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12484 GLADSTONE AVENUE, SYLMAR, CALIFORNIA

EMPIRE 5-4623 TWX: 213-764-5923

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Title: EVALUATION AND TEST OF XENON LAMPS (PHASE IV)

Written By: T. L. Hershey
F. N. Benning

Approved By: F. N. Benning
Program Nanager

Approved By: E. L. Ralph, Manager
Research & Development

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I INTRODUCTION TO VOLUMES I & II

Contract History

The study of anode history in high powered xenon arc lamps came about as a result of the NASA/MSC and USAF/AEDC interest in such lamps for use in solar simulators for large area thermal vacuum testing of space vehicles.

During the performance of USAF/AEDC contract #AF 40(600)-1140, the short arc lamp was identified as an important component in the modular solar simulator. It had been found that the original carbon arc lamps which had been proposed for Mark I at Tullahoma, Tennessee and were in use in Chambers A & B at NASA/MSC did not possess the desired performance characteristics for high fidelity solar simulation. By converting to xenon arc sources, it was determined that optical performance could be improved and the stability and reliability could be vastly improved. However, the high powered xenon lamps required (near 20 KW input power) were only being built in small quantities, and accurate life data did not really exist to substantiate the reliability. In order to better define this important criteria, USAF/AEDC contract AF 40(600)-1140 was directed towards a multi-phased effort of evaluation and test.

The life test results at the end of Phase III of this contract were inconclusive and it was found that the mechanism of failure was not well known. While the lamps had shown greater than 200 hour life, there had been no apparent reason for failure. In the meantime, industry had also found some lamps running as long as 1,000 hours.

A contract modification was made to allow further study of the failure characteristics of the xenon lamps, with specific emphasis towards the water cooled anode problems. This phase was jointly funded by USAF and NASA/MSC. As the scope of this effort expanded and development problems arose, the limited AEDC funding did not allow completion of this phase. Subsequently, NASA/MSC funded under a separate contract NAS 9-9831, the continuation of the study.

While this report is really the final report under NAS 9-9831, the reporting under the previously USAF and joint USAF/NASA contract are referenced, and in some cases repeated herein in order to add clarity.

Scope of the Preceding Phases

Phase I resulted in report for AEDC "Research.....Lamps" dated 7 December, 1966. A summary of the work conducted in Phase I is as follows:

a. A xenon compact arc source working in conjunction with a collimating mirror system similar to that originally proposed for Mark I can be built that will satisfy the performance requirements originally specified for Mark I.

b. Such a system can be built without requiring major change to existing chamber and building structure.

c. The predicted input power requirements for the compact arc source are within existing state-of-the-art power levels.

d. While accurate and reliable data does not yet exist for arc lamps in this required power level, (below 20 KW) a reasonable projection of present experience would indicate that the lifetime of these sources would be in excess of 400 hours. Results from the testing phase of this contract are expected to provide further information on this subject.

e. For the compact arc module, a revision in the collimation angle from 1° to $1\frac{1}{2}^{\circ}$ is recommended because of the significant gain in the overall system efficiency.

f. In order to minimize interference with existing rib structure on the vacuum chamber, it is recommended that the module collimating mirror dimension be changed from 40.0 inches to 41.625 inches across the flats. Efficiency analysis indicates that the compact arc module will have sufficient energy to illuminate this larger area.

g. Pending satisfactory results of the life testing phase program, a compact arc modular solar simulator is the recommended approach to satisfy the AEDC Mark I requirements.

Phase II A lamp evaluation program restricted to a particular set of early developmental lamps from several manufacturers.

Phase III Life test program on a selected lamp. Parameters studies:

a. Degradation of lamp output with time

b. Spectral distribution

c. Polar distribution and integrated radiant power output

d. Micro-radiance distribution

e. Input current and voltage

f. Envelope temperature

g. Power dissipation in the electrodes

h. Intensity output in the spectral range for 0.38 to 1.1 microns.

Phase IV which will be covered in this volume was directed at the testing and evaluation of different anode configurations for 20 KW xenon arc lamps. These evaluations were used to determine performance characteristics for the lamp and to determine the failure mode, if possible. Special attention was given to the study of the thermal heat transfer characteristics for water cooled copper anodes for such lamps. A method to warn of impending failure of a short arc lamp prior to its demise was not perfected, however, a technique was developed which bears further investigation and promises to lead to a better understanding of the heat transfer properties and may offer a failure warning or malfunction alarm. During the final months of the contract, one lamp was successfully run for a brief period with minute thermocouples embeded within the anode shell. Further, an extensive data collection was made on a second lamp which operated over a wide range of power and anode coolant flow conditions.

II INTRODUCTION TO VOLUME I (PHASE IV)

This report covers the work accomplished under the National Aeronautics and Space Administration Contract Number NAS 9-9831 with the NASA Manned Spacecraft Center, Houston, Texas. The objective of the contract was to test and evaluate several different anode configurations for xenon short arc lamps. These evaluations were to be used to determine failure modes and performance characteristics for the lamp and anodes. The long run objective was to add to the technology and understanding of water cooled electrodes in high powered xenon short arc lamps towards improving the reliability and extending their useful life.

III TEST PLAN

An original premise established at the commencement of the contract was that high powered xenon short arc lamp failures were largely caused by thermal failure of the anodes; further, the proper shell thickness for optimum heat transfer in copper anodes was not known. Originally, the intent was to assemble as many lamp assemblies as possible during the course of the contract with three anode shell thickness specified in the basic contract to cover a broad range and the remainder to be sized based as the result of the tests of the previous anode thickness. Later, the contract was amended to emphasize the incorporation of the temperature measuring devices in the anode shells and to allow the number of anodes fabricated to be determined by funding and schedule constraints.

Lamps were tested in the vertical orientation in an open test cell with no collector or other obstructions present to perturb the operation of the lamp. A closed loop water system was used which was filtered to maintain a particle size of 5 microns or less throughout lamp operation. The ph of the water was maintained at 7 ± 0.5. The conductivity was maintained at less than 50 mho/cm. Due to the shortness of the test no determination on the amount of scale deposite or similar deposition was detectible. The coolant inlet pressure to the lamp had a maximum range of 300 psig. Continuous chart recording was made of three pressure values for the coolant, flow and the temperature differential between the inlet and outlet. The precision of these measurements was compatible with the recording device and the other instrumentation. The input water pressure for the anode was equal to greater than 200 psig where it was possible to obtain the desired flow (as the test was reduced in water flow rate the inlet pressure was reduced accordingly, to obtain the corresponding flow required).

The stabilization time required between power settings varied from one run to the next, therefore, the time to reach a stable value was observed by the operator on the continuous chart recorder before proceeding to the next point. Due to the instrumentation used, the power level was increased to 50 ampere steps in lieu of 1 KW steps. (The use of power steps would require a calculation while the adjustment was being made as the voltage and the current both vary with increasing power).

Any over-shoot would not be amenable to lowering as a possible hysteresis would probably develop; this has been shown in the past to happen with arc attachment on the cathode. In both cases where the lamp failed, the mode of failure was the observed formation of a crater accompanied by a molten condition of the anode tip.

IV LAMP SPECIFICATIONS AND CONSTRUCTION

Initially, attempts were made to fabricate copper anode shell by the conventionly method of stamping from soft copper stock and added the instrumentation after the desired shape was formed. Also, a technique was investigated to embed thermocouples within successive copper shells. However, this method did not warrant further consideration due to the thermal gradient uncertanties between the various shells.

All anodes were designed to be similar to Riise Anode as described in NASA Tech Brief 67-10247 dated November 1967. Figure I shows a cross-section of the lamps tested. X-rays were taken of the anodes after assembly and before installation within the lamp, however, due to the double radii of the inner constrictor and the similarity of the materials only qualitative conclusions could be made from the radiographs.

All interior surfaces were either machined to close tolerances or were formed by electrodepositing high purity oxygen free copper on a silvered substrate which examplified mirror like surface finish.

Initially, the plan was to fill the lamp envelope with a charge of xenon somewhat lower than the five atmospheres specified in the Statement of Work and upon a second filling increase the pressure to the five atmospheres. However, the intensity of the lamp on the first filling was of a sufficient high value to indicate that a second filling was not required. The arc gap after the final copper plate was 12.7 $\pm$.2 mm when assembled within the envelope with mechanical seals.

The envelope and end flange configuration conformed to the JIC specification control drawing #015564.

V SPECIAL INSTRUMENTATION

The original intent was to obtain temperature data in the interior of the anode to allow verification of the thermal analyses previously accomplished by others, Hornbaker and Ralls[1], and Hakala[2]. Unfortunately, insufficient data was obtained to warrant intense theoretical analysis of the few data points and the limited creditability of the data. Therefore, greater emphasis was placed on the remaining data specifically the flow, temperature differences, and radiant and other output characteristics of the lamp which did not have the thermocouples present. Appendix A is a copy of the paper presented at the IES meeting in Boston on April 12, 1970, and it summarized the difficulties encountered in the development of the attachment of thermocouples within the anode. Although, the problem was solved with the use of electrodeposition techniques there was insufficient time or funds remaining on the present contract to carry out the necessary fabrication and assembly, and testing of the finally developed lamp with eight thermocouples attached. In the data contained in Appendix B, one can see the limited thermocouple data listed under Lamp #2, Table B-7.

An infrascope was used which measured the temperature of the quartz envelope by viewing the quartz at an oblique angle and using as narrowband in the infrared spectrum. The temperatures of the quartz are tabulated in Appendix B-4.

On the Lamp #1, as seen in Table B-3, it was found that there was negligible heating of the lamp seals and the recording of this parameter was deleted to allow more important parameters to be continuously monitored.

The quartz envelope was photographed with a polariscope prior to acceptance. However, during the mounting and initial pumpdonw phase of the envelope with a graded glass seal, a highly localized stress was developed which caused a crack to develop and cause rejection of the envelope from further consideration. The other envelope has been viewed with polarized light since the operation on two different occasions and no noticeable stresses are present. This is as expected as the operation of the lamp is in a temperature range where little residual stresses should remain after any appreciable operation. Government furnished multichannel recorders are used to record continuously the following parameters which are also tabulated in Appendix B Tables; Lamp voltage, Lamp current, Xenon pressure within the lamp, Water flow within the anode, Radiant intensity, Temperature differential from the anode inlet to outlet, the water pressure, within the anode at three positions one at the tip, and one upstream 0.594 inch, and one downstream 0.594 inch.

Polar scans were made for each power level that the pump was operated at. This allowed the spatial variation of the arc to be studied as a function of power as were over an extended period of time. As mentioned above, the intensity was also recorded continuously by the use of a solar cell. This was to look at any short duration fluctuations of the intensity even though the spectral response of the solar cell was different than the DR-2 detector and solar cell which were used for the polar distributions.

During run 1 of Lamp #1, strain gauges were employed, however, little information could be gained from their application and it was determined that the discoloration to the quartz by the adhesive was a greater risk to the life of the lamp than the amount of information which may have been gained by its presence.

Also on the intial runs of the Lamp #1 in its first configuration, high speed motion pictures were made, subsequent photographs were made with the use of fast shutter still camera to determine the degree of arc wander present and only quantitative statements can be made.

In lieu of a small angle detector to measure polar intensity and iso-brightness profiles two other techniques were employed. First, a set of detectors were used for the polar intensity distribution which had a limited aperature. A set of these data are shown in Figures 12a to 12g in Appendix B. Additionally, a set of chemically sensitized paper was exposed to the projected image of the arc for varying periods of time for a set of power levels of the lamp and a quantitative measurement of the iso-brightness profiles was obtained.

VI DATA

The presentation of the data is in Appendix B with both a tabulated and graphically format which will allow a quick display of the relation of the various parameters one to another. The following brief discussion of the data and its reduction and collection will follow the same organization as in the appendix to minimize confusion on the part of the reader and allow ready cross reference.

Lamp #1 Run #1 & 2 (1968)

Table B-1 contains the summary of the data taken on the first lamp in the fall and winter of 1968. Lamp #1 (1968) was the first lamp successfully constructed using an electroformed copper anode shell with a laminated plating technique. The purpose was to insure that the copper deposition could be stopped to allow the addition of thermocouples and then the plating continued. The thickness of the anode shell after final assembly was 0.072 $\pm$ .002 inch. The construction of the anode and lamp is similar to that described in Appendix A except for the omission of the thermocouples. There were tow basic runs for data collection. One with the lamp at an initial fill pressure of 44.1 psi. This first run was for instrument checkout as well as to check the procedures for the filling of the lamp with the high purity xenon gas. After the lamp was run for a few minutes, the original charge of xenon was removed and a second charge at a much higher pressure was filled into the lamp. The second run was started at 6.66 KW and increased in approximately 1 KW steps until the power level of 14 KW was observed. At this point, high speed motion pictures of the arc was made to observe the stability characteristics of the arc as well as record the failure of the arc anode if it were to happen while the lamp was being run. From 14 KW to 21.42 KW the power was increased while the movies were continued to be made. At 20 KW, the acoustic detector first registered a sound which could have been boiling. It was periodic and seemed to follow the occasional anode arc foot wandering.

Quite suddenly molten balls appeared on the anode surface. The condition appeared to be worsening with time, but no conclusive evidence of true surface melting could be obtained. With the camera on high speed, the current was increased to 470 amps, 45.6 volts (21.43 KW) and held at that level to determine if evidence of melting occurred. The balls of molten material seemed to increase in density, but were more characteristic of cathode residue than molten copper. At any rate, the presence of this material made it extremely difficult to detetmine the exact point where melting occurred, if it occurred at all. In the absence of data from the narrow band microradiometer, it was determined that the run should be discontinued for lack of reliable melting data.

Lamp #1 (1969)

The next lamp which was tested was actually the same lamp as in the first runs as listed in Table B-1 through B-3. However, the same procedure was followed in the pressurization of the high purity xenon as was in the case of the anode with the thermocouples. This data is listed as Lamp #1 (1969) on the top of Appendix Tables B-4 through B-6. It is this data which are plotted in the Figures B-1 through B-12.

Lamp #2 (1969)

Tests on this lamp were conducted almost exactly one year after Lamp #1 (1968). Following the development of the method of attachment of the embedded thermocouples (as described in Appendix A), an anode assembly with .092 shell thickness was fabricated. Although four thermocouples were installed, at the time of final assembly, only three thermocouples were operational. It was this second set of data collection which the paper attached as Appendix A is making reference to. This data is listed in the last three rows of Appendix Tables B-4, B-6, and B-7 as Lamp #2. This lamp contained the same pressure port system within the anode cooling passage as the first lamp in addition to the thermocouples. However, only three data points were obtained on this anode prior to its failure.

VII RESULTS

In general, the results will be shown in the attached tables and figures and only the most general comments will be made. If a further continuation of the programs warrants the more detailed analysis, it will also include the data gathered here.

Table B-1 tabulates the voltage and current for the Lamp #1 (1968) which was the first to have the pressure pickup within the anode water flow. The envelope temperature, xenon pressure and a relative measurement of the intensity are also tabulated.

Table B-2 lists for the same run of the Lamp #1 (1968) the anode flow rate in gallon per minute, the inlet and outlet temperature as well as the difference from these values, the power absorbed within the anode water was calculated as well as the normalized power, i.e., the ratio of the power absorbed in the water to the total electrical power delivered to the lamp.

Table B-3 lists the flange temperature as measured with a thermocouple attached to the anode flange. The three pressure transducers were connected in such a way to record the inlet pressure to the near tip of the anode, the pressure at a hydrophone also near the tip of the anode and the pressure differential from the inlet to the outlet again in the vicinity of the anode tip. Also, listed is the cathode flow rate as well as the cathode inlet and back water pressure values.

Table B-4 lists the same values for the Lamp #1 (1969) which was the same lamp as tabulated in Tables B-1 to B-3 as well as the Lamp #2 which had the three thermocouples. However, six runs were made this time with four for the purpose of data collecting. The approach was to increase the heat flux into the anode (by decreasing the flow rate of the anode coolant) until the lamp failed. The purpose was to determine the actual point of failure and to note any indicators which may lead to a warning system in future lamps. This table lists the same properties as that in Table B-1.

Table B-5 lists the anode water flow rate, the temperature difference for the water flowing through the anode, and the calculated power absorbed within the water as well as the normalized power on a per input kilowatt basis. Additionally, the power radiated is estimated on a basis that exactly 9 steradians of the total 4π steradians through the quartz envelope and not absorbed by either the electrodes or the quartz (this value is probably good for most applicatons, particularly around the 18 or 20 KW range, however, as the power goes up, the efficiency changes and the use of the value in the 30 degree cone centered at the normal probably needs some correction. (This can be seen by totaling the power in Run at data point #7 which would indicate 109% total power for the system which does not include the 7 to 10 percent loss in the cathode heating). However, for comparative number, the relative value is acceptable. The normalized values are on a per kilowatt basis.

Table B-6 lists the pressure differential on the inlet and back pressure for the anode and the cathode as measured at the flange. Three water pressures are measured at the anode tip, one at a position 0.594 inch upstream of the tip, one at the tip and a third at the same distance downstream.

Table B-7 gives the thermocouple readings for the three thermocouples located within the anode shell. The values are in degrees centigrade and the location of the thermocouples are as follows: #2 was 0.020 inch from the interior of the anode shell as measured from the cooling water side and was centered on the axis of the electrodes. #3 was also 0.020 inch from the interior of the anode shell as measured from the cooling water side and 0.200 inch off the electrode axis at right angles to the direction of coolant flow. #4 was 0.020 inch from the exterior of the anode as measured from the arc (xenon) side and was 0.200 off the electrode axis in the direction of the coolant flow.

Figure B-1 is a composite of the voltage current and power for the Lamp #1 as run in 1969 from the data in Table B-4.

Figure B-2 is the composite of the four runs on the envelope temperature as a function of lamp power as measured with the infrascope.

Figure B-3 is the xenon pressure for the Lamp #1 which shows a close correlation between the runs number 3 and 5 as well as 2 and 7. However, no correlation between the two sets.

Figure B-4 shows the intensity over the 30 degree band centered normal to the electrodes axis. One should note the degrees in the intensity from one successive run to the next where chronologically the runs were in the order 2, 3, 5, and 7. There may be some correlation with the relative time of the run at the life of the lamp. However, probably not with the differing flow rates which the different runs actually depict.

Figure B-5 - this depicts the flow rate of the various runs for the different power levels. While the water flow rate was set at the onset of the operation of the lamp, when the power was increased the flow rate had a tendency to increase when the lamp power was reduced before shutdown (not shown), the water flow rate had a tendency to return to the original value set prior to the lamp operations. In future runs, the sensitivity of the flow measurement must be increased as the power into the anode coolant is directly dependent on the precision of the measurement.

Figure B-6 - the water temperature differential from the anode inlet to the outlet was measured by a system of three thermocouples in the inlet and three thermocouples in the outlet lines of the anode flow lines and the difference was measured electrically.

Figure B-7 shows the relationship between the power absorbed with the input power as a function of the various runs. The power absorbed was calculated from the product of the thermal capacity of the water, the flow rate and the measured increase in the temperature of the water.

Figure B-8 is a normalization of the preceding curves where the calculated value of power absorbed into the water was divided by the power input to the lamp. The units are thus kilowatts absorbed per kilowatt incident. One can see the range is between 28 to 38 percent absorbed.

Figure B-9 is the estimation of the power radiated in kilowatts with the following assumptions: the intensity averaged over the range from 75 to 105 degrees is similar to other lamps tested and summed over the complete range, that the total solid angle into which the lamp radiates is nine steradians, the view angle of the detector is not greatly affected when the lamp is operated at the product of nine steradians times the intensity. In the following paragraph, one can see how realistic the assumptions can be.

Figure B-10 - this is the normalization of the radiated power by the incident power level to the lamp. Here, as discussed earlier, one can see more dramatically that the percentage of power radiated, i.e., efficiency of the lamp, increases with increase in power. Nominally, the power radiated goes from the low 50 to low 60 percent level as the power of the lamp increases from 10 kilowatts to 28 kilowatts. (Again, the last point in the run #2 may well be out of bounds as the total energy for that one case, when added to the known power, absorbed in the water and the assumed 7 to 10% in the cathode cooling would total more than 100 percent.

Figure B-11 is a relatively "busy" graph, in that it contains all the data on the water pressure probes within the anode region for all four runs at all power levels. However, since no attempt at further reducing this data or showing its relevance to the other parameters by either calculation or similar means, the graphical dependance show many of the generalizations which could be drawn.

Figure B-12a through 12g is a set of polar distribution curves for the Lamp #1 (1969) run number 3. The plots are radiant intensity in watts per steradian as a function of polar angle (zero degrees corresponds to the anode and the 180 degrees in the direction of the cathode. The ordinate watts per steradian only applies to the curves plotted for the detector marked DR-2. Where the scale is marked with a 5 mv/div, a factor of two is required to read the intensity directly off the ordinate. The solar cell readings are not for absolute values and are for relative changes only. Due to the spectral response differences between the two detectors and the different time response, the two curves can be used to detect slight changes in the detection technique or other characteristics such as, temporal response of the polar scan arm if the scan is made too fast.

Figure B-13 is a photograph of the Lamp #1 (1969) immediately after shutdown after run when the power was shut off due to a small hole appearing in the anode tip. The lamp envelope filled with water until the pressure within the envelope came to equilibrium with the xenon pressure.

Figure B-14 shows a close-up picture of the anode of Lamp #1 showing the hole in the anode where the electron beam of the arc drilled a passage through the copper shell.

Figure B-15 shows the close-up picture of the anode of Lamp #2 (which had the thermocouples within the shell. This lamp was also shut down when a small hole appeared on the surface of the anode. The hole did not extend through the shell and therefore no water was present within the lamp envelope. However, the thermocouple leads did indicate the water had passed from the high pressure cooling channel within the anode into the air cavity which contained the thermocouple leads and prevented any further testing of this lamp.

VIII CONCLUSIONS

The method of embedding thermocouples within a copper anode shell has been perfected for at least three cases, and one anode underwent both calibration test up to 600 degrees centigrade and was measuring temperatures in excess of 200 degrees centigrade when failure occurred in the anode. The time response of the thermocouples was on the order of a few hundred milliseconds. A large quantity of data and a systematic approach of data collection and evaluation has been developed which would be of great value if future work were to be pursued in this area.

