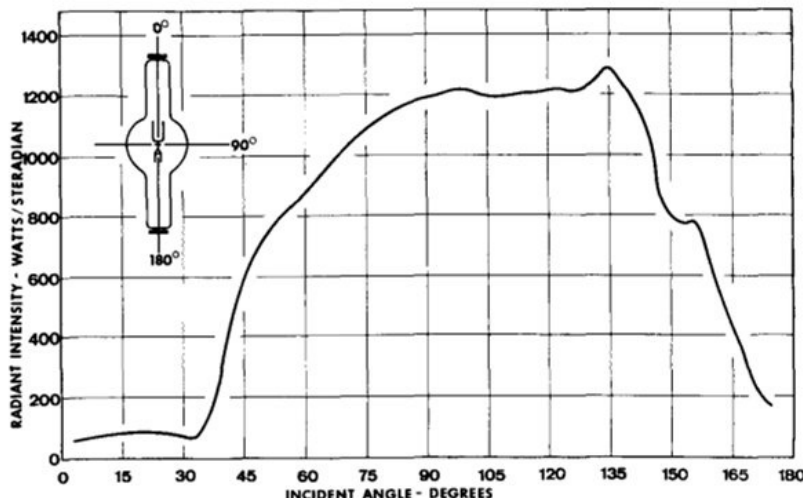
Two lamps exploded non-operating at two and 238 hours.

Two lamps exploded in operation at 17 and 1352 hours. Five lamps developed anode failures; three of these were at under 400 hours.

One lamp was broken during a lamp change.

In summary, of 85 lamps 10 have so far failed before 400 hours. The average life for all lamps cannot be de-

Figure 7. 15 to 25 kW xenon compact arc lamp for solar simulation (type XE 20000 D). Polar distribution of radiation output (average from six lamps, measured with DR2 thermistor radiometer of TRW at 18 kW input).



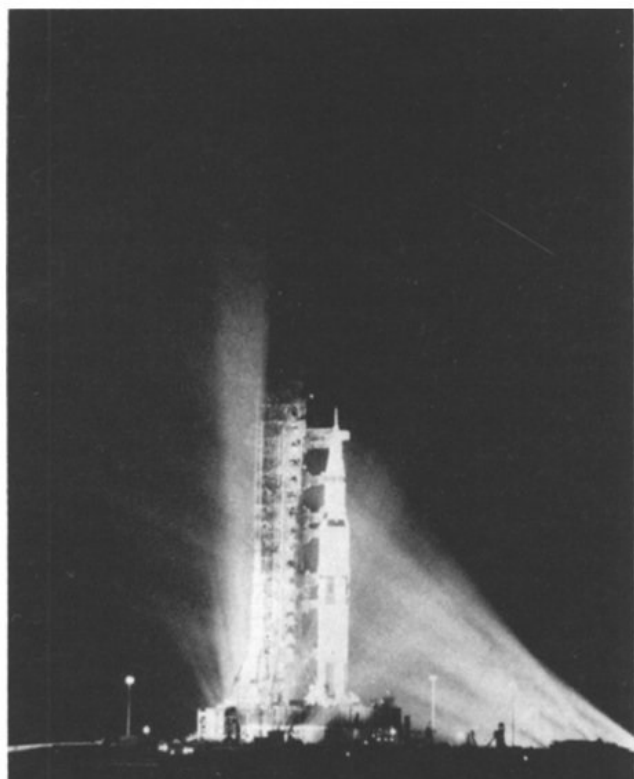


Figure 8. Floodlighting installation at Kennedy Space Center in operation during launch preparations for Apollo moon flight; approximately 50 30-inch (76 cm) searchlights with 20 kW xenon compact arc lamps type XE 20000 C produce over 100 footcandles on rocket-spaceship assembly, launch tower swingarms and fuel lines.

terminated yet because 31 lamps are still operational; it is certain, however, that it will surpass 480 hours because this value had been reached in September 1971. Twenty-eight lamps so far have been operated over 600 hours and 10 lamps over 800 hours.

700 Ampere Lamp (Type XE 32000 D)

For the desired extension of the power range of xenon compact arc lamps to 30 and 35 kW (corresponding to 600-700 amperes operating current) a considerable improvement of the anode design is necessary. If anodes of the construction shown in Fig. 2A are operated at currents in the 600 to 700 ampere range cracks develop in the front part of the tungsten body. These cracks appear usually after 70 to 100 hours of operation and lead to anode failure within the following 10 hours.