Although preparations were made for the analytical treatment of the temperature data within the anode, no attempt was made to analyze the limited data taken on the brief period of the Lamp #2. These techniques previously developed would be applied to any future effort where significant quantities of data were forthcoming.

For the lamp which had the water pressure probes and no thermocouples the following conclusions can be made:

a. The xenon pressure within the lamp behaves as shown in Figure B-3.

b. The envelope temperature at the maximum radius behaves as shown in Figure B-2.

c. A decrease in the power absorbed in the anode cooling water and the power radiated decreased with time as the lamp was run. No explanation at present exists for this behavior.

d. Although the lamp was intentionally run to the point of failure by constantly decreasing the coolant flow rate, the lamp exhibited much greater cooling capacity than originally estimated. This could indicate that the possibility of higher power lamps using this type of cooling may not be much past the present state of the art.

IX RECOMMENDATIONS

More work along the original line of the Statement of Work continues with empphasis on the incorporation of instrumentation techniques which will allow for the warning of impending failure of the lamp during operation. Also, the work should continue to determine which characteristics optimize higher power lamps operation at the present cooling rates with extended life.

X REFERENCES

1. J. Rochester - Progress Report #36 AF 40(600)-1140 dated 23 February 1969.

2. J. Hakala, Boeing Company dated 25 January 1958 (2-7885-00-21).

3. Other references contained in references of paper in Appendix A.

VOLUME I

APPENDIX A

PAPER REPRINT FROM 1970 PROCEEDINGS OF
INSTITUTE OF ENVIRONMENTAL SCIENCES
PRESENTED AT 16TH ANNUAL MEETING IN
BOSTON, MASSACHUSETTS

RESEARCH ON HEAT TRANSFER IN XENON SHORT ARC LAMPS

BY: T. L. Hershey, Spectrolab, Inc.

Mr. Hershey is the Engineering Manager of the Systems Division of Spectrolab, Inc., with primary responsibility in large area solar simulation systems. Before joining Spectrolab in January 1969, Mr. Hershey was a Nuclear Research-Physicist Officer in the Research Division of the Arnold Engineering Development Center (Capt. USAF.) with responsibilities in solar simulation, high intensity light sources, high temperature and density gas properties. He has authored numerous papers and reports on thermal effects on materials, space simulation and high intensity arc sources. He was chairman of Government/Industry group on the Development of High Intensity Arc Sources, and Air Force representative on the joint service Military Standard 810 Test Method 517 on space simulation.

He has a B.N.E. and M.S. in Nuclear Engineering from North Carolina State University and two years of graduate study in Astrophysics at the University of Maryland. He is a member of A.I.A.A. and a senior member of I.E.S.

INTRODUCTION

An experimental program has been underway for over three years on the understanding of the operation of 20-30 KW xenon short arc lamps with emphasis on the anodes and their heat transfer. The purpose of the program was to develop diagnostic techniques which would yield information of the limitations of the lamps for various power levels as a function of design restraints and operational parameters. (Ref. 1 & 2.) The power range in question requires that the lamps be of a water cooled variety. At the present time anodes are being tested with varying heat exchange thicknesses to establish the recommended operational limits for a given water flow, fill pressure of the xenon gas and arc stability, which will yield the longest life.

In the smaller lamps e.g., lower wattage with radiation cooling, the life expectancy ranges from one to two thousand hours. However, in the 20 KW variety only three lamps, as of the writing of this paper, have exceeded 1000 hours and one of these just barely. Although the lamps are, in general, warranted for four hundred hours operation, a more realistic figure for operational life would be more like two hundred and fifty hours and a mean life probable more like one hundred and fifty hours.

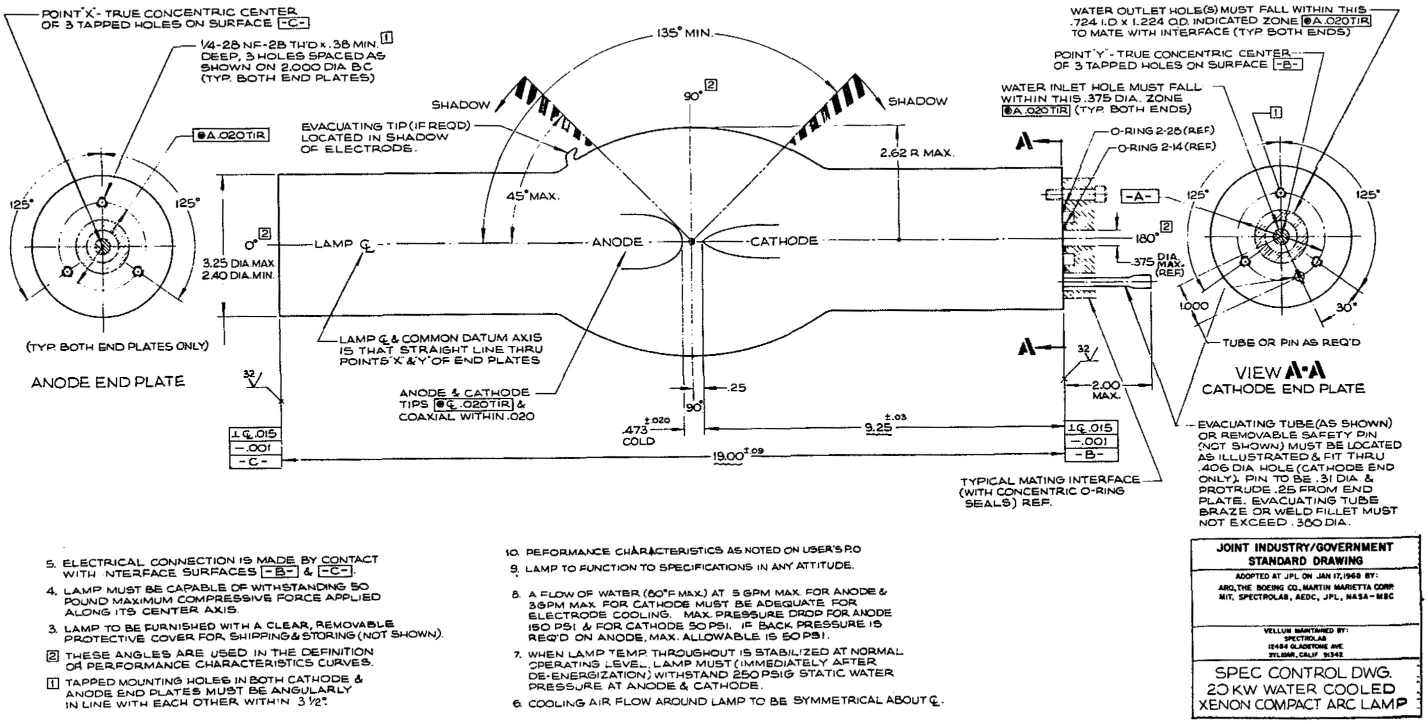
There are two basic types of anodes used in the high power lamps. First, the use of high melting point materials which have a high operating temperature e.g., tungsten or molybedium. Second, the use of copper which has a high thermal conductivity which allows the absorbed energy to be more easily transferred to a heat exchange fluid e.g., water in most solar simulators and antifreezes in some of the airborne or military all climate uses. Each type has its advantages depending on the ultimate use of the lamp. In general, the tungsten lamp has a tendancy to darken with time due to the continual deposition of tungsten vapor within the envelope from the high temperature anode which will vaporize and eventually be deposited on the cooler walls of the lamp. Techniques are presently being developed which will minimize the deposition on the quartz and selectively collect any vapors on the cooler anode support. The mode of failure of this type of lamps is either the gradual degradation of the lamp output as a function of lamp life or the failure of the anode due to cracking of the brittle tungsten from the constant temperature cycling.

The copper anode, due to its operating at a much lower temperature, has less degradation with time in the light intensity. However, three (3) modes of failure are noted with this lamp:

1. The greatest number of failures is due to the blockage of the water cooling channel which is directly beneath the arc column and experiencing the greatest heat flux. This blockage is caused by one of two mechanisms either the obstruction of the flow by the gradual build up of contaminants in the coolant; or the collapse of the thin copper shell normally a tenth of an inch in thickness - due to the imbalance of pressure between the xenon gas of ten atmospheres pressure and the water pressure inside the anode.

2. When the electron column in the arc is too confined or the heat transfer is not sufficient to remove the peak load at the anode tip the arc acts as a drill and bores through to the cooling passage. It can be noted here that this type of failure does not result in a catastrophic explosion as might be first expected, but after the xenon pressure is first relieved into the water stream and the water partially fills the hot (500 - 600°C) quartz envelope. The arc is almost immediately extinguished and the lamp collects only a small amount of water.

3. An ever increasing mode of lamp failure is the gradual loss of pressure within the envelope. Some examples are the xenon leaking



SPECIFICATION CONTROL DRAWING NO. 015978

FIGURE 1

through microcracks within the tungsten anode, or through mechanical seals or bellows.

At the time of the writing of this paper, only limited data has been taken on the first anode. This included high speed motion picture techniques for arc temporal stability and pressure data in the xenon gas and water flow channels. The second anode has undergone extensive development for the incorporation of thermocouples within the anode wall between the arc and the coolant.

THEORETICAL BASIS

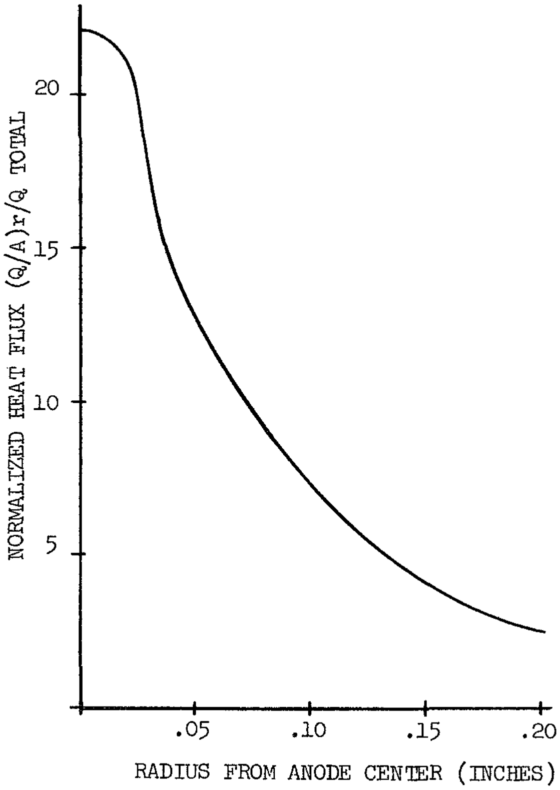
Before expounding too far on the subject matter, it should be pointed out that many other techniques have been investigated and at present others are still underway to replace the short arc lamp. The literature is filled with experimental apparatus which fulfill many of the requirements for a radiation source and in general only possess one or two limitations from being the solution to all source requesters. (Ref. 3 - 7). However, in the final analysis - at this time, the short arc lamp appears to be the most reliable source for the energy range in question, i.e., 20 to 40 KW.

Two avenues have been followed in the development of an anode which will withstand the extremely high thermal environment within a sealed short arc xenon lamp. The short arc lamp is typified by that shown in Figure 1. (Ref. 8 & 9). The cathode is watercooled internally and normally consists of a tungsten tip which has a very high operating temperature. The anode is separated from the cathode nominally by 10 or 14 mm. It is this anode which the present study has investigated and instrumented to determine the physical parameter while the lamp is operating. As will be shown later, the heat loads per unit area are among the highest obtainable for apparatus which operate continuous in excess of a few seconds. A comparison of the various heat loads encountered in the various industries is in reference 10 and 11.

Numerical solutions were generated by the Boeing Company for the energy profile anticipated within the electrode spacing. Detailed discussions of this are in references 12 and 13 as well as private communication with Boeing scientist, references 14, 15, and 16. Figure 2 shows the typical heat flux normalized for the lamp operating power as a function of radial position of the anode.

Other programs of research into the understanding of lamp operation and failure are also underway and are included here by reference. (Reference 17 - 21).

It was the intent of the program to verify the analytical values on the thermal input to the anode and to utilize the combined empirical and analytical model to design anode thickness and operating condition for optimum use. In the following section the apparatus will be described and the approach to obtain the required data.



NORMALIZED HEAT FLUX AS A FUNCTION OF POSITION

FIGURE 2

APPARATUS

In order to understand the operation of the high power arc lamp, and to perform diagnostics for analysis of the variables it was necessary to construct specially instrumented lamps. In this manner some instrumentation could be built into the lamp anode and envelope while still maintaining the same basic construction techniques. Thus, the apparatus consisted of special lamps and laboratory measuring equipment. The basic types of instrumentation and the effects which were observed can be classified into five categories:

I Radiant Flux Measurement

II Water Quantities and Qualities

III Xenon Gas Conditions

IV Electrode Properties and Conditions

V Envelope and Associated Hardware

It will be obvious from the discussion that many properties tested give meaningful data which applies to more than one area.

I Radiant Flux Measurement

Radiant flux measurements were used to determine:

a. Spectral distribution of the radiation

b. Total or integrated intensity

c. Polar distribution of radiation

d. Micro brightness distribution within the arc

e. Specific wavelengths for observing line spectra associated with vaporization of the anode material

f. Radiometrically observing the temperature of the various components of the lamp.

II Water Characteristics

The characteristics of the coolant water has been shown to be very important in the testing and operation of the high pressure xenon lamps so particular care was taken to observe the following properites of the coolant:

a. Inlet and outlet temperature

b. Inlet and outlet pressure

c. Maximum particle size of contaminate in the coolant

d. Electrical properties, i.e., conductivity and the Ph.

e. Flow rate

III Xenon Gas Properties

The quality of the initial charge of the xenon gas was known prior to filling the cleaned, degassed, vacuum pumped lamp. The lamp envelope was heated prior to the addition of the xenon to allow vacuum degassing and surface contaminates. Other components in the gas filling system were also degassed and dried prior to use of the xenon. During the operation of the lamp the following properties of the gas were observed:

a. The effects of contaminates by spectral line emission

b. Xenon pressure by a transducer

c. Rate of gas flow within the envelope as estimated by the use of high speed photography.

IV Electrode Properties

The anode and cathode were instrumented to the greatest possible extent. The water pressure and temperature were observed in the cathode only in the total or integrated effect throughout the cathode, however the anode used many ports and thermocouples internally for precise and quick response data. The major items observed were:

a. Temperature of the anode in at least three positions within the outer shell.

b. A thermistor at the base of the thermocouple connections read the temperature at the junctions

c. Voltage across lamp only

d. Current through the anode and cathode

e. Color temperature and the gettering of either the special cathode material or getter was optically observed

f. Pressure within the water flow channel in three positions, one directly at the tip of the anode and one on either side of the flow

g. An acoustical probe was installed near the tip of the anode within the water channel to record the onset of nucleate boiling

h. Arc stability was observed both visually, by projected imagery, and with high speed film.

i. The formation of the molten material on the electrodes was visually observed as well as any massive movement of material from the cathode to the anode

j. Arc wander, detachment, and attachment was observed during power excursions

k. Arc size and position was measured by a projection of the image technique

V Lamp Characteristics

The quartz envelopes used during the test were observed for internal stresses upon receipt and were monitored periodically to insure no stresses were developed during operation. The quality of the quartz is extremely high with no visible marks, stria, or lamination within the material. No bubbles are present. Elaborate precautions were taken to avoid contamination of the envelopes and extensive cleaning operations were used prior to assembly. The following parameters were monitored on the envelope and associated hardware:

a. A strain gauge was cemented directly upon the quartz envelope in the radiation shadow of the anode

b. A radiometer was used to measure the effective temperature of the quartz not in the shadow of the electrodes

c. A thermocouple was used to measure the temperature at the seals of the envelope to the flanges

PROCEDURE

After assembly of the specially instrumented lamp and set up of the laboratory test equipment, the test procedure was to simultaneously measure all of the above quantities while the lamp was running. The first lamp was started at a minimal wattage (approximately 10 kilowatts) and allowed to establish equilibrium. The data collection was inspected to note changes from the preceeding run and then the power was increased to the lamp. After a noticeable change in the arc profile or position on the anode the arc would be photographed. The procedure is repeated until the anode or lamp suggest that a failure is immanent. For this, a failure was defined as one of the following occurrences:

1. The tip of the anode shows molten copper of a predetermined size.
2. Other physical indicators such as water temperature, pressure, xenon pressure, or lamp temperature at either envelope or seals show variations which cannot be explained as normal.
3. The electron beam-core of the arc causes a puncture to develop in the anode.
4. The film boiling at the internal anode surface approaches the uncontrolled point where punch-through is immanent.

However numerous difficulties were encountered in the fabrication of the anodes and consequently the majority of the program time and funds were expended upon resolving difficulties which are reported herein. In addition to the actual fabrication other typical difficulties were also present e.g., incompatibility of the various signals with the recording equipment, annoying and intermittent vacuum leak detection detection during the assembly phases of the lamp.

DISCUSSION

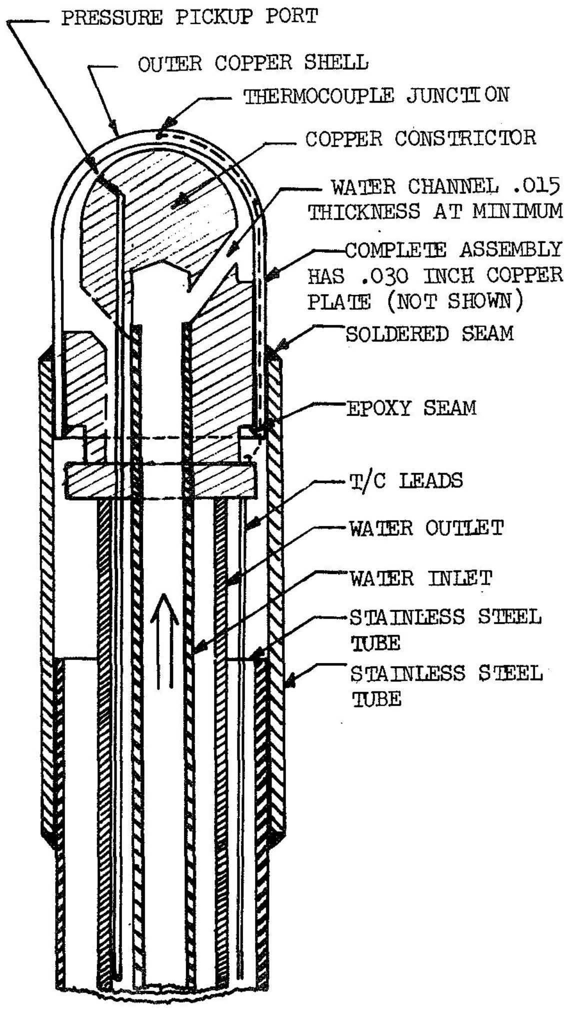
Component Fabrication

The greatest difficulty was encountered in the fabrication of the instrumented anode. This discussion centers on the work in this area. The rather routine operations and assembly steps are summarized in the remainder of the paper.

Figure 3 shows the cross section of the water cooled anode as it was conceived over two years ago. The basic design is similar and copied after the Riise anode which was designed for the solar simulator lamp used by the Jet Propulsion Laboratory. A description of this anode is included in references 20 and 21. The instrumentation which has been added to the Riise anode was the purpose of this program, with an ultimate aim of providing a technique which would give an advance warning to the ultimate failure of the lamp. Hopefully such a warning would be some radical or predictable change in one or more of the physical parameters measured.

The design concept for the anode cooling involves a flow of high pressure, high velocity water entering a constricting channel which would cause the water velocity to increase to a maximum value at the very tip of the anode. From that point the channel would widen and the water would be returned to the heat exchangers.

Originally, the anodes were made from a shell over an inner machined surface. The outer shell was fabricated using thin walled copper which was pressure formed to a machined mandrel. This concept was modified to include instrumentation within each of the components. The inner component has a carefully machined surface which controls this flow of the coolant while measuring the local pressure variations. The outer shell is electrodeposited over a mandrel with thermocouples at varying depth and position to determine thermal gradients locally.

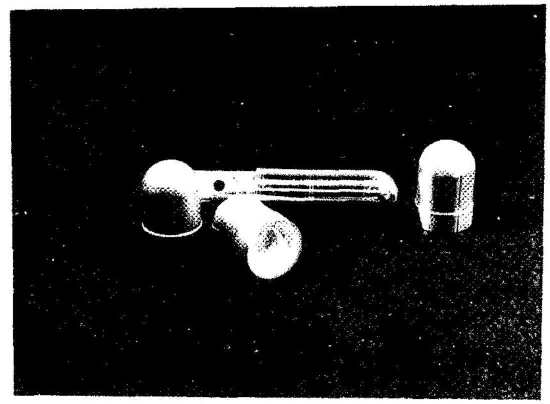


CROSS SECTIONAL VIEW OF ANODE

FIGURE 3

Only one of the three pressure ports are shown in figure 3, however, it is typical of the other two which includes one for an acoustical probe. The dotted lines within the outer shell represents the thermocouples which were installed in the shell. These thermocouples were enclosed within a nickel sheath with an outside diameter of 0.007 inch (therein lies the difficulty.)

Near the tip the anode assembly consists of two major components. An internal component has been named the constrictor for its action in the flow of the cooling water. This part contains the water passages, the pressure ports, the tie-down posts for the thermocouple junctions, a thermistor for the measurement of the thermocouples junction temperature, and the outer radius to which the gas seals are made. The other component is a thin shell of electrodeposited oxygen-free, high purity copper. The outer shell is electroformed on a mandrel to a thickness of 0.150 inch and then machined to 0.014 inch at the tip and increasing in thickness to 0.065 inch back on the shell as shown in Figure 4. The anode is then cut with four grooves to allow the placement of four thermocouples.