The cracks in the tungsten body are caused by thermal stresses that exceed the strength of the material when the current is increased from the 450/525 ampere into the 600/700 ampere range. The thermal stresses increase linearly with the power input into the anode. The power enters the anode body mainly through the small circular area of approximately three mm radius around the arc axis on the front surface.¹¹ Fig. 9A schematically indicates the locations of the cracks. Radial cracks mostly begin to appear at the periphery of the front surface and gradually extend inwards. Generally, radial cracks do not impede the heat transfer to the coolant and are not destructive as long as they do not lead to leaks in the anode

assembly. More detrimental are cracks that appear as approximately circular on the surface and regularly extend into the tungsten body as indicated in Fig. 9A. They usually appear in the area between 0.4 and 0.7 of the full anode radius and are very destructive because they directly hinder the heat transfer between impinging arc plasma and coolant.

In order to understand the regular pattern of developing cracks, it is useful to determine the thermal stresses to be expected in a tungsten body like the used anodes. Fig. 9B indicates how the actual anode shape has been approximated for this purpose by a sphere sector of inner radius r_i (=3 mm) and outer radius r_o (=16 mm). The thermal stresses in such sphere sector can be calculated with equations developed for determining the thermal stresses in quartz lamp envelopes.¹²

As a result of the calculations the approximate pattern of thermal stress distribution shown in Fig. 9C is obtained. The thermal stresses are not given quantitatively because their values strongly depend upon anode dimensions and heat load; also, the material constants of tungsten, especially their variation with temperature, are not known well enough to determine the stresses with sufficient accuracy. However, the qualitative stress pattern sufficiently explains the pattern of developing cracks. The tangential stress component is positive and largest at the outer radius and thus causes the regularly observed radial cracks. At approximately half the anode radius the tangential stress becomes zero. This explains the absence of radial cracks in this area. Toward the center of the anode surface the tangential stress grows to high negative or compressive values, explaining the occasional occurrence of radial cracks there. The radial stress component is entirely compressive and disappears at the periphery and near the center of the anode surface. It is relatively great between 0.3 and 0.7 of the full radius. As it must be considered as the cause of the circular cracks, the regular appearance of such cracks in this area is understandable.

The numerical values of the stress components—as

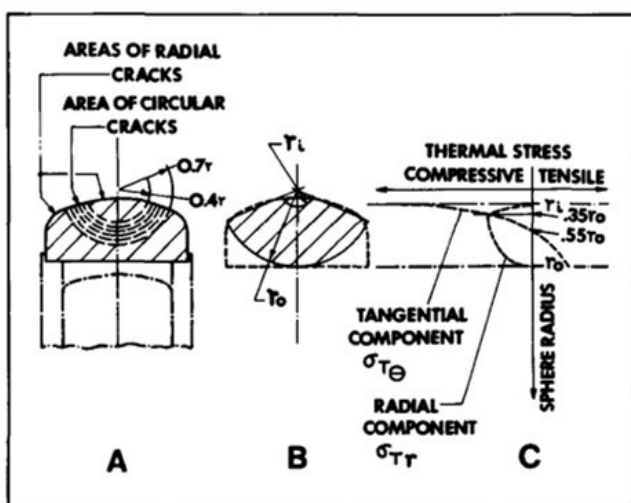


Figure 9. Liquid-cooled tungsten anodes for high wattage xenon compact arc lamps. Thermal stresses during operation can cause cracks. A: General location of radial and circular cracks. B: Sphere sector used for estimating thermal stresses. C: Approximate pattern of thermal stress distribution.

far as they can be determined with the available data of tungsten—seem to confirm the experimental experience. At the heat input corresponding to currents in the 450/525 ampere range the tungsten material is strong enough to withstand the thermal stresses without cracking. The stresses increase in direct proportion to the heat input which essentially is proportionate to the arc current. When this is raised into the 600/700 ampere range the material cannot sustain the stresses over longer periods and cracks develop in the locations of greatest stress. The lamp operating time after which these cracks appear is generally between 70 and 100 hours, when a 50 minutes on, 10 minutes off switching cycle from no load to full load (and conversely) is employed. If lamps are operated over longer burning periods per start the damage at the anode tips may occur much later during life.

The described results led to the idea of constructing an anode with a main body of copper and a tungsten front piece which is divided into several parts by narrow crevices where the destructive cracks usually appear. The crevices have to be filled with relatively elastic but sufficiently refractory metal and thus prevent development of excessive thermal stress.

According to this concept the anode construction shown in cross section in Fig. 2B was developed. It consists of a relatively thick copper body that is faced with a relatively thin tungsten front piece. The tungsten front is divided into a center part of approximately 0.6 of the total diameter and a ring surrounding this center part. The circular crevice between center part and ring is filled with platinum. The center part extends mushroom-like over the crevice in order to protect its filling from direct contact with the fringes of the impinging hot arc plasma. Both parts of the tungsten front are embedded into the anode body of copper by vacuum casting.

The described anode construction seems to combine the advantages of pure copper and pure tungsten anodes and appears to overcome many of their disadvantages. One-piece tungsten anodes develop cracks at higher input levels as discussed in preceding paragraphs; copper anodes tend to lose their mechanical stability, require relatively intricate internal cooling channel arrangements, and are sensitive even to very short periods of accidental overloading or coolant flow interruption. Fox, Thomsen and Schmidlein have discussed the properties of many different anode designs in detail.¹³ Several other authors have reported experimental and theoretical studies concerning anode design concepts.¹⁴⁻¹⁸ Most of their work is also directed toward extending the power range of xenon compact arc lamps into the 30-35 kW range. The authors have made experiments in similar and other directions. They found the "divided" tungsten anode construction to be the most promising for meeting the requirements of reliable lamp operation up to 700 amperes.

Experimental lamps with "divided" tungsten anode according to Fig. 2B were operated at currents in the 600/700 ampere range for more than 300 hours (50 minutes on, 10 minutes off no load to full load switching cycle) without the appearance of cracks in the tungsten parts. However, the useful life of such lamps was usually terminated by a gradually-increasing deposit of copper on the bulb. This copper evaporated from the exposed copper parts of the anode. Therefore, the "divided" tungsten

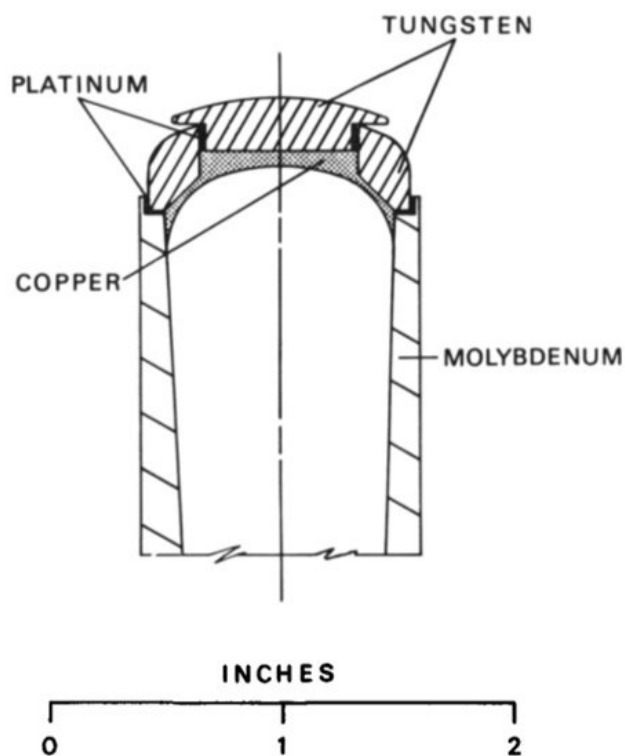


Figure 10. Cross section of "divided" tungsten anode for 700-ampere xenon compact arc lamp (type XE 32000 D).