ELECTROFORMED AND MACHINED ANODE SHELLS WITH MANDREL

FIGURE 4

The thermocouple junctions are indexed to the anode tip and the water flow channel inlet is at an angular position of 0°. All located within the 0.092 inch thickness copper wall. One thermocouple was located at the anode tip with the junction 0.014 inch from the (water flow) internal surface of the shell. A second junction was to be at .022 inch from the outer surface of the shell also at the tip, however one lead was broken during final assembly. The next thermocouple junction is located at 0.014 inch from the inner surface of the shell and 0.100 inch from the tip in the direction of the water inlet. The last thermocouple was located 0.022 inch from the outer surface of the shell (0.070 inch from the internal surface) and 0.100 inch from the anode tip in a direction 90° from the third thermocouple i.e., at right angles to the water flow direct. The original intent was to locate eight thermocouples - four on each of two layer and at 45° spacing around the circumference. Also, the spacing from the tip was to range from 0 to 0.200 inch.

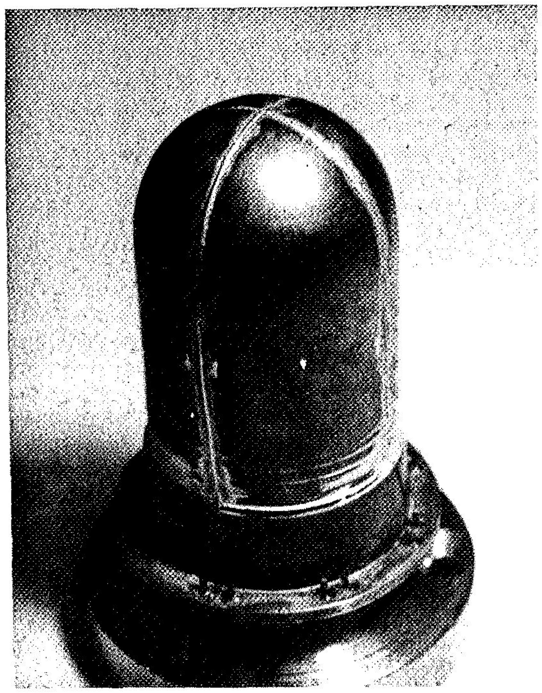
It was at this point in the program that the first great difficulty was encountered. The attachment of the thermocouples was complicated by two factors, the size of the thermocouples was selected to be as small as possible to minimize the effects of thermal gradients within the thin shell wall and thereby negating the whole experiment, and second the insuring of positive and complete attachment of the thermocouple to the shell.

The two factors were working against one another from the very start. Initially the thermocouples were to be attached by the use of furnace brazing. A lengthy program was undertaken to determine the proper brazing compound, flux thermocouple material and an appropriate procedure to insure a satisfactory bond. Two vendors tried unsuccessfully to attach the thermocouple and in desperation a vacuum furnace was constructed inhouse and numerous shells were attempted, however, the results were not acceptable to proceed with the remainder of the anode fabrication. Figure 5 shows the vacuum furnace in which the anodes were fabricated and Figure 6 shows an anode which was brazed with this technique, however, this thermocouple was attached with too much braze material and the integrity of the thermocouple was not maintained. At this point the electroless copper plating of the thermocouple on the shell was attampted but the bond allowed the trapping of electrolyte and voids were formed at the point of contact between the thermocouple and the anode shell. This technique was attempted on both the grooved shells as well as shells which were unscored. Figure 7 shows a photomicrograph (original X50) where the thermocouple was positioned in a groove

At this point several attempts were made at attaching the thermocouples to the shell using an electroplating technique which consisted of the following steps:

a. Chemically cleaning the surface with acid solutions

b. Activating the surface of both the shell and the thermocouple sheath with a copper cyanide strike



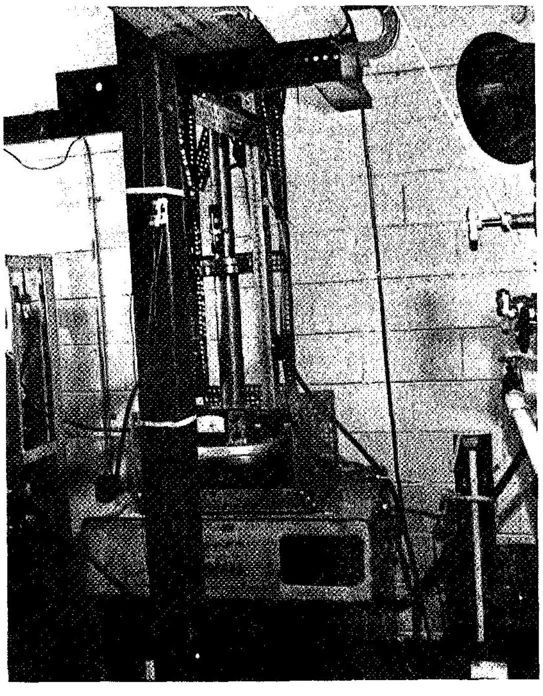
ANODE WITH BRAZE THERMOCOUPLES

FIGURE 6

c. Bonding the thermocouples to the surface with adhesive over short lengths

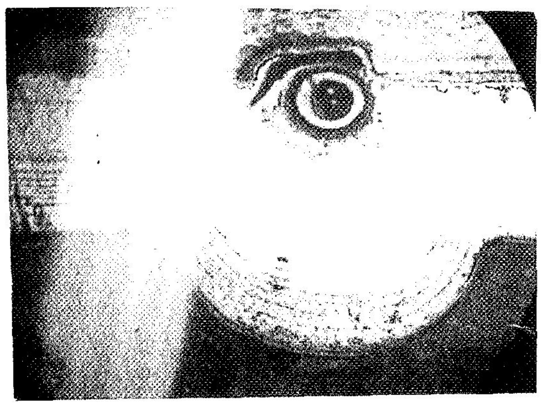
d. Electroplating a small amount of copper to hold the thermocouple in place

e. Removing the adhesive both mechanically and chemically



ANODE THERMOCOUPLE VACUUM BRAZING FURNACE

FIGURE 5



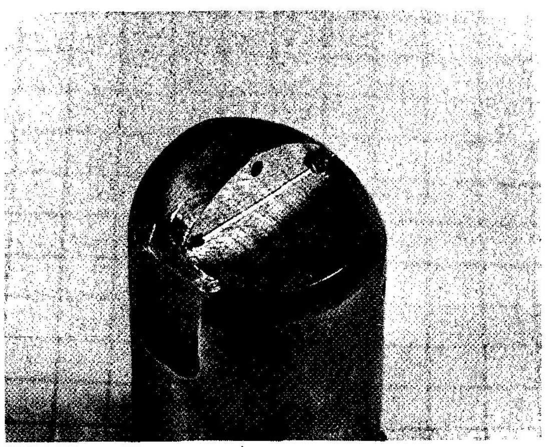
PHOTOMICROGRAPH (X 50) ELECTROLESS PLATED THERMOCOUPLE

FIGURE 7

f. Returning the anode into the copper sulfate electrodeposition bath until the required depth was overcoated on the thermocouple.

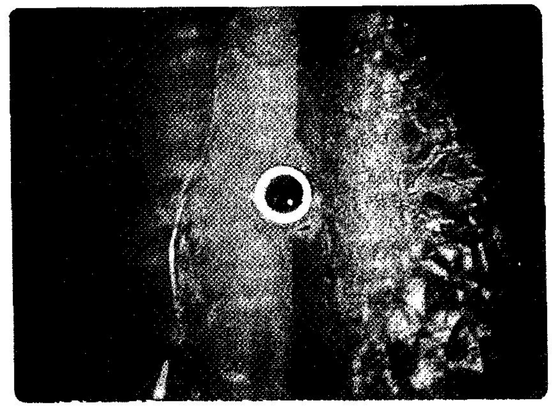
At this point the anode was subjected to a machining operation to turn down the shell to the predetermined thickness. On two shells the thermocouple leads were either mechanically broken or later encased within the subsequent electrodeposited copper layers and were left useless. Again, the approach was revaluated and determined to best of the alternatives available, thereafter the assembly procedure was altered to allow for reduction in the handling of the anode assembly after the thermocouples were on the surface.

Figure 8 shows the inner component of the anode assembly which contains the pressure ports and the water passages. This constrictor was drilled and assembled with gold plated - insulated feedthroughs for the thermocouple terminals. Then, the constrictor was cemented within the previously machined outer shell (which has grooves cut for the thermocouple but as yet empty.) At this point the anode is attached to a fixture which allows the connection of the terminals for the plating operation and the process of the electro-deposition of copper to attach the thermo-couple is repeated. The design of the terminal fixture also allowed the accurate measurement of the deposition of the copper as well as a fixture for the necessary machining of the face and radius of the shell. After the first layer of thermocouples were in place and the surface was machined to the necessary radius, the whole process was repeated a second time and a second layer of thermocouples were encapsulated in place. Figure 9 shows the photomicrograph of a test specimen where a 0.007 inch diameter nickel sheath containing a platinum-platinum rhodium thermocouple has been encapsulated within the surface of a OFHP copper substrate. Under selected illumination and etching conditions the copper strike using the cyanide process and the copper sulfate deposition can be distinguished. One of the thermocouple leads is visible within the nickel sheath. The original magnification of the photograph was X50.



CUTAWAY VIEW OF ANODE CONSTRICTOR SHOWING WATER PASSAGE, PRESSURE TRANSDUCER PORTS AND COMPOUND RADII FOR WATER FLOW CONTROL

FIGURE 8

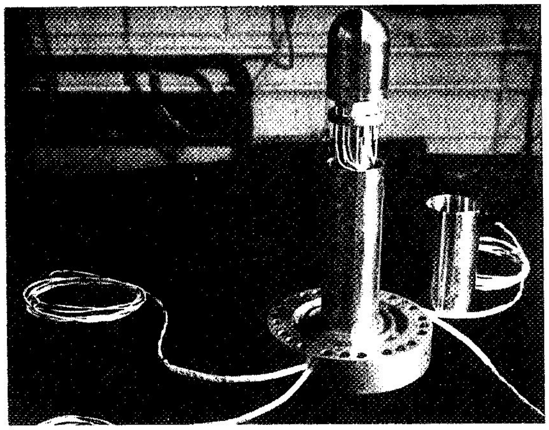


PHOTOMICROGRAPH (X 50) ELECTRODEPOSITED NICKEL SHEATHED THERMOCOUPLE TO COPPER SUBSTRATE WITH GROOVE

FIGURE 9

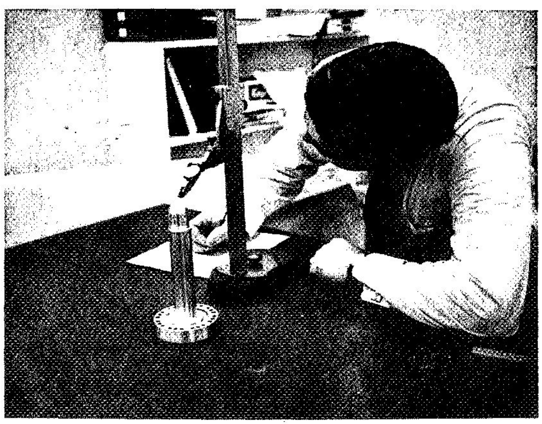
After the second electrodeposition of copper takes place the assembly is once again returned to the lathe where it is turned down to the final thickness minus 0.012 inches. The anode subassembly is then ready for the installation of the thermocouple leads, water passages to the lamp flange, the acoustical and pressure transducer lines, and a signal line to a thermistor located within the just fabricated anode assembly where the thermo-couples make a junction with the gold plated feedthroughs. Figure 10 shows the anode assembly just prior to final encapsulation. This thermistor was added to the instrumentation to measure the temperature at the feed-through flange. The internal water lines are epoxied in place to grooves provided for that purpose. The outer stainless steel shell was then soldered in place.

The completed anode assembly was then returned to the electroplating bath and a final layer of 0.030 inch copper was plated over the whole assembly from the tip of the anode to the flange surface. Figure 11 shows the completed assembly after a final machine cut of 0.012 inch to give the precise length necessary to properly mate with the envelope and cathode assembly. Figure 12 shows the quartz envelope and the mechanically sealed (o-ring) cathode assembly. Figure 13 shows the same arrangement for the quartz enve-lope which has a graded glass seal to the cathode assembly.



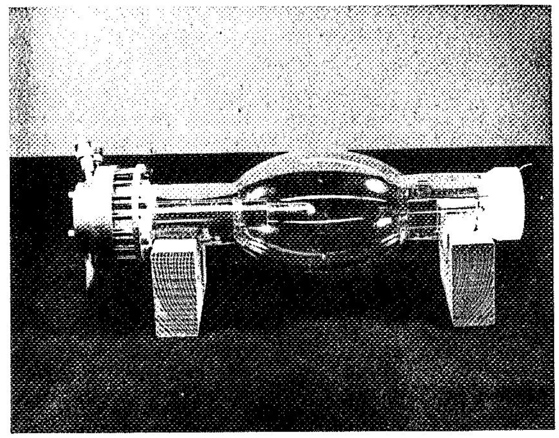
ANODE ASSEMBLY PRIOR TO FINAL ASSEMBLY AND ELECTRODEPOSITING

FIGURE 10



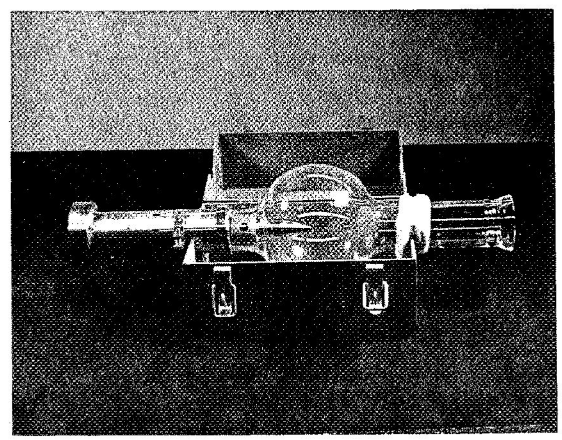
ANODE ASSEMBLY WITH FLANGE AFTER FINAL ELECTROFORM AND MACHINING

FIGURE 11



QUARTZ ENVELOPE WITH MECHANICALLY SEALED FLANGE TO CATHODE

FIGURE 12



QUARTZ ENVELOPE WITH GRADED GLASS SEALED FLANGE TO CATHODE

FIGURE 13

COMPONENT ASSEMBLY & ANCILLATORY SYSTEMS

In addition to the anode assembly just described, there are three other assemblies and systems used namely:

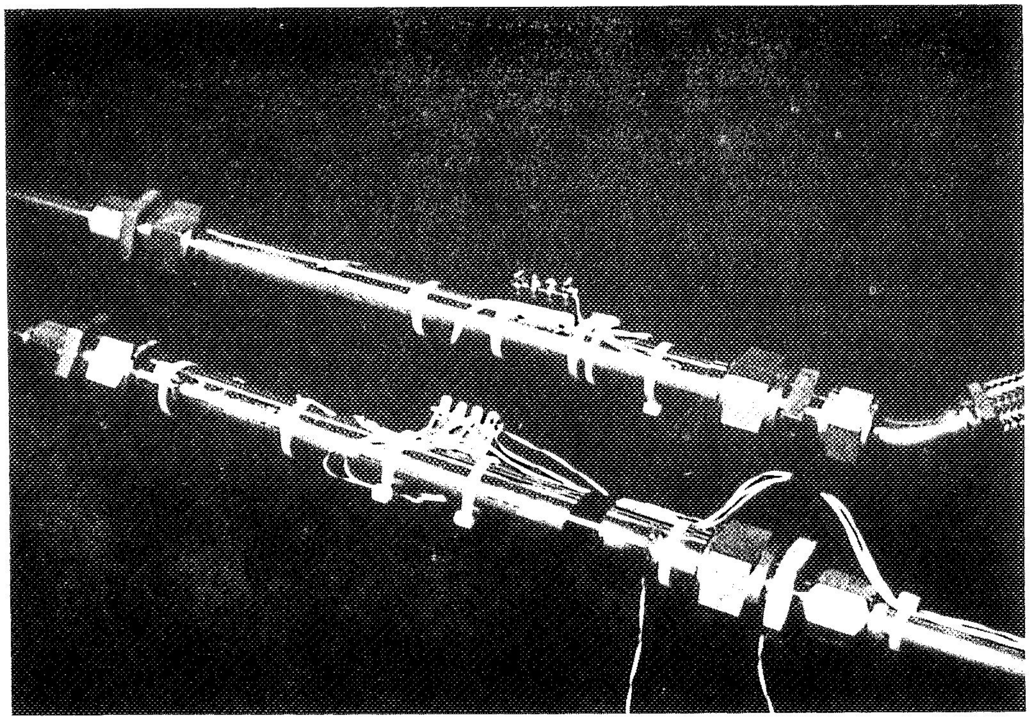
a. Anode inlet and outlet temperature monitoring manifold

b. Gas evacuation and pressurizing system manifold

c. Water conditioning system and heat exchanger

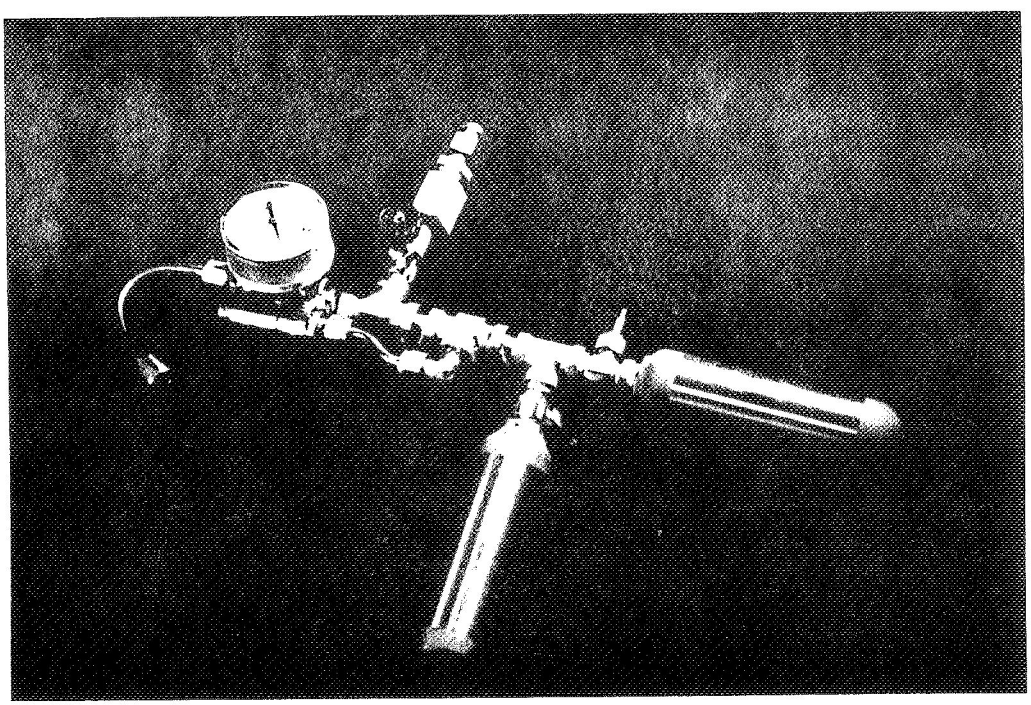
The anode cooling water passes through a series of three thermocouples prior to entering the anode and on the return to the heat exchanger again passes through a second series of three thermocouples and a difference signal is recorded which is proportional to the temperature differential in the anode water. Figure 14 shows the two pipes in which the thermocouples are located. The assembly is placed within a few feet of the anode connection out of the direct light from the lamp.

The xenon pressurization system for the first lamp is as shown in Figure 15. In the second lamp tested, an additional tee was inserted in the line to the stainless steel



ANODE INLET AND OUTLET WATER
THERMOCOUPLE ASSEMBLY

FIGURE 14



XENON PRESSURIZATION SYSTEM

FIGURE 15

pressure vessels shown. The following description is the method used on the second lamp and is essentially the same as the first except for the interplay of the various gas bottles during filling. A helium leak detector/ vacuum pump system was connected to the apparatus in the upper left of the figure. The line at the top of the figure goes to the lamp pressure xenon fill tube. The steps used in filling a previously clean and assembled envelope and anode/flange assembly are:

1. Evacuate the manifold system
2. With the pump running, crack all valves to remove any residual contamination
3. After the lamp and manifold has returned to a hard vacuum, pump overnight to remove any slow outgassing products absorbed within the envelope and internal components
4. Heat lamp assembly with torch to enchance any remaining outgassing - temperature limit on seal to 150°F
5. Fill lamp envelope to 200 micron pressure
6. Apply high voltage to glow discharge the lamp
7. Pump xenon out of lamp
8. Pressurize the lamp with the xenon from the stainless steel cylinders to desired pressure
9. Seal off system and run lamp for brief period at minimum power level
10. Exhaust xenon to atmosphere (at this point the xenon could be cryogenically pumped back into one of the cylinders if desired to reclaim.)
11. Evacuate system and refill lamp with high purity xenon from additional bottle attached to manifold (not shown) to desired pressure
12. Seal off manifold and lamp from pump

The water system is a closed loop system which can produce coolant with the following characteristics:

a. Maximum particle size 5 microns
b. Electrical conductivity 50 micromhos
c. Maximum pressure 465 psia
d. Maximum flow 15 gpm
e. Inlet temperature maximum 80°F
f. Deionized to passivate ions present
g. The pressure head in the water system is evacuated and then filled with helium

Figure 16 shows the first lamp tested which uses the mechanical seals on both flanges. This lamp did not have the thermocouple incorporated within the anode. Figure 17 shows the lamp mounted in the vertical position within the test cell. The test cell has circulating air which is augmented by an exhaust fan however the circulation in the vicinity of the lamp is essentially natural convection.

RESULTS AND CONCLUSIONS

At the time of the writing of this paper in late January 1970, the second anode within the mechanical sealed envelop had just completed the glow discharge phase of cleaning the interior of the lamp and was in an extended outgassing vacuum pumping for the weekend. It is anticipated that by the time the paper is presented in April that the lamp will have been successfully run over the anticipated test program of variable power levels, water flow rates and xenon fill pressures to provide the necessary data for correct interpretation of the heat transfer for this lamp.