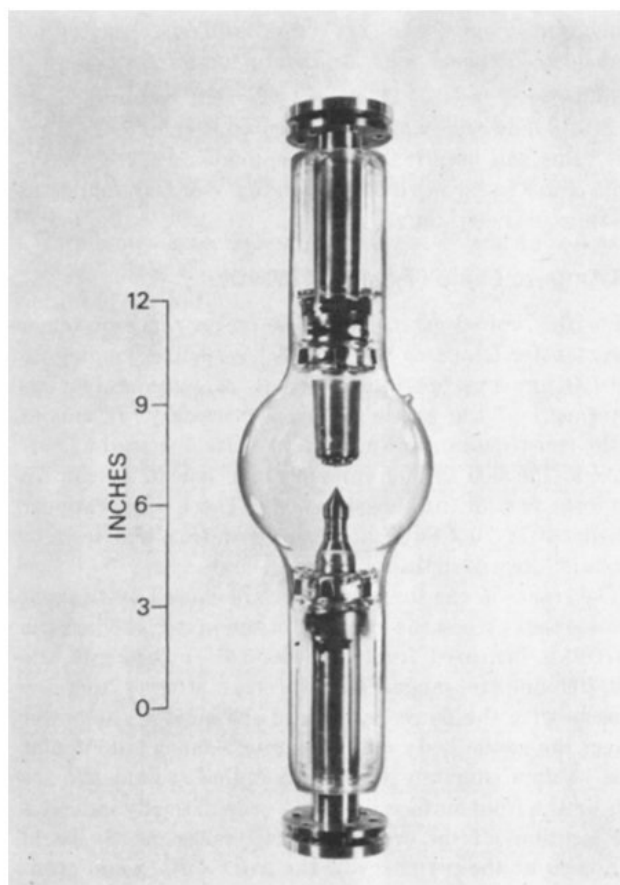
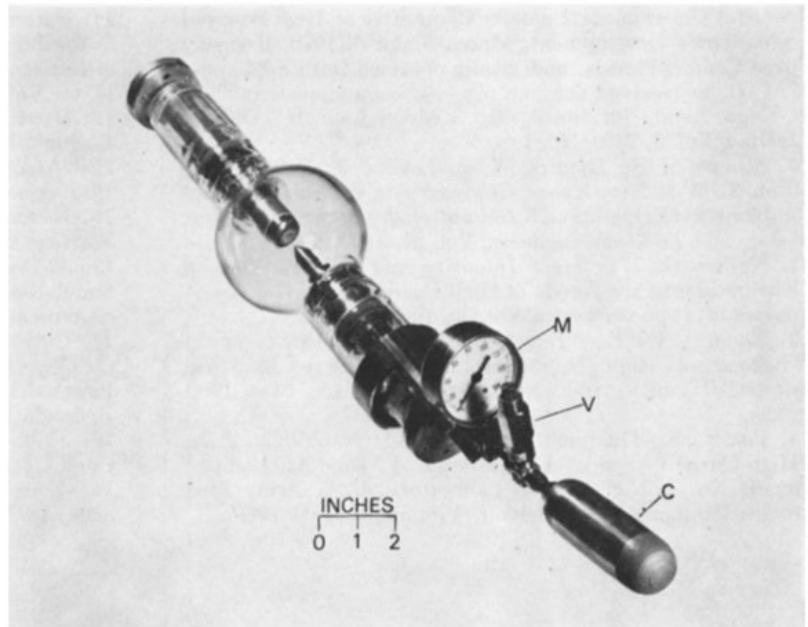


Figure 11. 700-ampere xenon compact arc lamp with liquid-cooled electrodes (type XE 32000 D).

Figure 12. 20 to 25 kW xenon compact arc lamp (type XE 20000 D) equipped with depressurization elements. C: high-pressure gas container; V: high-pressure valve; M: pressure indicator.



anode design of Fig. 2B was replaced with the modified construction shown in Fig. 10, which has no exposed copper parts.

Fig. 11 shows a "700 ampere" lamp with the described "divided" tungsten anode. The cathode of this lamp has a relatively short tungsten shaft embedded into copper by vacuum-casting for more efficient heat removal and better maintenance of the cathode tip angle at the high operating current. The combined electrical and cooling connectors of this lamp conform with the Joint Industry/Government Standard for solar simulator radiation sources. Its main data are given in Table I.

Depressurization

High power xenon compact arc lamps have at room temperature a gas fill pressure of at least three atmospheres (44 psi). Therefore, a safety hazard exists when lamps have to be handled or adjusted in the optical equipment after removal of the generally supplied protective case. In order to eliminate this hazard, it has been suggested by users of solar simulators and searchlights to provide lamps with depressurization facilities.

These usually consist of three parts:

- (1) a high pressure gas container of small dimensions connected to the lamp's inner volume through narrow metal tubing,
- (2) a vacuum-tight high pressure valve for closing the gas container,
- (3) an indicator, e.g. a manometer, allowing to recognize whether the lamp is pressurized or not.

For depressurization, the fill gas is condensed at least partly into the gas container by means of liquid nitrogen and the valve is closed. Pressurization is achieved by opening the valve.

Fig. 12 shows a lamp of the type XE 20000D with depressurization elements. The other lamp types described in this paper can be similarly equipped, if the additional costs are considered justified by the greater margin of safety obtainable.

Acknowledgments

The authors gratefully acknowledge the valuable interest and assistance of Messrs. W. Ramaccia, H. A. Anderson, L. Thorington, A. P. Wasdyke, Jr., D. H. Trutner, T. W. Hunt, J. Beerman of Duro-Test Corporation. Mr. S. F. Cortorillo, now with ITT Electron Tube Division, Easton, Pa., contributed strongly to the reported work. The authors appreciate the advice and guidance from Messrs. J. Bailey, R. O'Neill, J. D. Pennington, S. M. Segal, S. B. Gibson, C. S. Fox of U. S. Army Electronics Command, Night Vision Laboratories, from Messrs. C. A. Starks, R. J. Ayling, The Strong Electric Corporation, Toledo, Ohio, manufacturer of the 30-inch searchlight, and from Messrs. J. W. Yerkes, F. N. Benning, W. Quillin, T. L. Hershey, J. N. Lovelady, Spectrolab, Sylmar, Calif., Division of Textron, Inc. Spectrolab also contributed polar distribution measurements. Messrs. L. Finch, J. Lutick, F. Lindsay, P. Saulnier, L. Costello, J. Rosete, J. Garofolo, C. Gautier, T. Hicks, and Mrs. M. Johnson of Duro-Test participated in making and testing lamps.