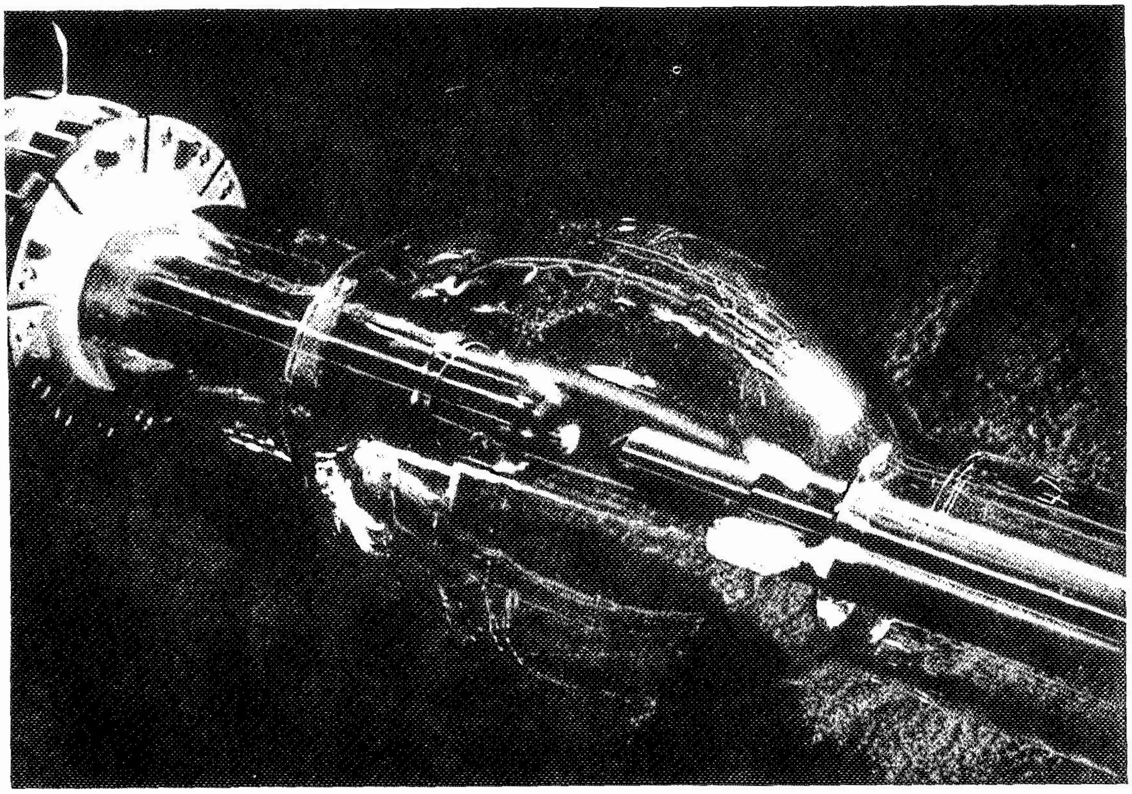
The only test data which can be reported at this time comes from earlier tests on the first lamp assembly. Although that lamp did not have the encapsulated thermocouples, the anode shell was electroformed. Pressure and temperature data was obtained on the water system and lamp envelope.

Figure 18 is a projected view of the arc on the first anode with pressure instrumentation only. The photograph is of the lamp at 17.2 KW with the xenon pressure reading 156 psia, and 1.80 gpm flow with a 104 psi pressure drop from the first to last pressure proble within the water passage in the anode. The pressure at the tip of the anode water passage was 320 psia. The temperature gradient from the anode inlet to the outlet was 13.1°C.

The reduction of the data obtained during the early part of spring 1970 will be made available at the meeting and will be included in the concluding slides.

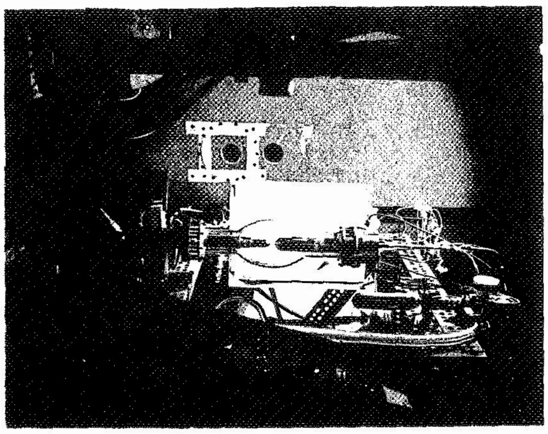
ACKNOWLEDGEMENT

I would like to acknowledge the fine work of the Engineering Development Laboratory at Spectrolab which carried out the fabrication and instrumentation of the lamp assemblies over a very long and arduous path. In particular, Jim Lovelady, Jim Rochester and Mike Onufrechuk. This work was initiated under the sponsorship of the Arnold Engineering Development Center, proceeded under the joint sponsorship of AEDC and the Manned Spacecraft Center, NASA, and at the present time is solely under MSC, NASA sponsorship NAS 9-9831 with Mr. J. P. Vincent the technical monitor. Mr. F. N. Benning of Spectrolab's Research Division is the Program Manager.



ASSEMBLED LAMP WITH MECHANICAL SEALS

FIGURE 16



LAMP IN TEST CELL DURING VACUUM CHECK OUT

FIGURE 17

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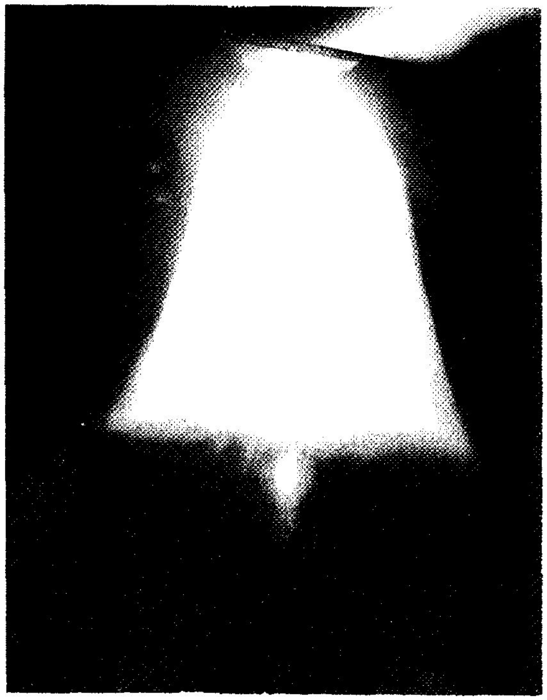

INSTRUMENTED ANODE WITHIN OPERATING LAMP
XE PRESSURE 156 PSIA POWER AT 17.2 KW

FIGURE 18

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19.
Y. Nakamura, Y. Onishi, and Y. Shimizu "High-Wattage Xenon Short Arc Lamps with Seals and Improved Liquid Cooled Electrodes," AIAA/ASTM/IES 4th Space Simulation Conference, Los Angeles, California September 1969 AIAA Paper No. 69-998.

20.
R. E. Bartera "Recent Solar Simulation Developments at the Jet Propulsion Laboratory," 13th Annual Meeting of IES at Washington, D.C., April 1967 pp 681-685.

21.
H. N. Riise "Water Cooled Anode Increase Life of High Temperature Arc Lamp," NASA Technical Brief 67-10247, November 1967.

VOLUME I

APPENDIX B

TABULATED DATA AND FIGURES

LAMP #1 (1968)	POWER (KW)	VOLTAGE (VOLTS)	CURRENT (AMPS)	ENVELOPE TEMP (°C)	XENON PRESS (PSI)	INTENSITY (VOLTS)
N 1						
NSTANT CHECKOUT						
N 2						
DATA POINT 1	6.66	33.3	200	140	124	25
2	9.20	36.8	250	200	136	34
3	10.15	37.9	265	215	138	35.5
4	11.82	39.4	300	235	140	39
5	13.09	40.3	325	255	148	47
6	14.1	41.1	346	265	150	49
7	14.95	41.6	357	275	154	54
8	16.4	42.2	389	285	156	55
9	17.24	43.1	400	295	160	56
10	18.13	43.6	416	305	164	56
11	18.13	43.6	416	310	166	56
12	18.92	44.0	430	330	168	56
13	20.11			345	172	56
14	21.43			350	176	56
15	18.3			320	168	56
16	15.3			280	160	56
17	12.2			255	152	47
18	9.95			230	144	37

TABLE B-1

DATA FROM LAMP #1 (1968)

LAMP #2 (1968)	POWER	ANODE WATER FLOW	TEMP. IN (°C)	TEMP. OUT (°C)	TEMP. DIFF. (°C)	KW INTO WATER	KW INTO H_2O / LAMP KW
RUN 1							
INSTANT CHECKOUT							
RUN 2							
DATA POINT 1	6.66	1.52	29.1	35.5	6.4	2.56	.385
2	9.20	1.56	27.9	35.5	7.6	3.12	.339
3	10.15	1.59	27.6	36.2	8.6	3.61	.344
4	11.82	1.64	28.0	37.6	9.6	4.16	.351
5	12.04	1.66	28.5	38.6	10.1		
6	13.09	1.72	29.3	40.4	11.1	4.43	.338
7	14.1	1.76	29.6	40.8	11.2	5.04	.358
8	14.95	1.76	29.5	42.0	12.5	5.20	.348
9	16.4	1.80	30.2	43.3	13.1	5.80	.354
10	17.24	1.80	30.5	44.6	14.1	6.22	.360
11	18.13	2.30	30.5	41.6	11.1	6.70	.369
12	18.92	2.27	30.4	42.6	12.0	7.18	.379
13	20.11						
14	21.43						
15	18.3						
16	15.3						
17	12.2						
18	9.95						

TABLE B-2

DATA FROM LAMP #1 (1968)

LAMP #3 (1968)	POWER	FLANGE TEMP. (°C)	TIP PRESS. (PSI)	HYDROPHON PRESSURE (PSI)	PRESS. DIFF. (PSI)	CATH. FLOW RATE (GPM)	CATHODE WATER PRES IN/OUT (PS
RUN 1							
INSTANT CHECKOUT							
RUN 2							
DATA POINT 1	6.66	70	330	165	180	4	50/8
2	9.20	100	330	180	175	4	50/8
3	10.15	110	330	190	165	4	50/8
4	11.82	110	330	205	145	4	50/8
5	12.04	115	330	215	140	4	50/8
6	13.09	120	330	225	132	4	50/8
7	14.1	125	330	235	120	4	50/8
8	14.95	130	330	240	120	4	50/8
9	16.4	135	330	260	105	4	50/8
10	17.24	150	330	270	104	4	50/8
11	18.13	150	310	180	145	4	50/8
12	18.92	150	310	180	165	4	50/8
13	20.11	165				4	50/8
14	21.43	166				4	50/8
15	18.3	155				4	50/8
16	15.3	140				4	50/8
17	12.2	130				4	50/8
18	9.95	110				4	50/8

TABLE B-3

DATA FROM LAMP #1 (1968)

TABLE B-4
DATA FROM LAMPS #1 (1969) AND #2 (1969)

LAMP #1	POWER (kW)	DC CURRENT (AMPS)	DC VOLTAGE (VOLTS)	ENVELOPE TEMP (°C)	XENON PRESS (PSI)	INTENSITY W/ster Avg.75°-105°
RUN 1						
TRIAL RUN						
RUN 2						
DATA POINT 1	10.9	293	37.2	450	93	680
2	13.5	350	38.8	487	100	850
3						
4	16.5	403	40.8	535	104	1075
5	19.2	450	42.6	565	110	1275
6	23.0	500	46.0	600	117	1550
7	25.5	550	46.3	645	122	2060
RUN 3						
DATA POINT 1	11.1	300	37.0	387	90	650
2	13.6	350	39.0	470	108	825
3	16.3	400	40.7	510	120	1000
4	18.9	450	42.3	550	130	1190
5	22.0	500	44.0	590	135	1425
6	24.7	550	45.0	612	142	1700
7	27.6	600	46.0	650	142	1940
RUN 4						
TRIAL RUN						
RUN 5						
DATA POINT 1	11.2	300	37.3	398	90	620
2	13.6	350	39	475	108	810
3	16.2	400	40.6	520	118	980
4	19.0	450	42.2	565	130	1140
5	22.0	500	44	600	140	1320
6	24.9	550	45.3	635	142	1580
7	27.8	600	46.3	655	142	1810
RUN 6						
TRIAL RUN						
RUN 7						
DATA POINT 1	11.1	300	37.0	400	95	575
2	13.5	350	38.6	470	100	740
3	16	400	40.1	515	106	890
4	19	450	42.2	555	113	1070
5	21.7	500	43.5		118	
LAMP #2						
RUN 1						
DATA POINT 1		250			65	~ 250
RUN 2						
DATA POINT 1	8.5	250	34.19		75	~ 360
2	11.0	300	36.8		82	~ 500

LAMP #1		POWER (kW)	ANODE-FLOW RATE (GPM)	WATER TEMP. DIFF (°C)[1]	POWER ABS. IN ANODE WATER		POWER RADIATED	
					KW	NORMALIZED	KW	NORMALIZED
RUN 1								
TRIAL RUN								
RUN 2								
DATA POINT	1	10.9	2.0	7.5	3.96	.363	6.12	.561
	2, 3)	13.5	2.0	9.0	4.74	.352	7.65	.567
	4	16.5	2.0	10.8	5.70	.346	9.68	.586
	5	19.2	2.3	12.0	7.28	.380	11.48	.598
	6	23.0	2.4	13.0	8.26	.359	13.95	.606
	7	25.5	2.4	14.5	9.20	.361	18.54	.727
RUN 3								
DATA POINT	1	11.1	1.7	8.4	3.78	.341	5.85	.527
	2	13.6	1.7	9.9	4.47	.329	7.42	.546
	3	16.3	1.7	11.3	5.09	.312	9.00	.552
	4	18.9	1.8	13.3	6.31	.335	10.71	.567
	5	22.0	1.8	25	7.35	.335	12.82	.583
	6	24.7	1.8	28.5	8.06	.327	15.3	.619
	7	27.6	1.9	27.5	9.26	.336	17.46	.633
RUN 4								
TRIAL RUN								
RUN 5								
DATA POINT	1	11.2	1.2	7.15	4.27	.380	5.58	.498
	2	13.6	1.2	8.85	4.85	.357	7.29	.536
	3	16.2	1.2	9.65	5.47	.337	8.82	.544
	4	19.0	1.2	10.7	5.92	.312	10.26	.540
	5	22.0	1.2	12.75	6.71	.305	11.88	.540
	6	24.9	1.2	13.85	7.44	.298	14.22	.571
	7	27.8	1.25	14.25	8.09	.290	16.29	.586
RUN 5								
TRIAL RUN								
RUN 6								
DATA POINT	1	11.1	.6	24.3	3.84	.346	5.175	.466
	2	13.5	.5	28.8	3.81	.283	6.66	.493
	3	16	.6	33.5	5.30	.332	8.01	.501
	4	19	.5	38.2	5.05	.266	9.63	.507
LAMP #2	5	21.7						
RUN 6								
DATA POINT	1		7.0				2.25	.260
DATA POINT	1	8.5	7.0	2.5	4.61	.543	3.24	.381
	2	11.0	7.0	2.6	4.81	.438	4.50	.410

TABLE B-5

DATA FROM LAMPS #1 (1969) AND #2 (1969)

TABLE B-6
DATA FROM LAMPS #1 (1969) AND #2 (1969)

LAMP #1	POWER (kW)	ANODE FLANGE WATER PRESS IN/OUT (PSI)	ANODE TIP WATER PRESS IN (PSI)	ANODE TIP WATER PRESS CENTER PSI	ANODE TIP WATER PRESS OUT (PSI)	CATHODE FLANGE WATER PRESS IN/OUT PSI (3 GPM)	ANODE FLOW RATE (GPM)
RUN 1							
TRIAL RUN							
RUN 2							
DATA POINT 1	10.9	300/60	230	38	38	45/22	2.0
2, 3	13.5		225	37	43		2.0
4	16.5		226	40	44		2.0
5	19.2		220	42	46		2.3
6	23.0		210	67	55		2.4
7	25.5		210	67	57		2.4
RUN 3							
DATA POINT 1	11.1	200/80	185	60	54	45/22	1.7
2	13.6		145	60	53		1.7
3	16.3		160	62.5	60		1.7
4	18.9		160	65	65		1.8
5	22.0		150	69	65		1.8
6	24.7		150	69	67		1.8
7	27.6		150	75	72		1.9
RUN 4							
TRIAL RUN							
RUN 5							
DATA POINT 1	11.2	130/65	190	62	65	45/21	1.2
2	13.6	125/65	184	64	66		1.2
3	16.2	125/65	134	63	66		1.2
4	19.0	125/65	155	65	67		1.2
5	19.0	125/65	155	65	67		1.2
6	24.9	120/65	155	70	71		1.2
7	27.8	120/65	145	67	67		1.25
RUN 6							
TRIAL RUN							
RUN 7							
DATA POINT 1	11.1	49/22	22	36	47	45/21	.6
2	13.5	49/22	22	37	47		.5
3	16	49/22	22	37	45		.6
4	19	50/20	22	37	45		.5
5	21.7						
LAMP #2							
RUN 1							
DATA POINT 1		198/100	145	137	145	50/33	7.0
RUN 2							
DATA POINT 1	8.5	198/100	132	144	192	50/33	7.0
2	11.0	198/100	134	142	195	50/33	7.0

TABLE B-7

TEMPERATURE DATA FROM ANODE THERMOCOUPLES

LAMP #2	POWER	THERMOCOUPLE (°C) No. 2	No. 3	No. 4
RUN 1 - DATA POINT 1		173	152.5	
RUN 2 - DATA POINT 1	8.5	185	175	205
2	11.0	220	220	217

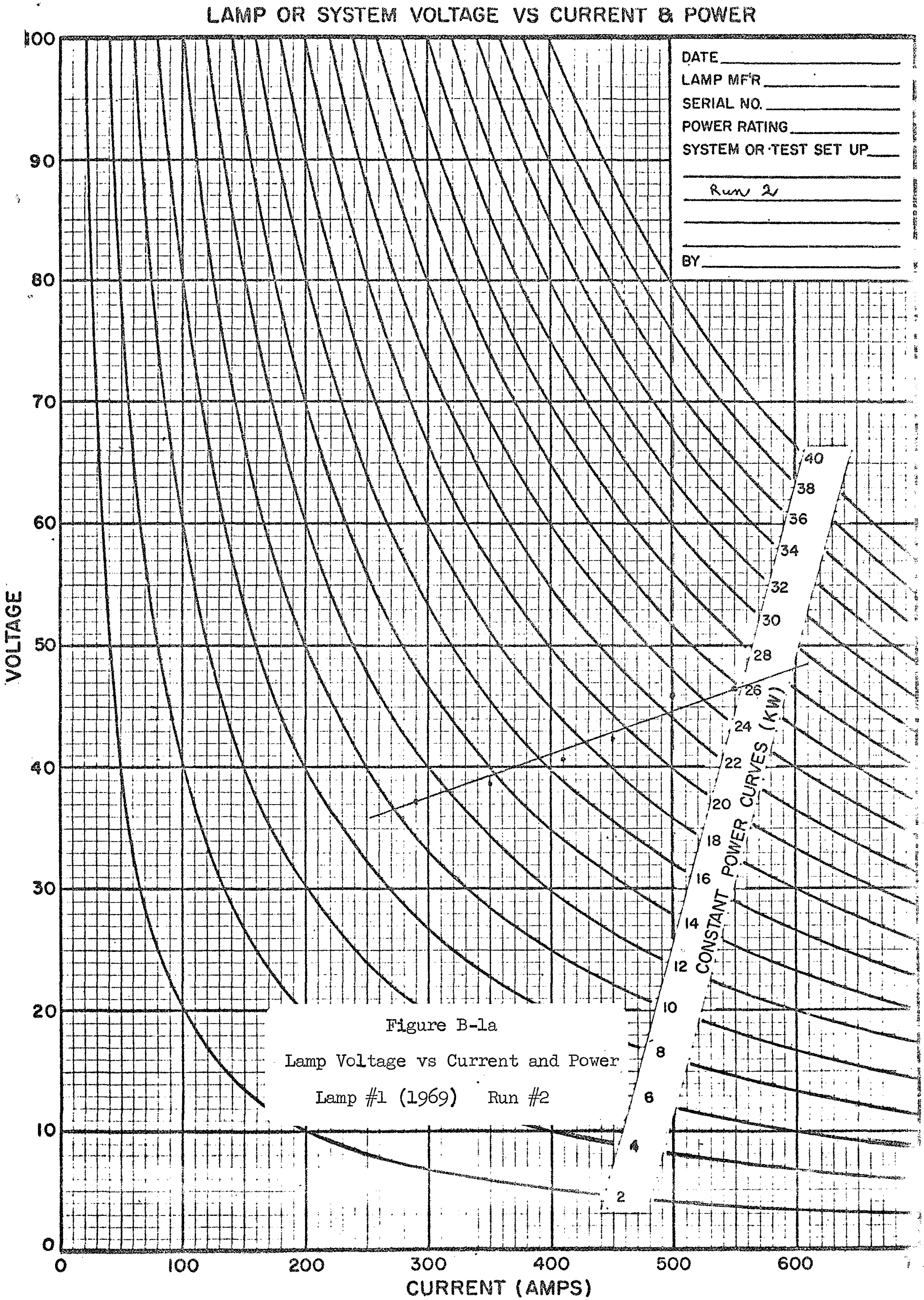

Figure B-1a

Lamp Voltage vs Current and Power

Lamp #1 (1969) Run #2

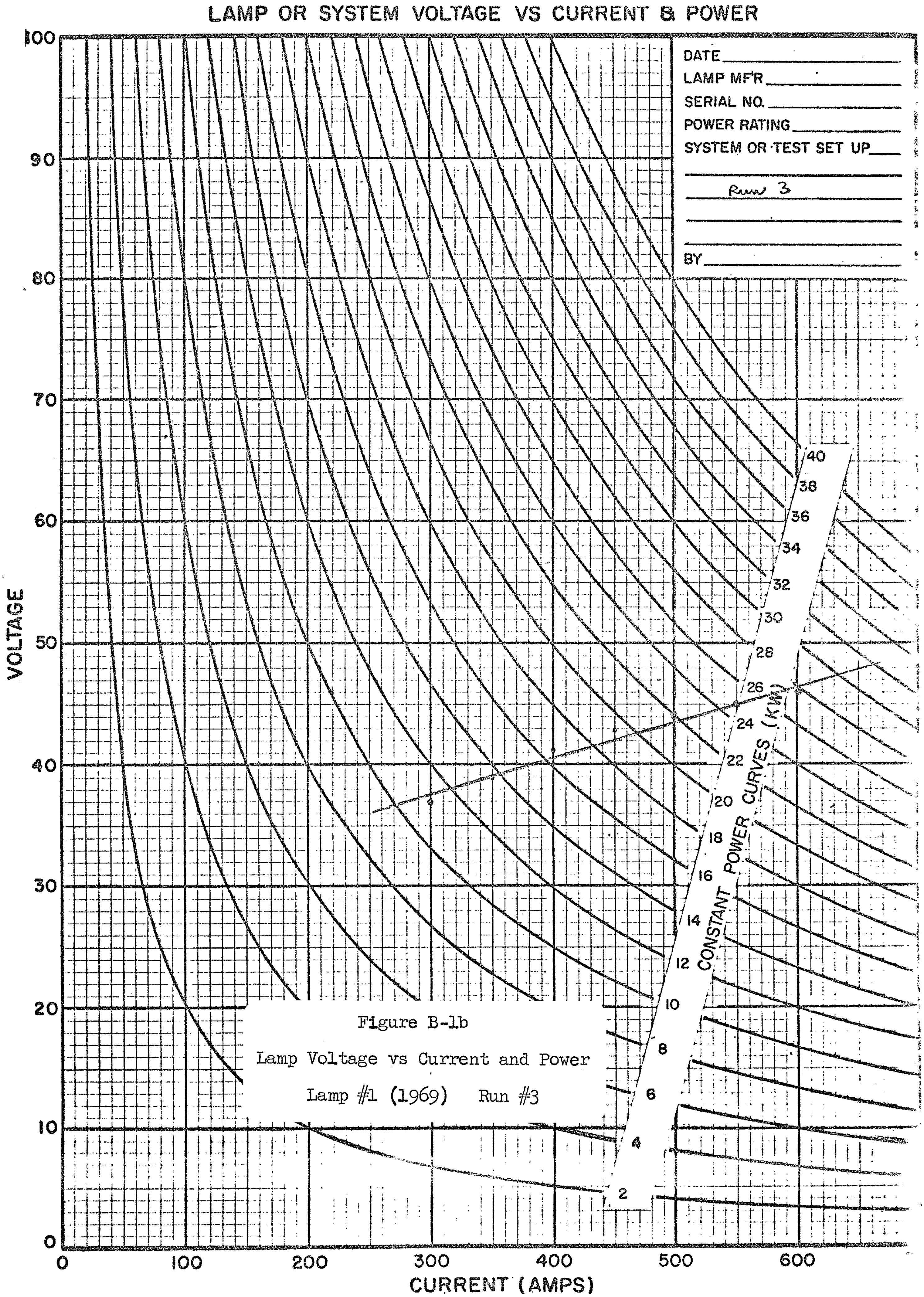

Figure B-1b

Lamp Voltage vs Current and Power

Lamp #1 (1969) Run #3

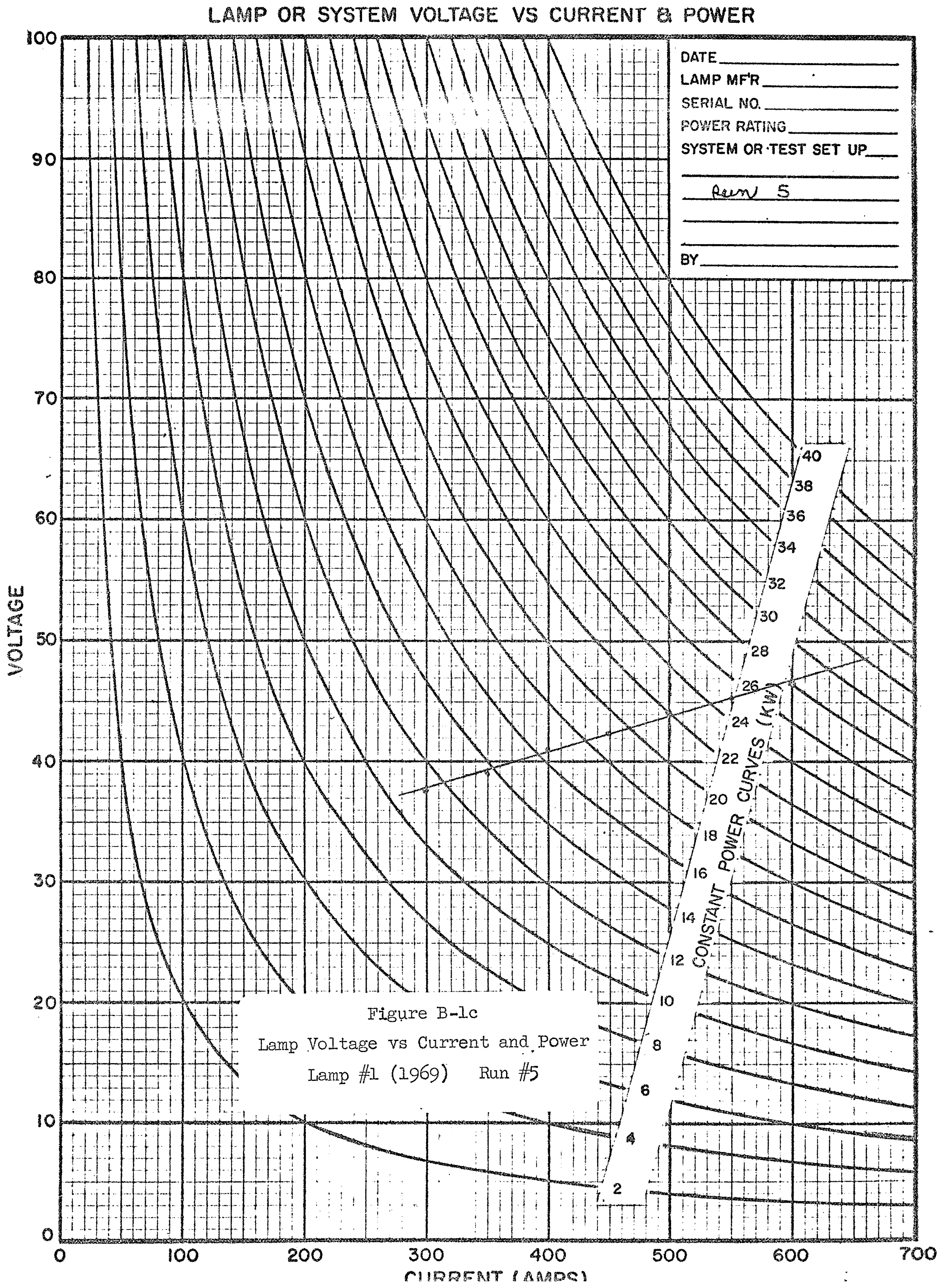

Figure B-1c
Lamp Voltage vs Current and Power
Lamp #1 (1969) Run #5

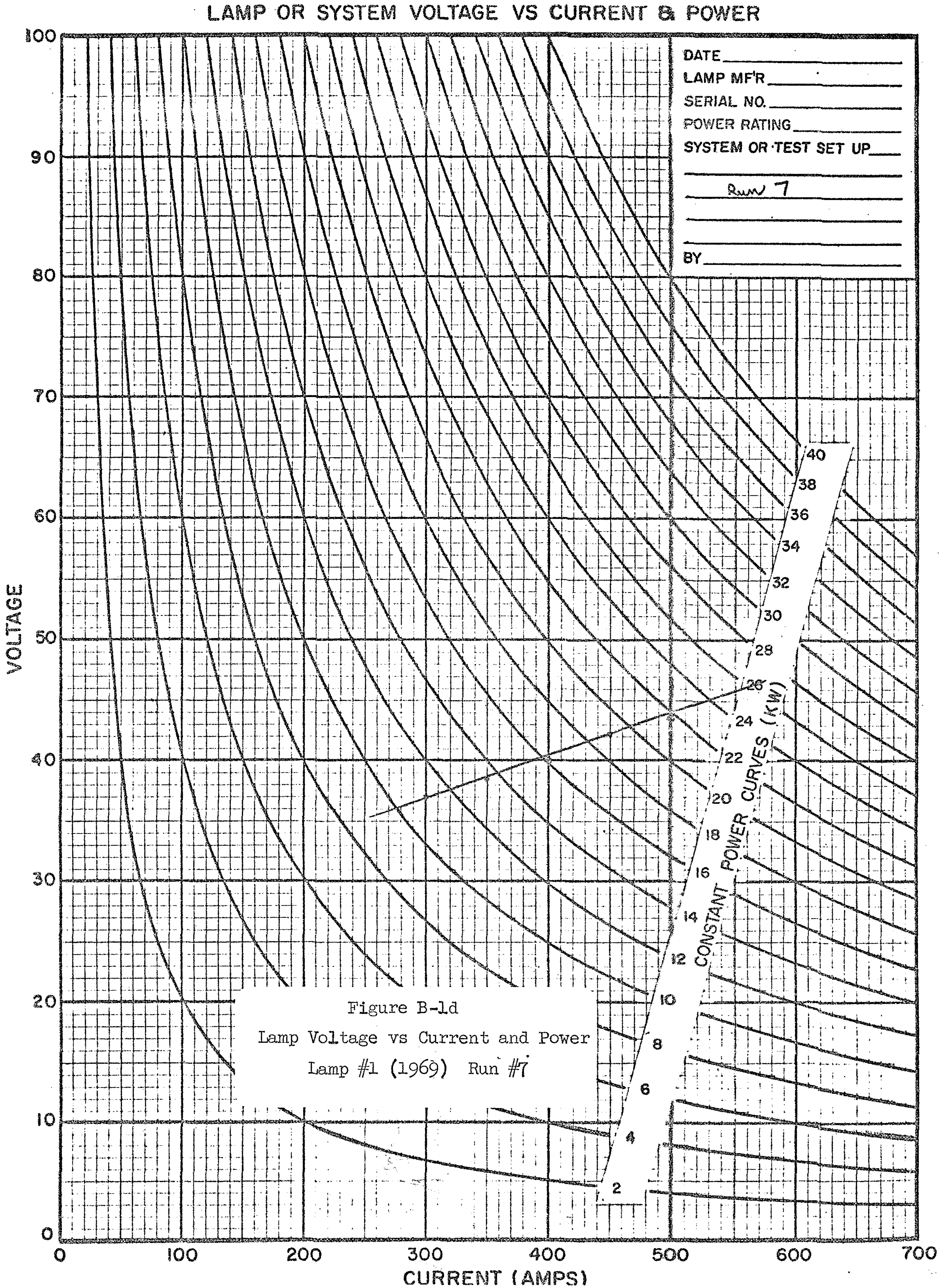

Figure B-1d

Lamp Voltage vs Current and Power

Lamp #1 (1969) Run #7

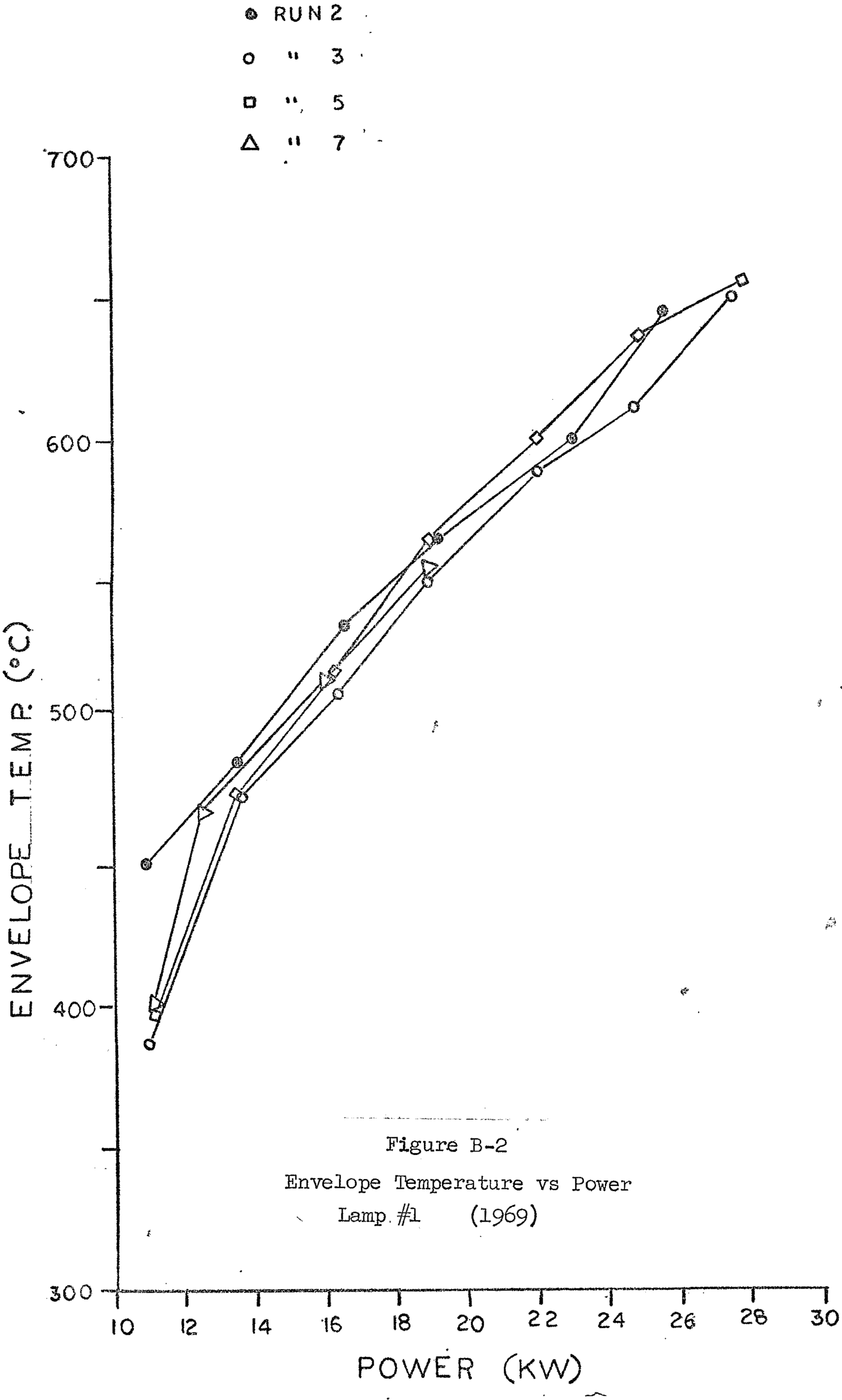

Figure B-2

Envelope Temperature vs Power

Lamp #1 (1969)

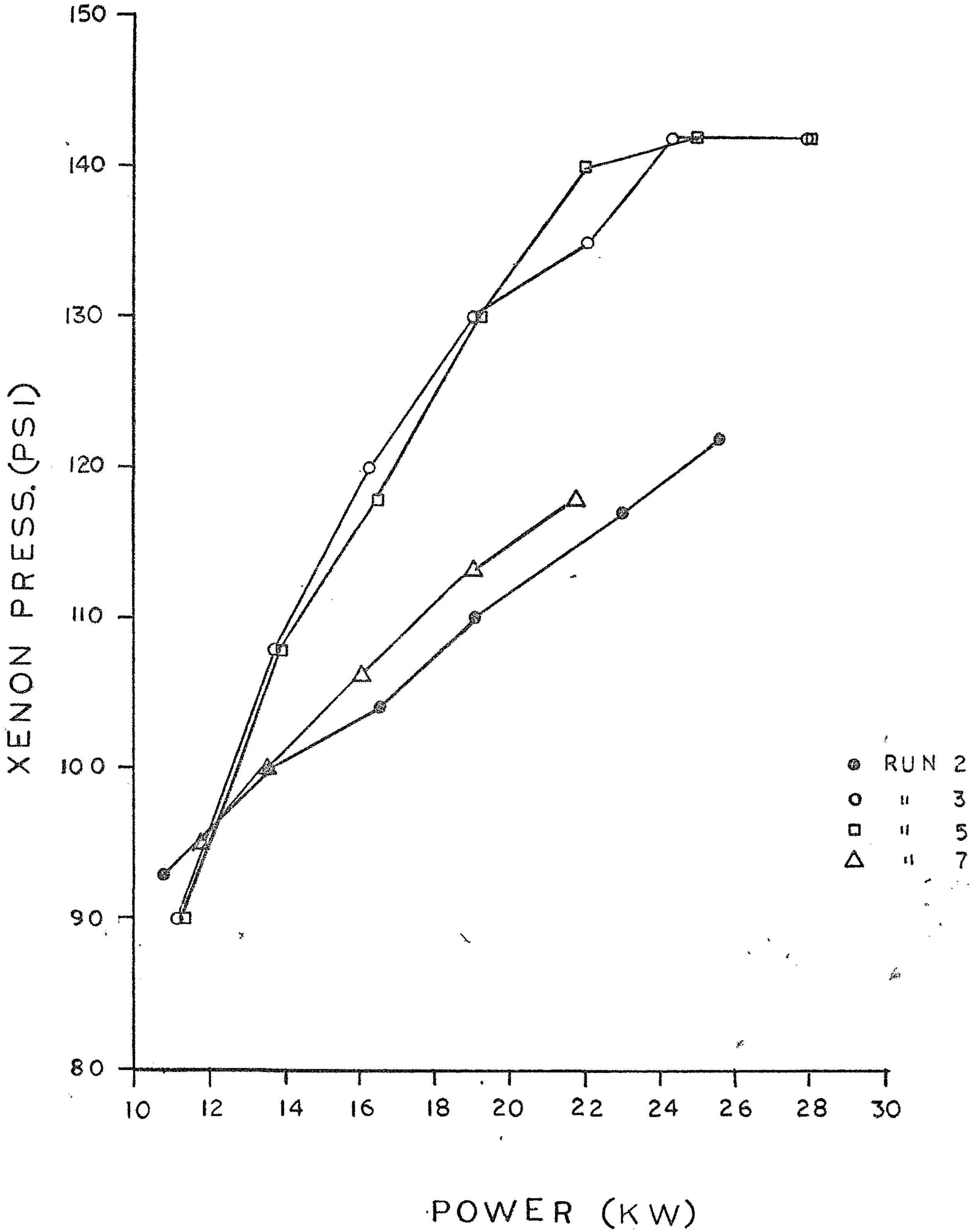

Figure B-3
Xenon Pressure vs Power
Lamp #1 (1969)

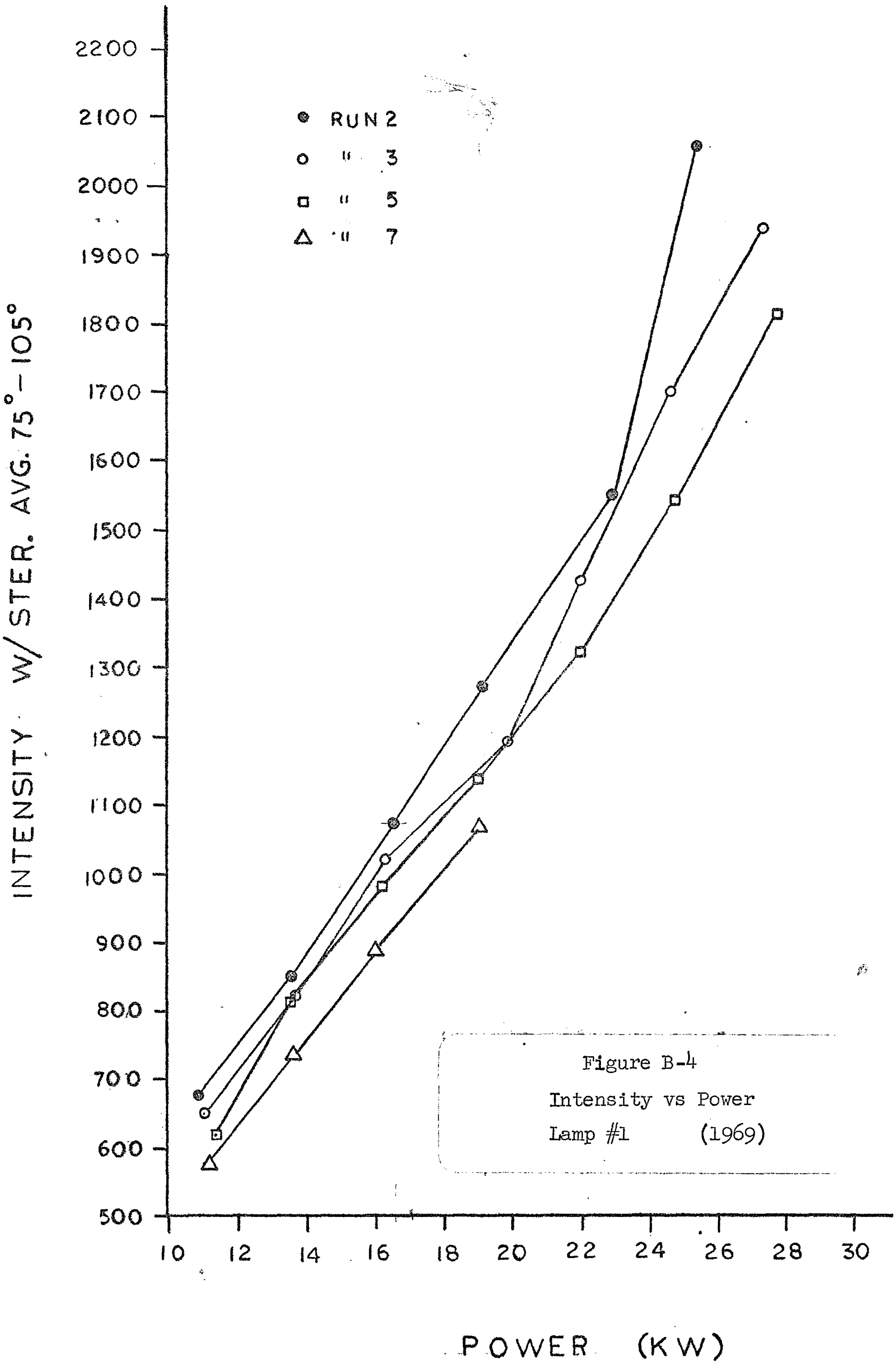

Figure B-4

Intensity vs Power

Lamp #1 (1969)