References

1. Thoutet, W. E., Strauss, H. S., Cortorillo, S. F., Kee, H., "High Brightness Xenon Lamps with Liquid-Cooled Electrodes," *ILLUMINATING ENGINEERING*, Vol. LX, May 1965, p. 348.
2. Lienhard, O. E., "Xenon Compact Arc Lamps with Liquid-Cooled Electrodes," *ILLUMINATING ENGINEERING*, Vol. LX, May 1965, p. 348.
3. Military Specification SCS-372 of 15 April 1970 on Lamp, Xenon Arc, Two Million Lumens.
4. Freeman, R. S., Ayling, R. J., "Xenon Arc Searchlight Illumination of the Appolo 8 Launch Areas," *Journal of the Society of Motion Picture and Television Engineers*, Vol. 79, 1970, p. 313.
5. Military Specification for Lamp, Xenon, Short Arc, 10/15/20 kW, MIL-L-55574(EL), dated 15 February 1968.
6. Military Specification for Searchlight, Xenon 10/15/20 kW, 30-Inch Diameter, Wheel Mounted: MIL-I-55573.
7. Strauss, H. S., "Design and Performance of 20 to 25 kW Xenon Compact Arc Lamps," Report for Conference of Government/Industry Committee on High Powered Light Source Development, March 5 and 6, 1970, Kennedy Space Center, Florida.
8. Hand, L. J. and Niles, C. B., "Usage of 20 kW Short Arc Xenon Lamps at Kennedy Space Center," Report for Con-

ference of Government/Industry Committee on High Powered Light Source Development, March 5 and 6, 1970, Kennedy Space Center, Florida, and results obtained until September 17, 1971, as received through personal communication.

9. "New Lights for the Apollo 8 Moon Launch," *Outdoor Lighting*, Vol. 9, 1969, No. 1, p. 4.

10. Strauss, H. S., Thouret, W. E., Leyden, J., Kee, H., and Hunt, T. W., "New Xenon Compact Arc Projection Lamps for Horizontal Operation," *Journal of the Society of Motion Picture and Television Engineers*, Vol. 81, 1972, p. 33.

11. Nestor, O. H., "Heat Intensity and Current Density Distributions at the Anode of High Current Inert Gas Arcs," *Journal of Applied Physics*, Vol. 33, 1962, p. 1638.

12. Thouret, W. E., "Tensile and Thermal Stresses in the Envelope of High Brightness High Pressure Discharge Lamps," *ILLUMINATING ENGINEERING*, Vol. LV, May 1960, p. 295.

13. Fox, C. S., Thomsen, M. P. R., and Schmidlein, J. A., "High-Current Anodes for High-Powered Xenon Arc Lamps," Report No. 4, Night Vision Laboratory, U. S. Army Electronics Command, Fort Belvoir, Virginia, August 1969.

14. Bartera, R. E., "Recent Solar Simulation Developments at the Jet Propulsion Laboratory," *Proceedings of the Institute of Environmental Sciences*, 13th Annual meeting, Washington, D. C., Vol. 2, 1967, p. 681.

15. Lunde, A. R., Yerkes, J. W. and Haslund R. L., "The Boeing 20-Foot Solar Simulator," Progress Report ASTM/IES/AIAA Second Space Simulation Conference, September 1967. American Society for Testing Materials, 1967.

16. Nakamura, Y., Onishi, Y., and Shimizu, Y., "High Wattage Xenon Sort-Arc Lamps with Seals and Improved Liquid-Cooled Electrodes," AIAA/ASTM/IES Fourth Space Simulation Conference, September 1969. American Institute of Aeronautics and Astronautics paper No. 69-998.

17. Cutchall, C. M., "35-kW Lamp Progress," ITT Report for Conference of Government/Industry Committee on High Powered Light Source Development, October 7 and 8, 1971, Redonda Beach, California.

18. Malloy, J. J. and Fox, C. S., "Development of a High Power High Reliability Short-Arc Xenon Radiation Source," IES-NASA/AIAA/ASTM Sixth Space Simulation Conference, April 30 to May 3, 1972, New York, N. Y.