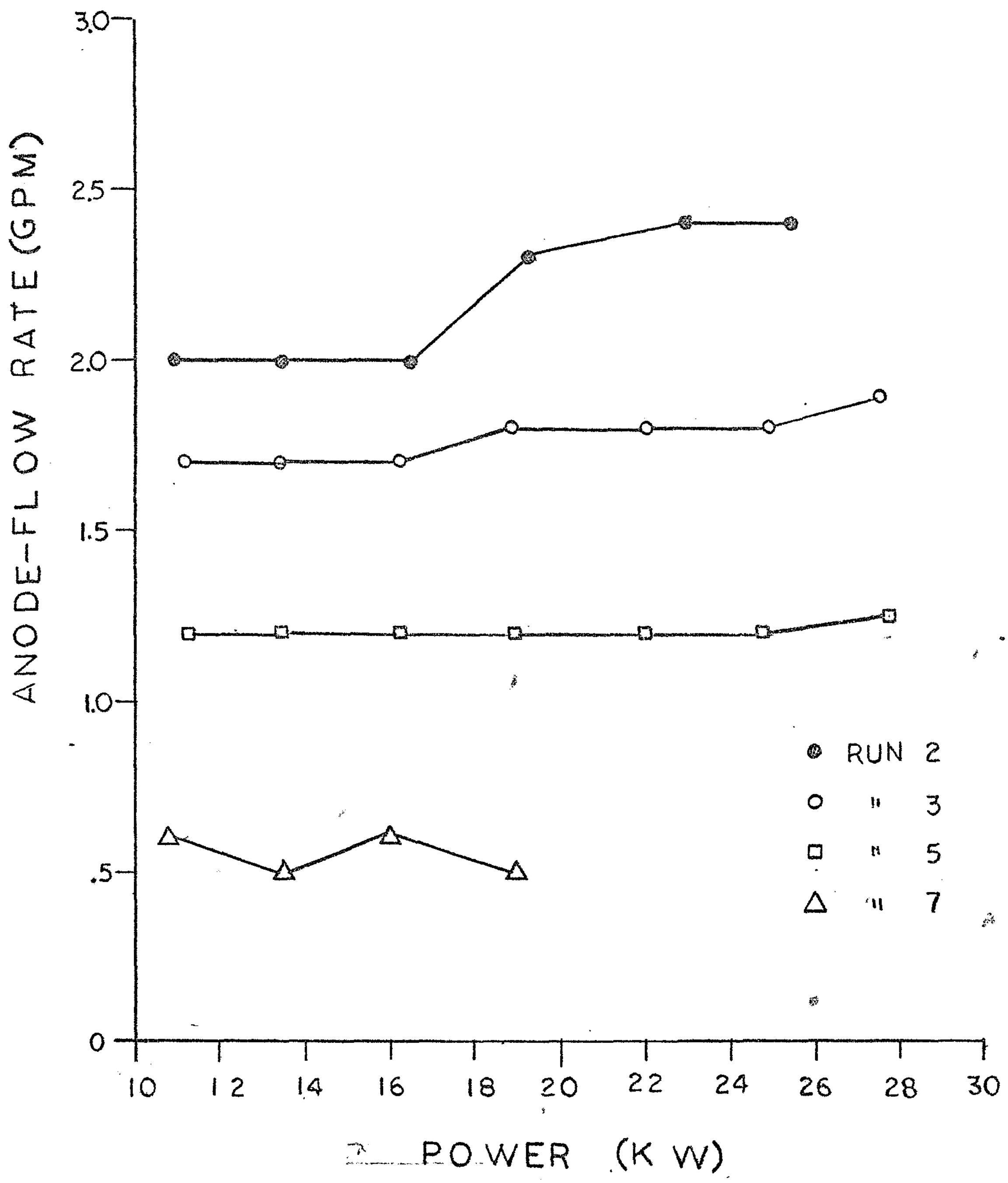

Figure B-5

Anode Flow Rate vs. Power

Lamp #1 (1969)

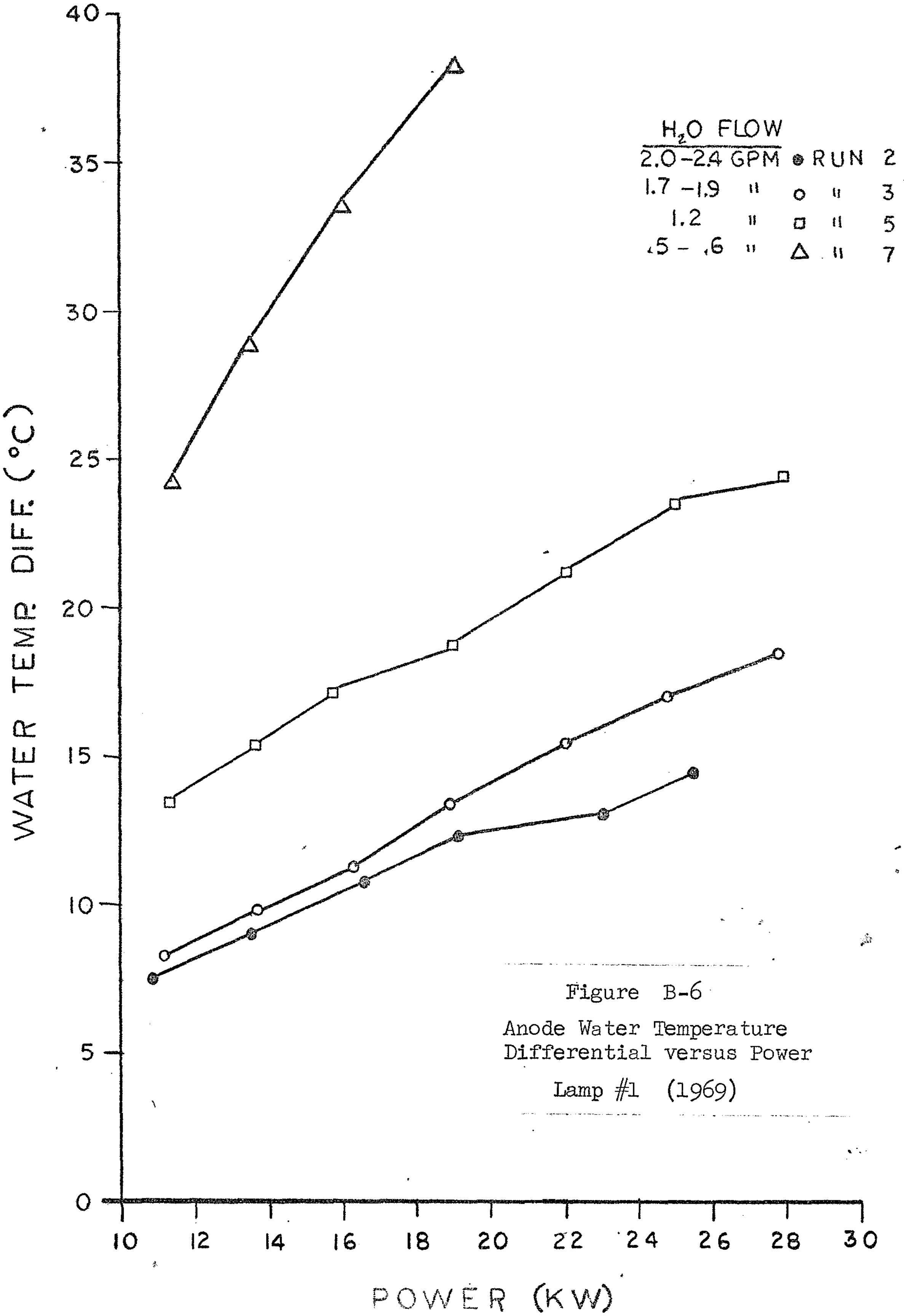

Figure B-6

Anode Water Temperature Differential versus Power

Lamp #1 (1969)

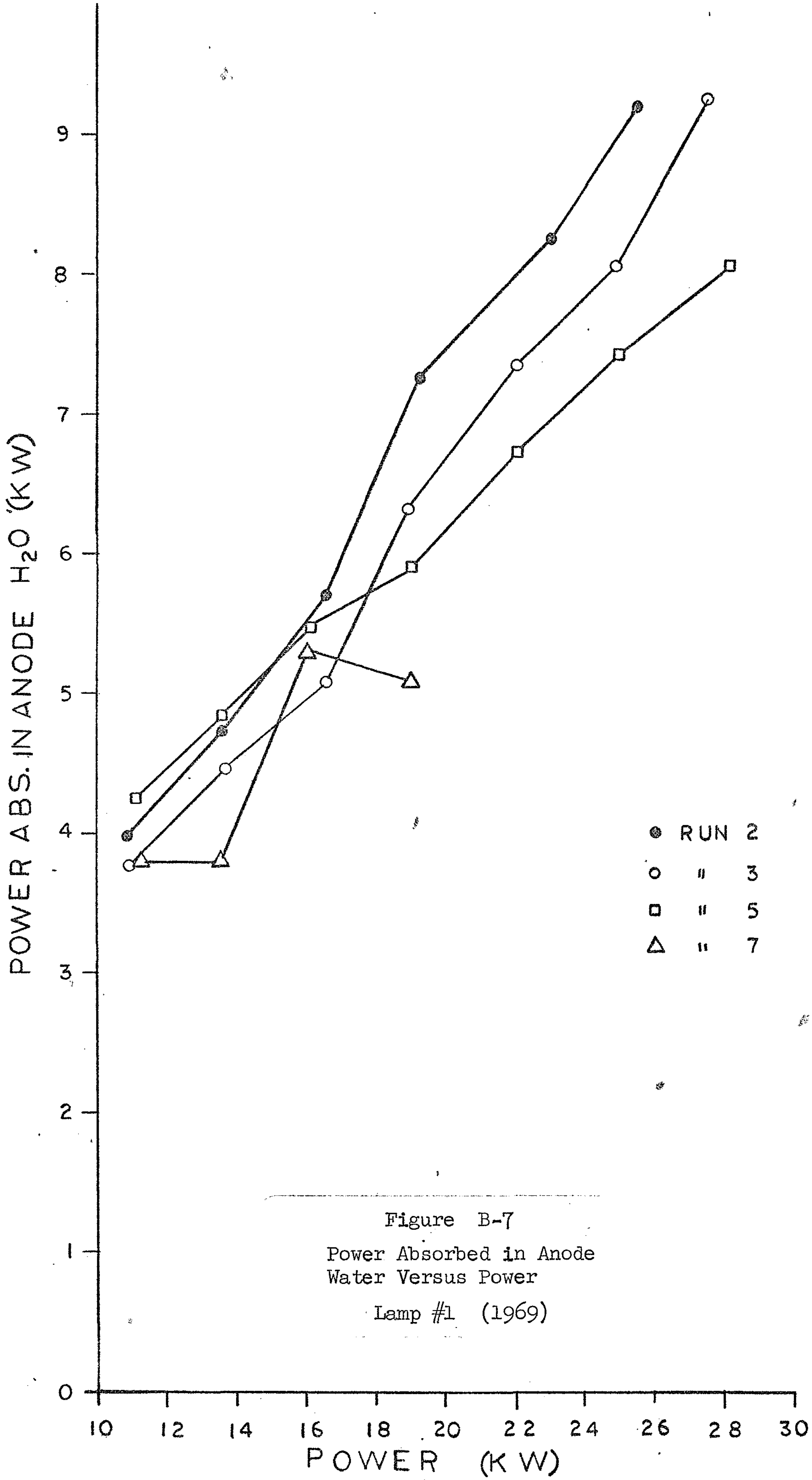

Figure B-7

Power Absorbed in Anode Water Versus Power

Lamp #1 (1969)

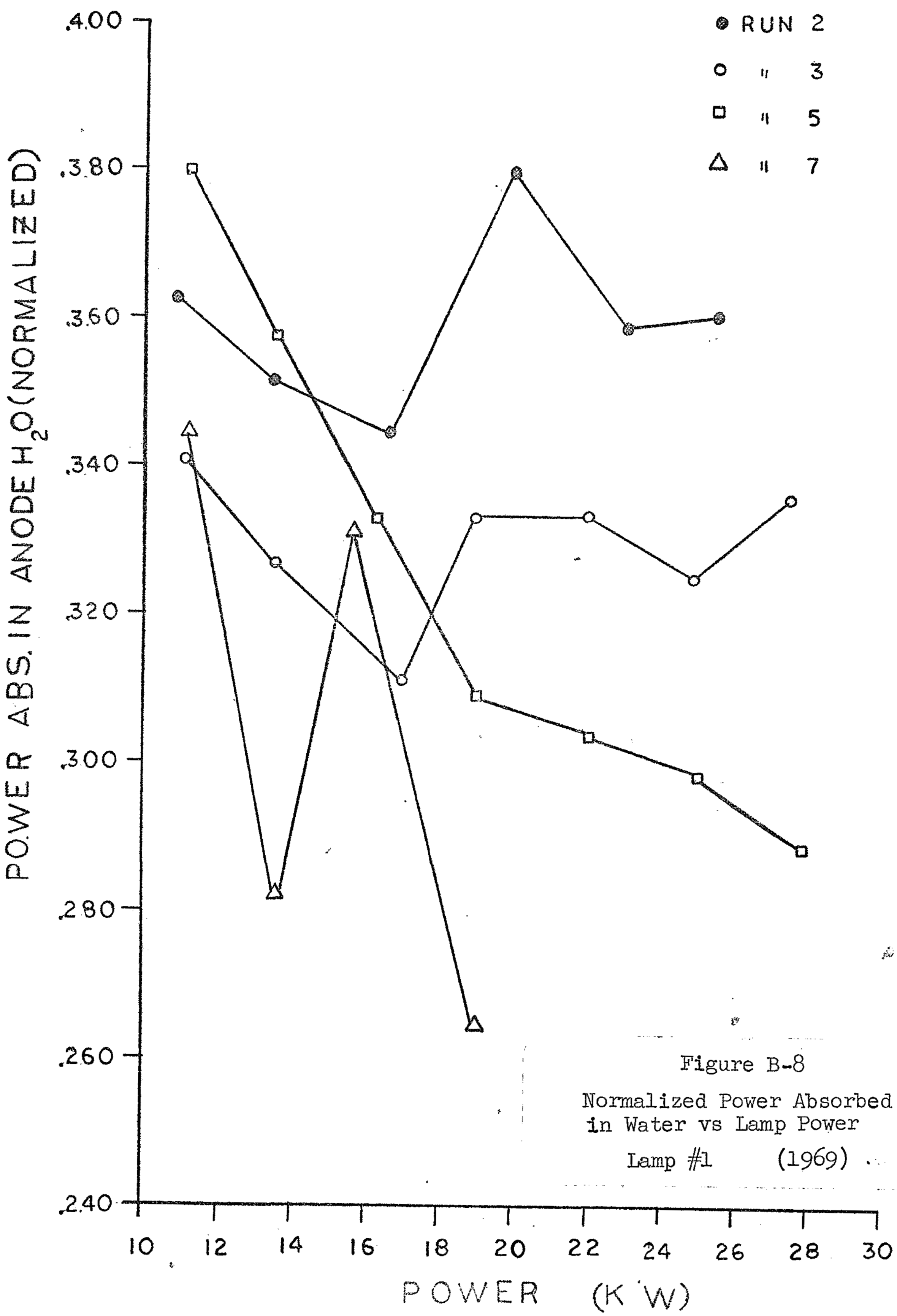

Figure B-8

Normalized Power Absorbed in Water vs Lamp Power

Lamp #1 (1969)

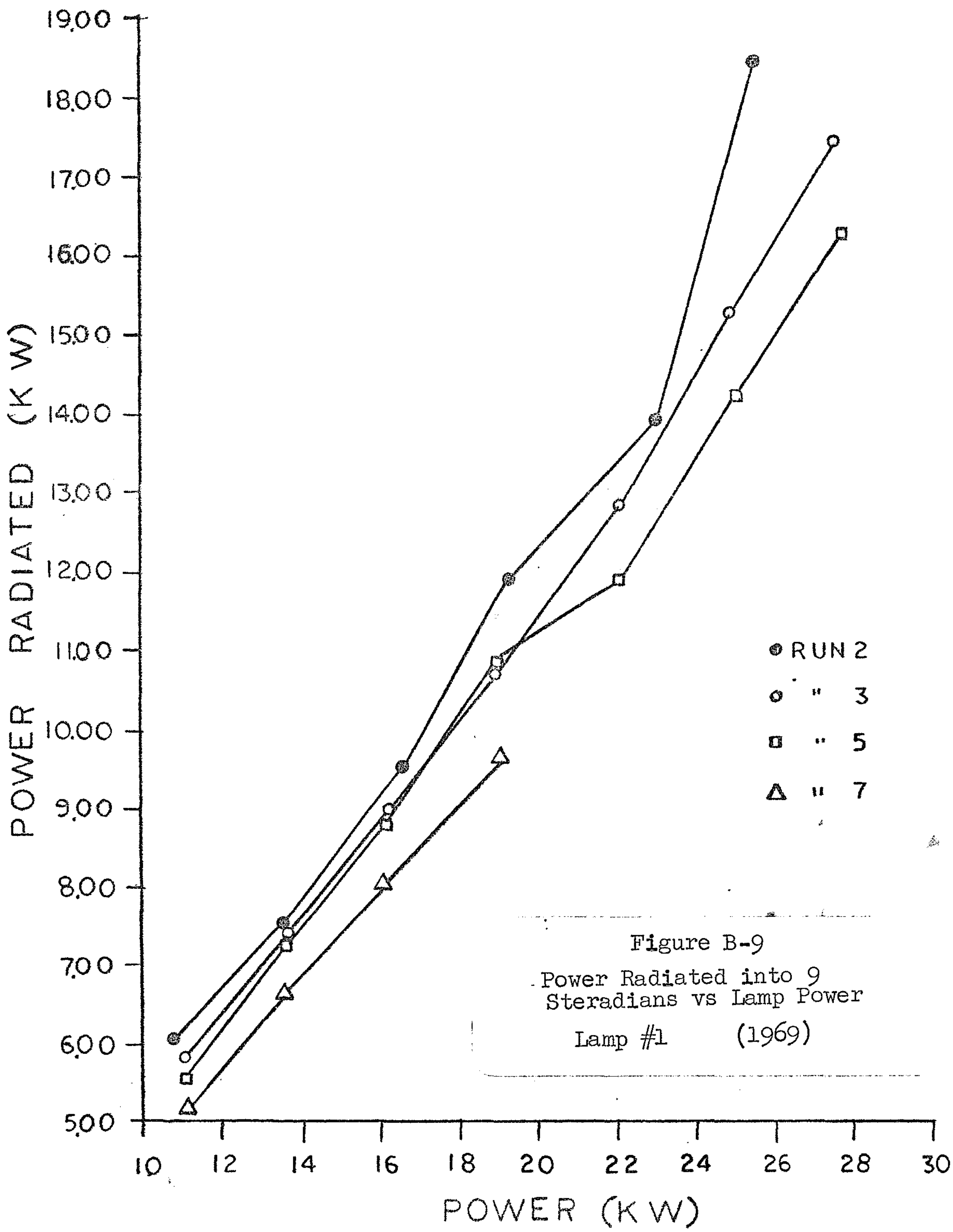

Figure B-9

Power Radiated into 9 Steradians vs Lamp Power

Lamp #1 (1969)

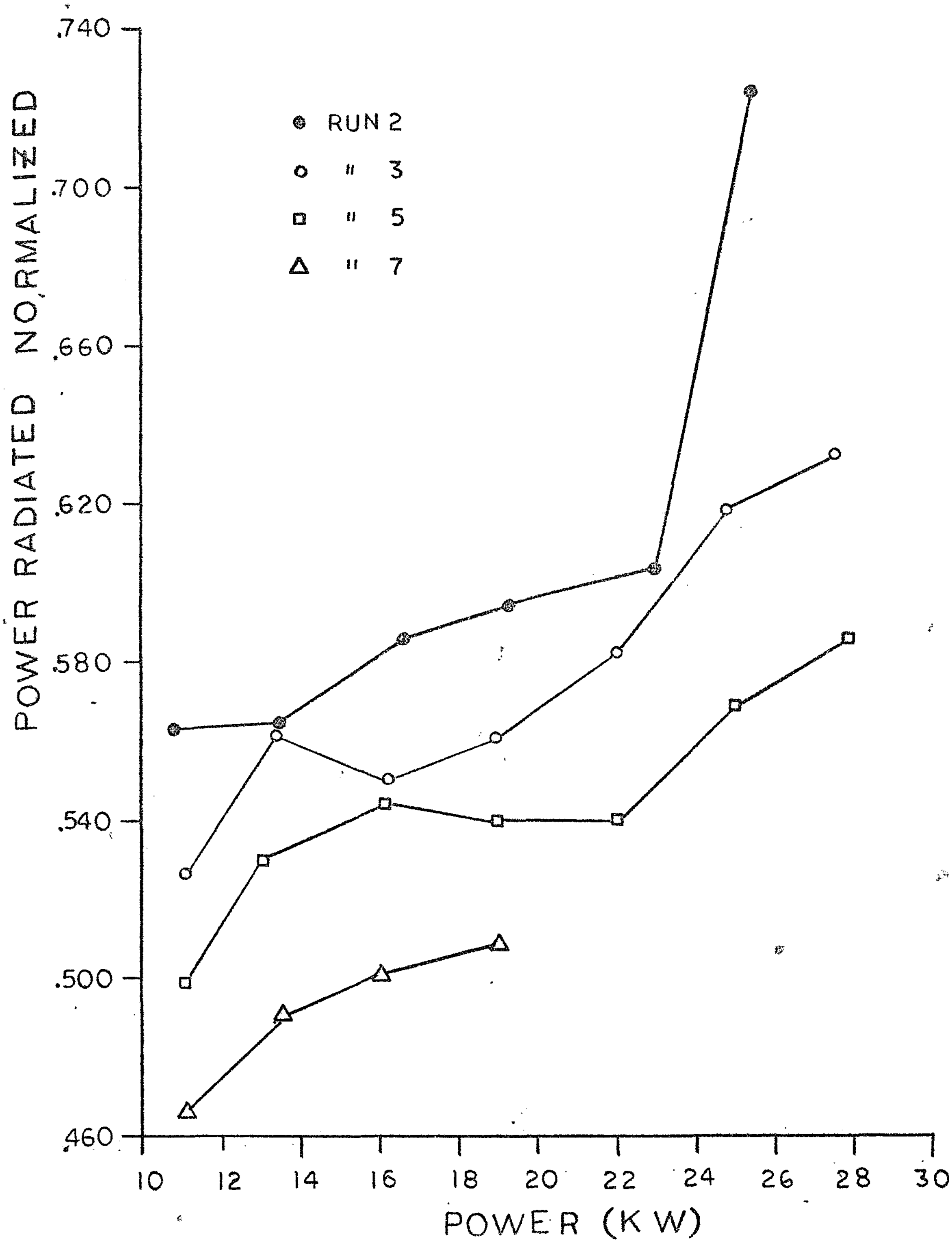

Figure B-10

Normalized Radiated Power
versus Lamp Power
Lamp #1 (1969)

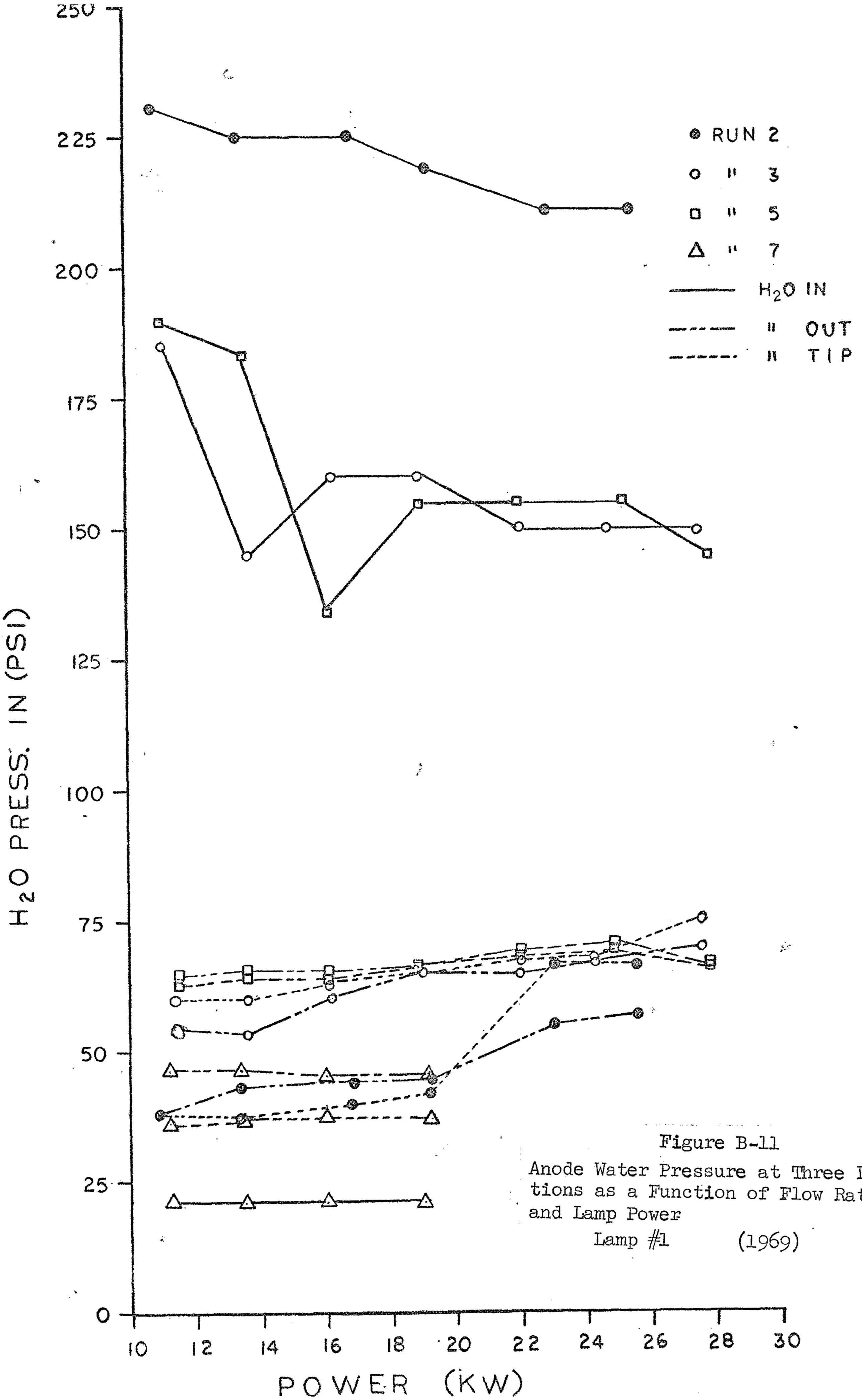

Figure B-11

Anode Water Pressure at Three Locations as a Function of Flow Rate and Lamp Power

Lamp #1 (1969)

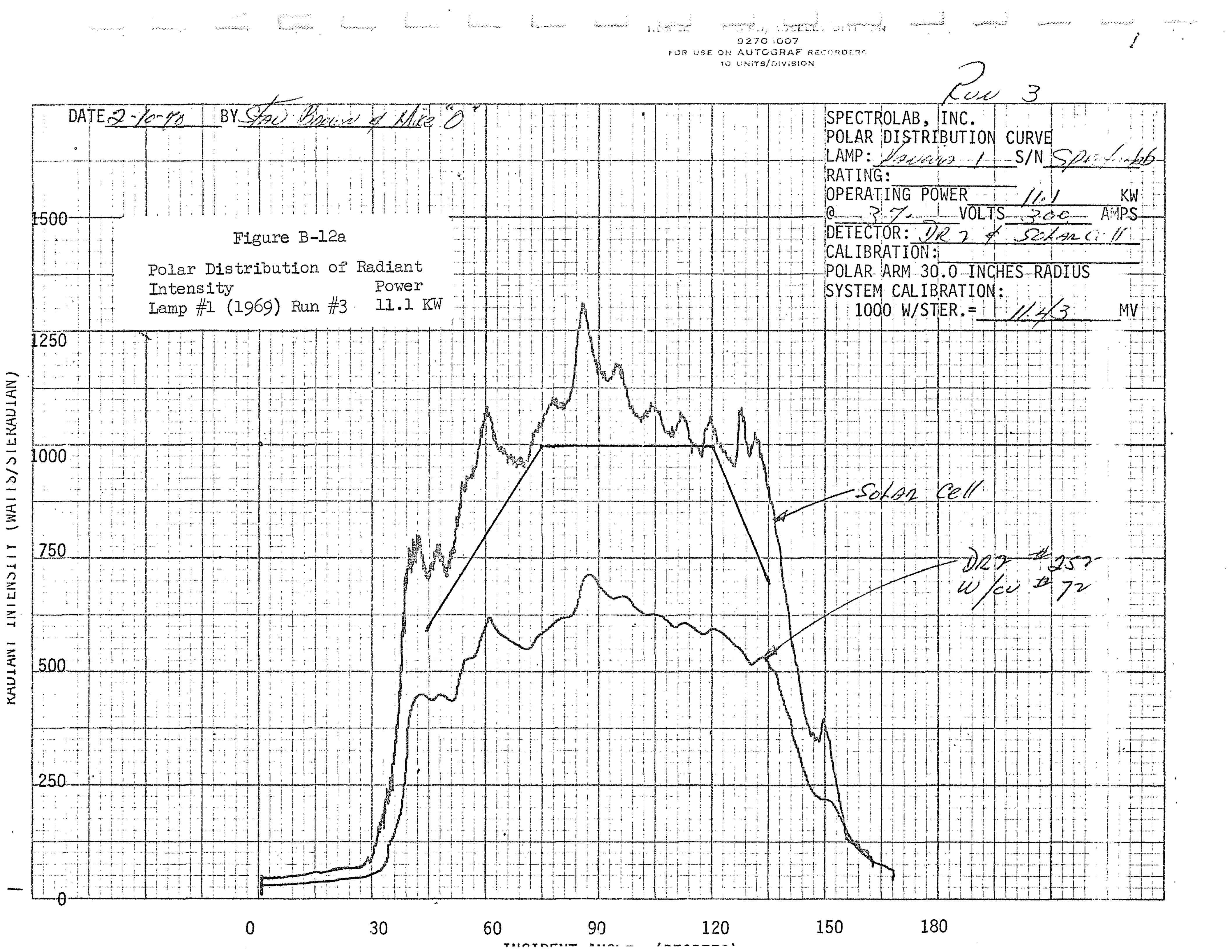

Figure B-12a

Polar Distribution of Radiant Intensity
Lamp #1 (1969) Run #3
Power 11.1 KW

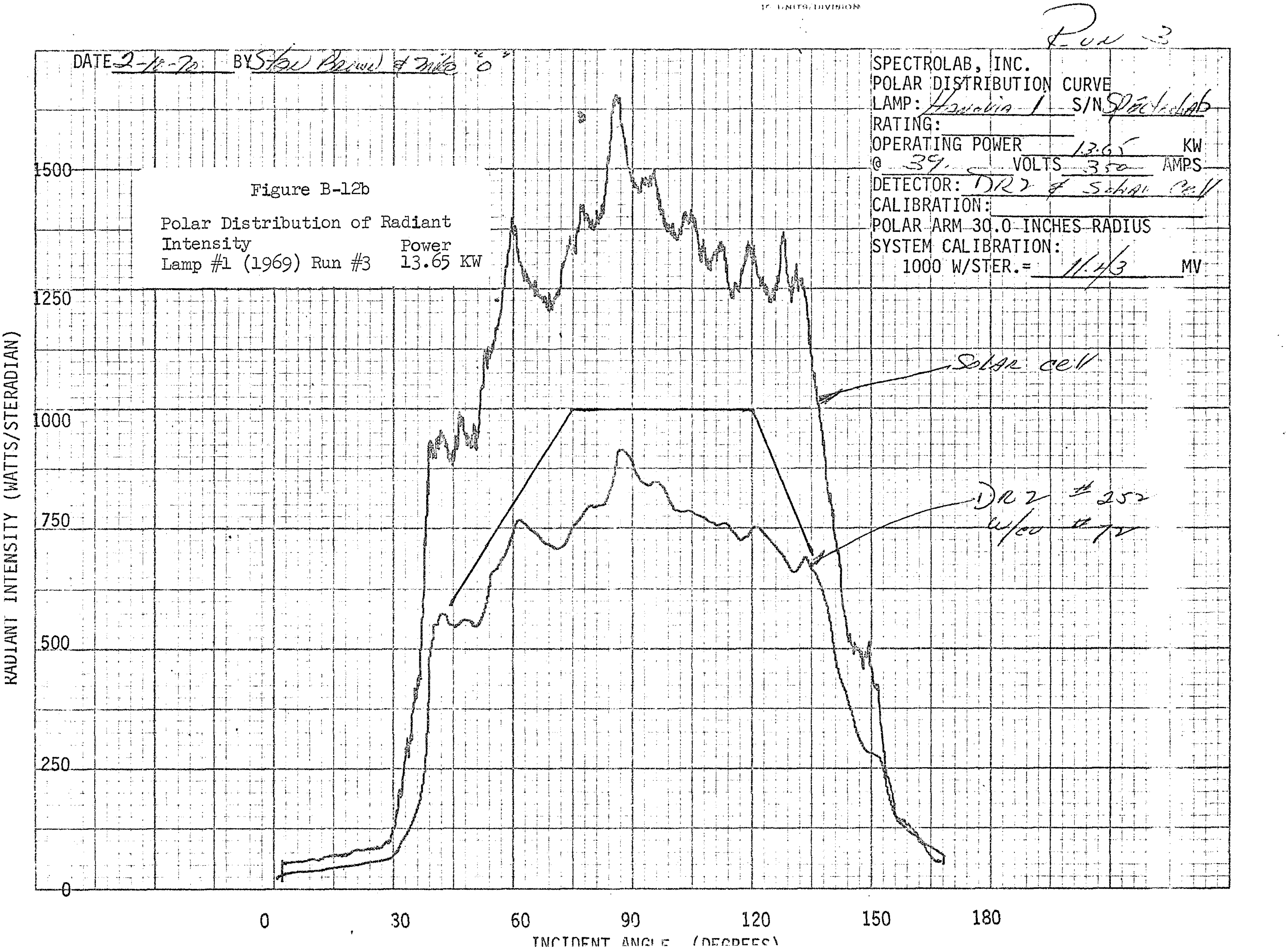

Figure B-12b

Polar Distribution of Radiant Intensity
Lamp #1 (1969) Run #3
Power 13.65 KW

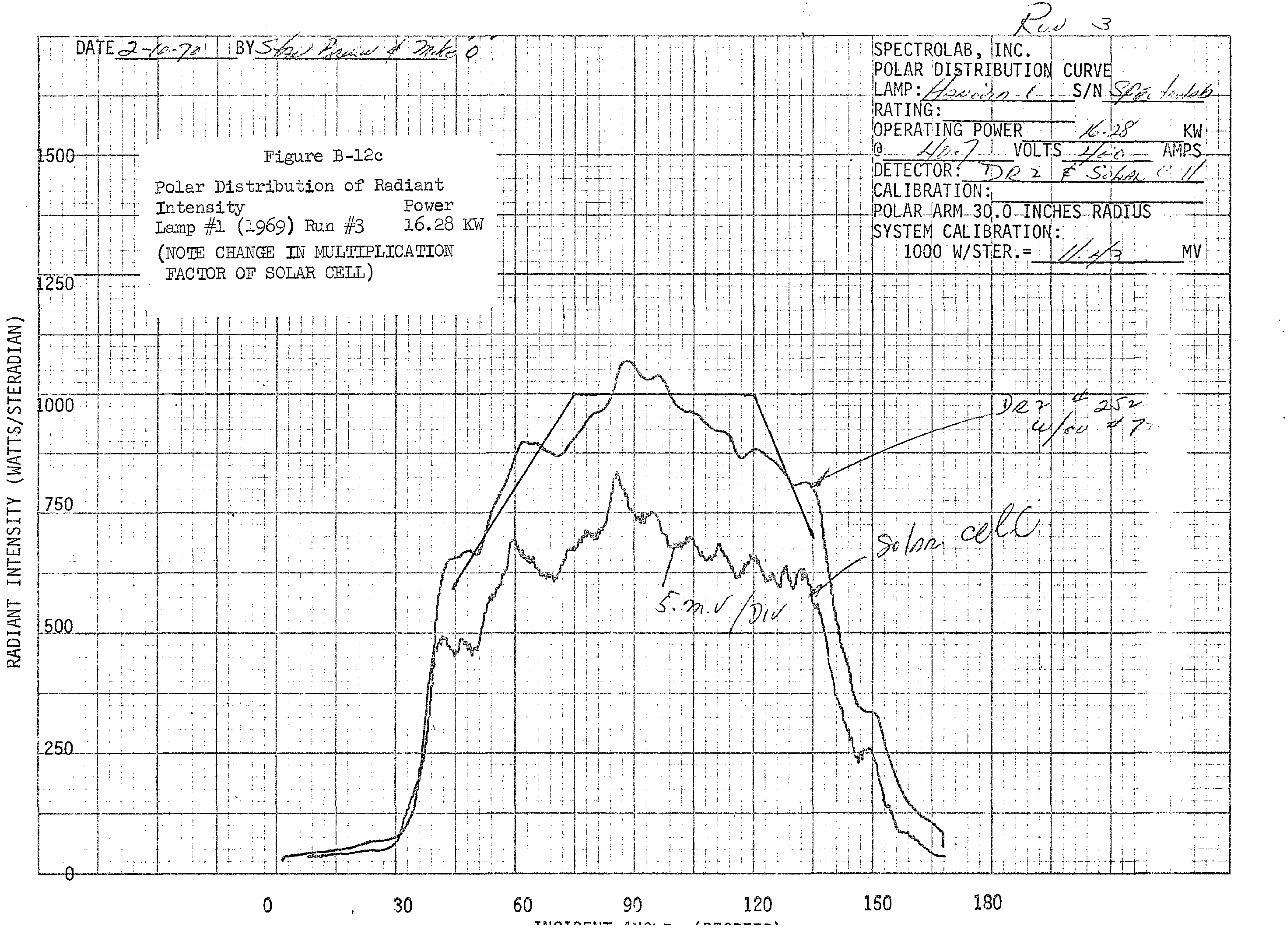

Figure B-12c

Polar Distribution of Radiant Intensity Power
Lamp #1 (1969) Run #3 16.28 KW
(NOTE CHANGE IN MULTIPLICATION FACTOR OF SOLAR CELL)

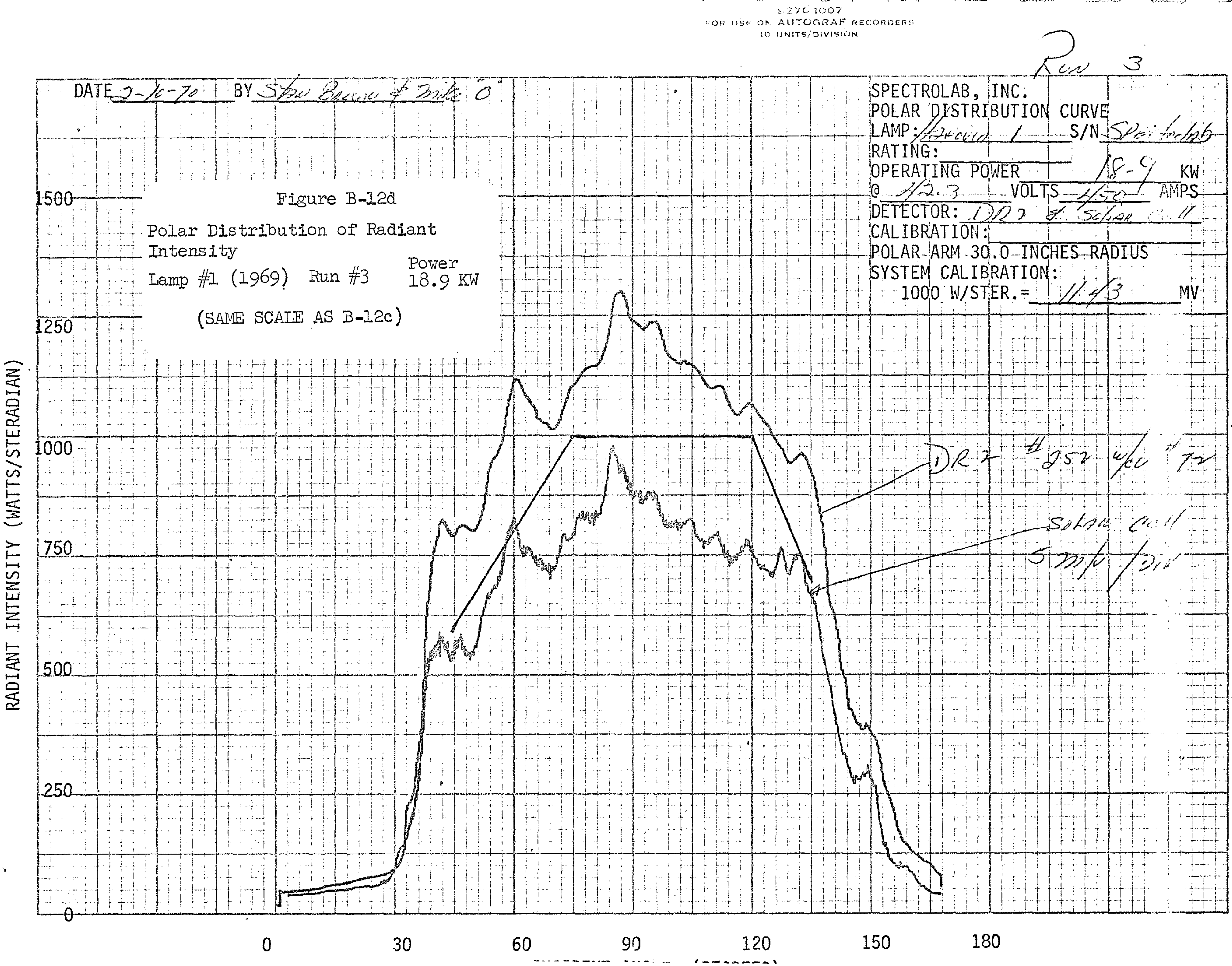

Figure B-12d

Polar Distribution of Radiant Intensity

Lamp #1 (1969) Run #3 Power 18.9 KW

(SAME SCALE AS B-12c)

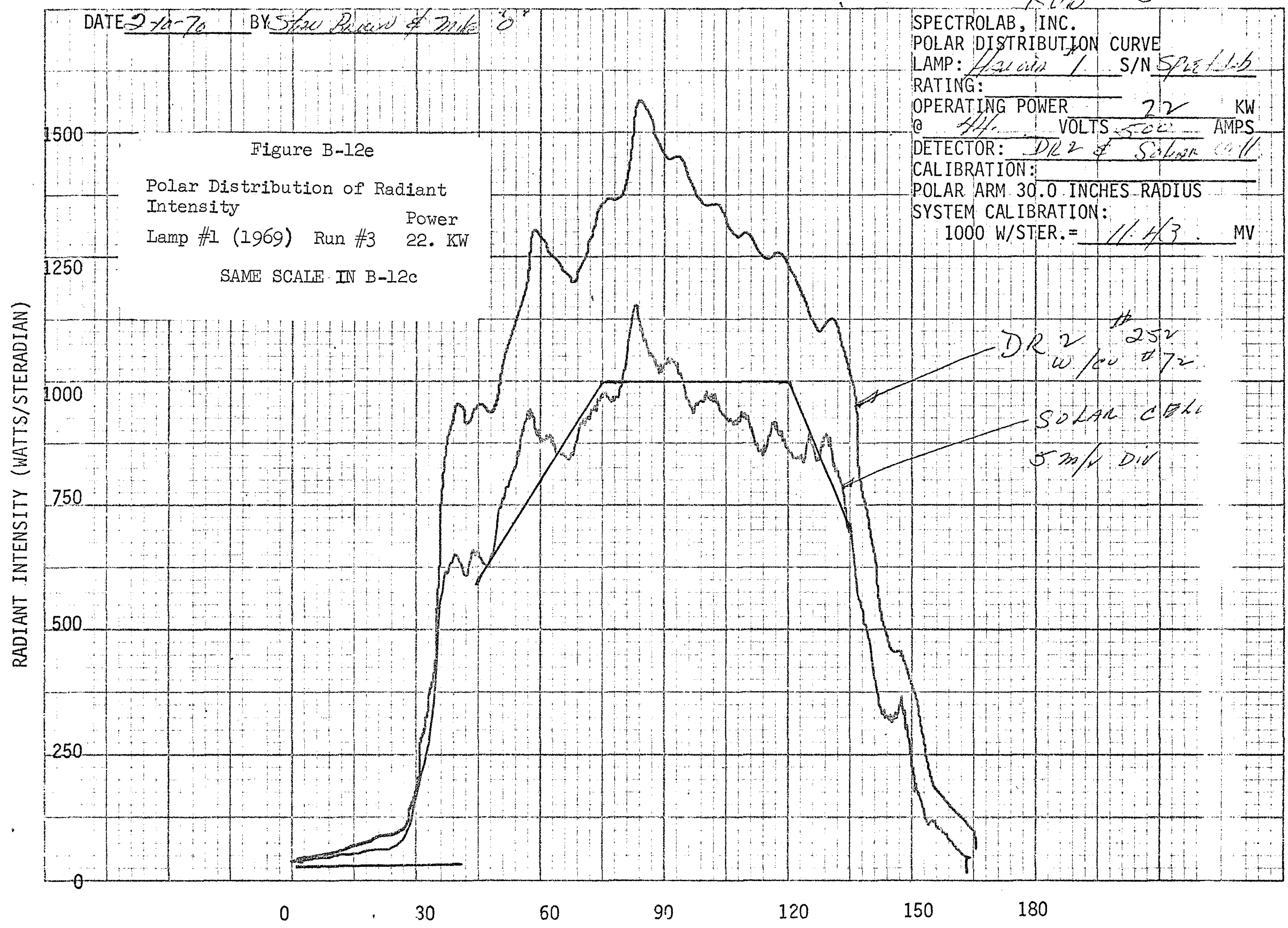

Figure B-12e

Polar Distribution of Radiant Intensity

Lamp #1 (1969) Run #3 Power 22. KW

SAME SCALE IN B-12c

9270-1007
FOR USE ON AUTOGRAF RECORDERS
10 UNITS/DIVISION

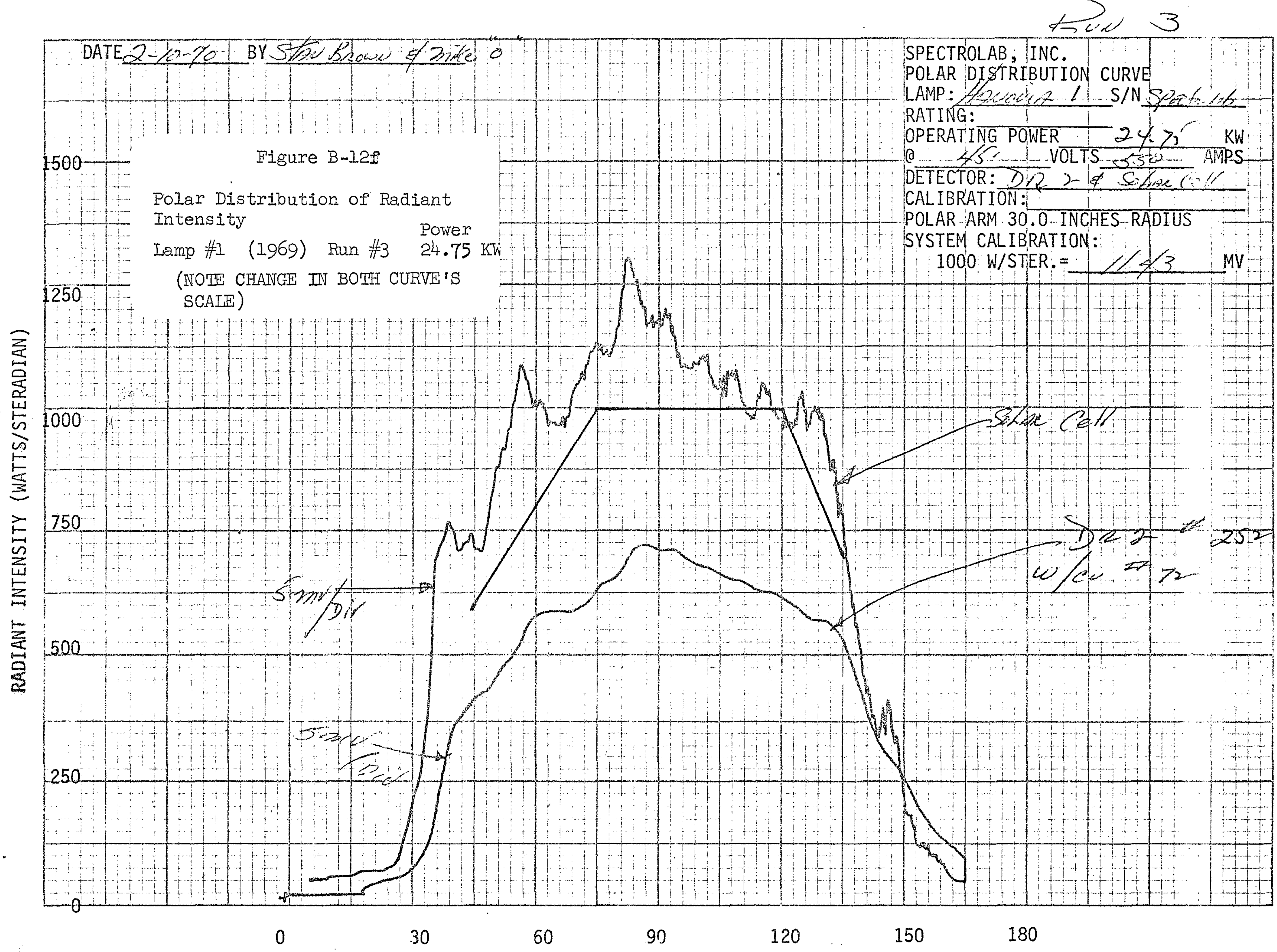

Figure B-12f

Polar Distribution of Radiant Intensity

Lamp #1 (1969) Run #3 Power 24.75 KW

(NOTE CHANGE IN BOTH CURVE'S SCALE)

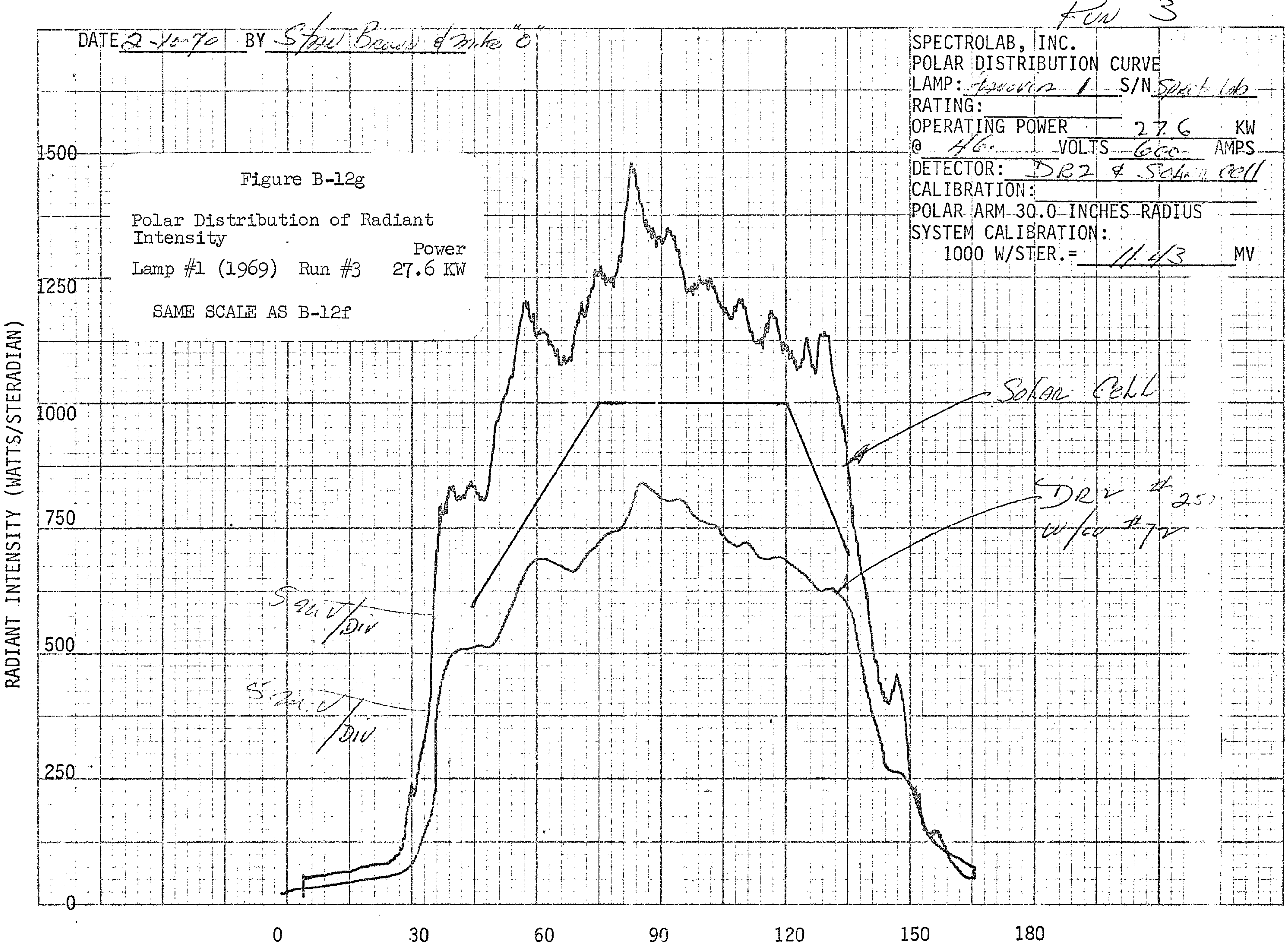

Figure B-12g

Polar Distribution of Radiant Intensity

Lamp #1 (1969) Run #3 Power 27.6 KW

SAME SCALE AS B-12f

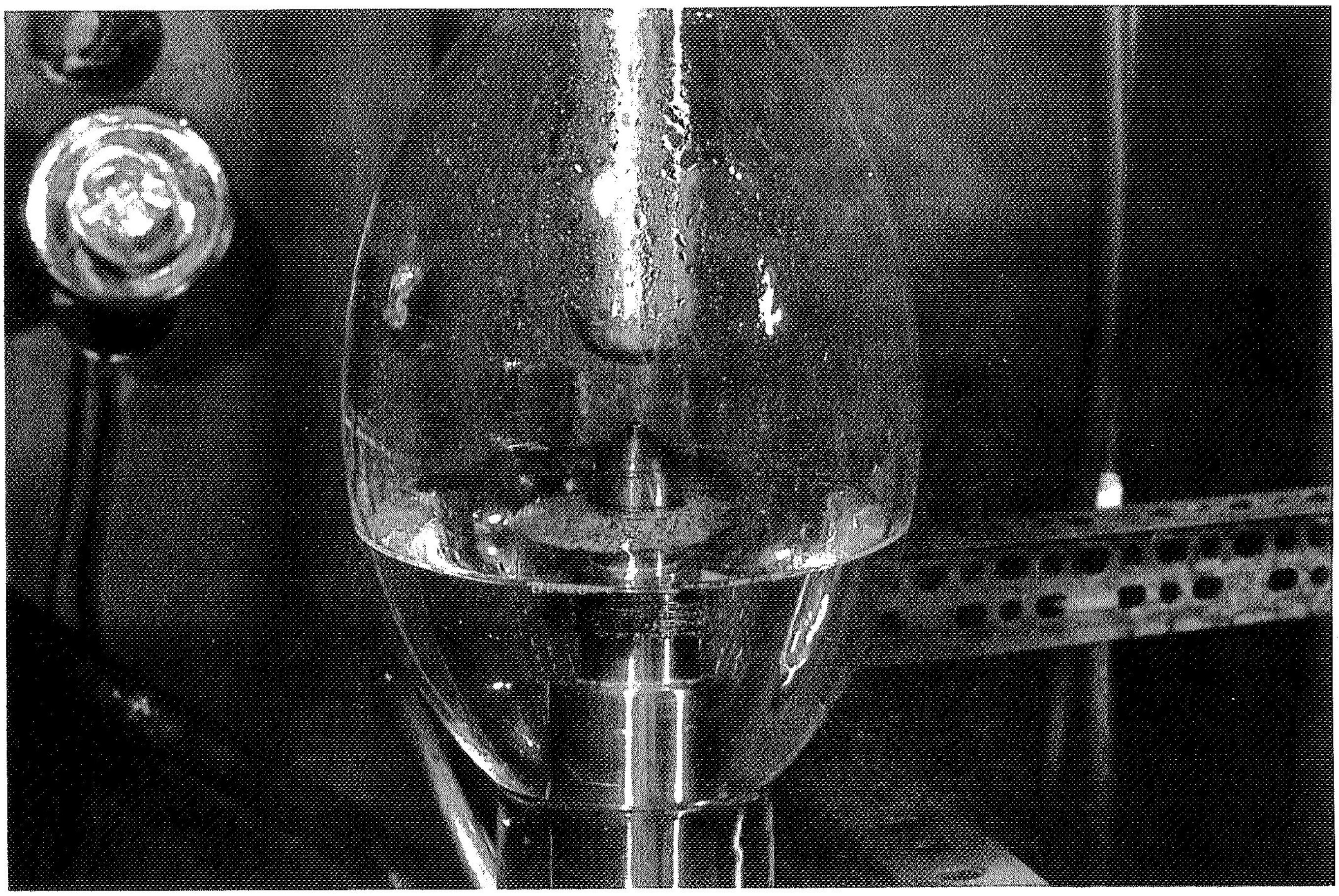

Figure B-13 - Lamp #1 (1969) After Anode Failed at 21.7 KW
With 0.5 GPM Water Flow

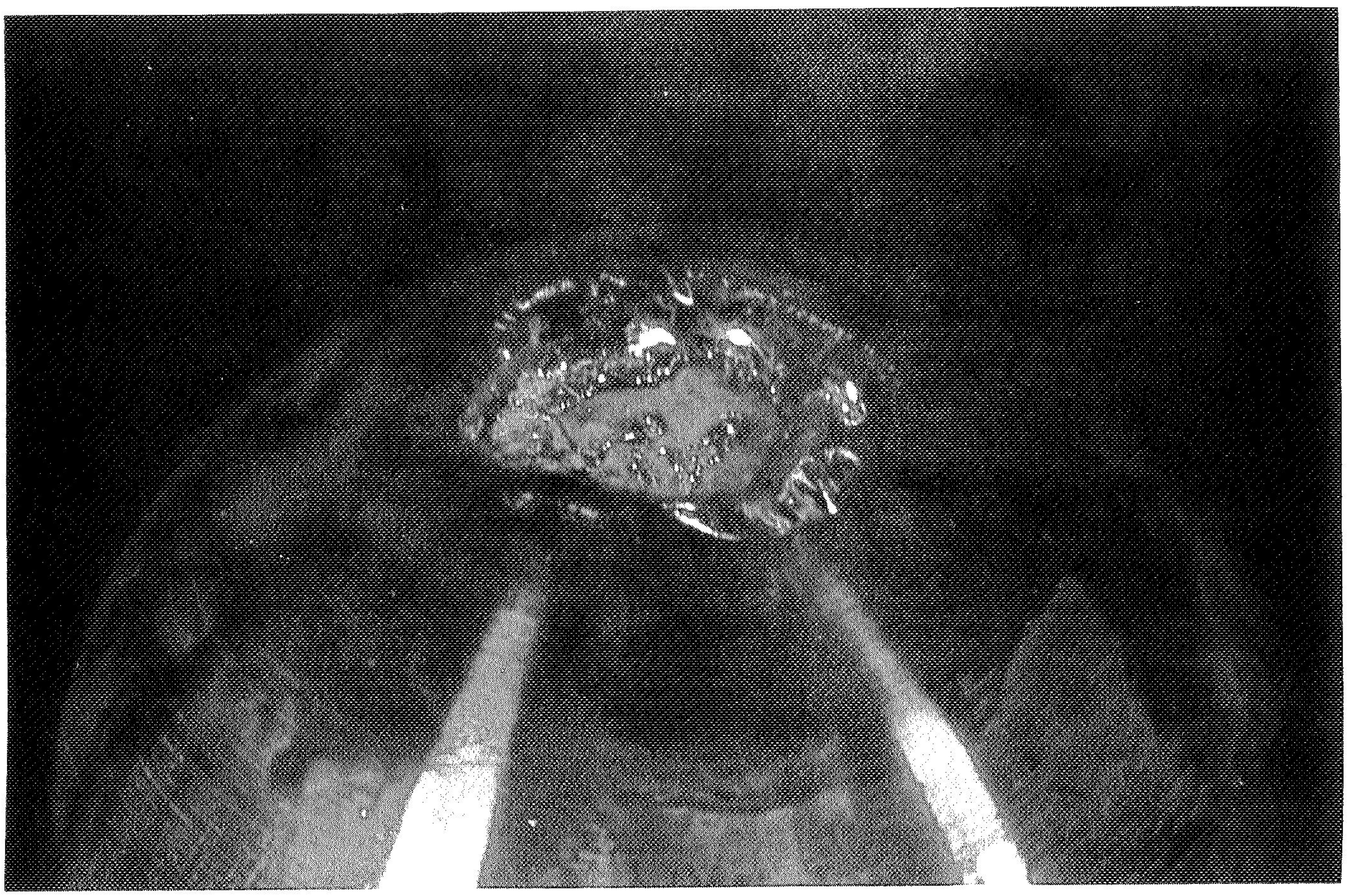

Figure B-14 - Close Up View of Anode Tip Showing Hole Caused
By Electron Beam Lamp # 1 (1969)

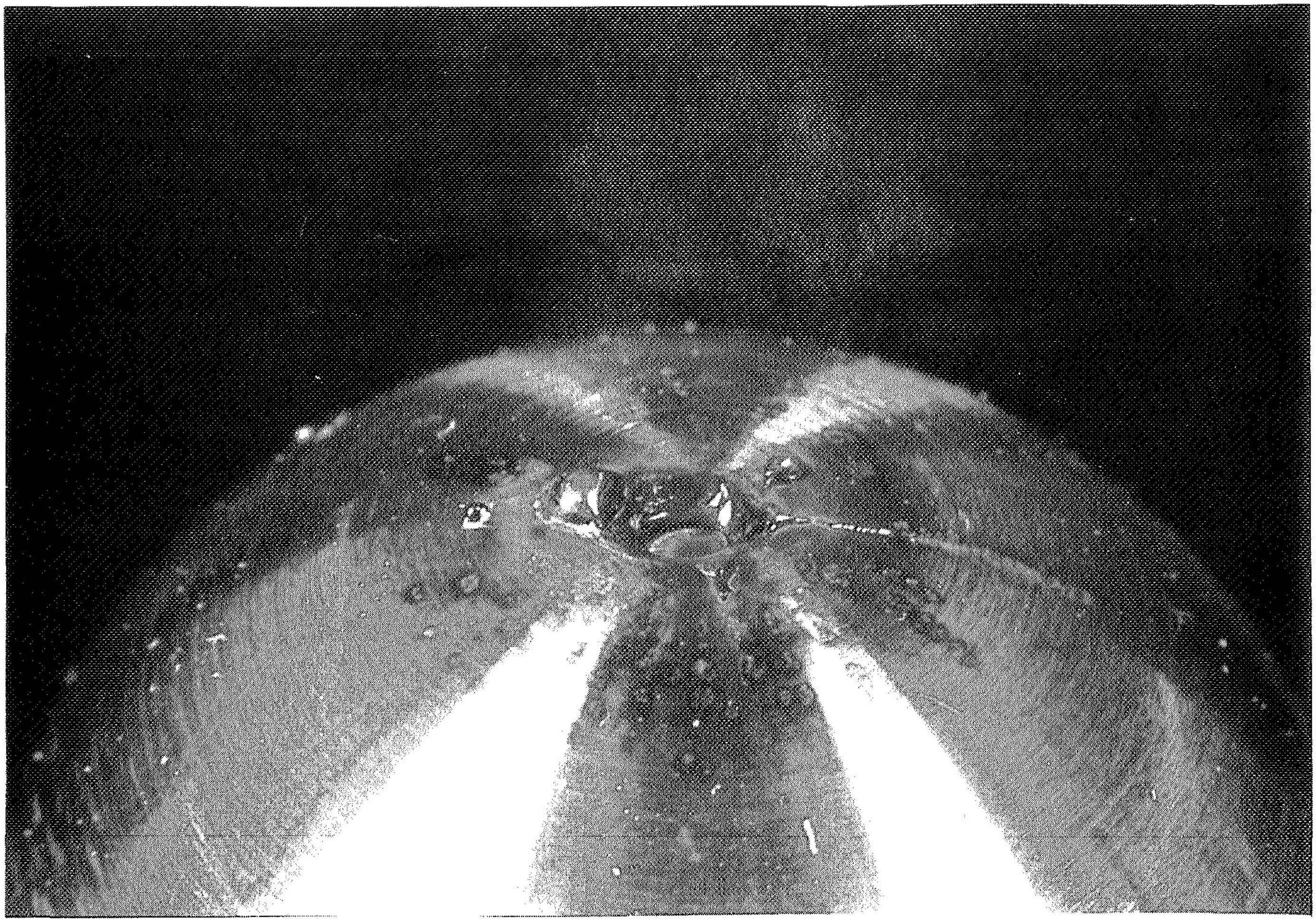

Figure B-15 - Close Up View of Anode Tip Showing Hole Caused

By Electron Beam Lamp #2 (1969)