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AMC EN-1038
REDUCED SCALE SOLAR SIMULATOR
SUPPLEMENTARY TEST REPORT

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ABSTRACT

The reduced scale solar simulator program conducted by the Advanced Manufacturing Center at Cleveland State University in 1992 provided sufficient data to support the selection of the uniform magnification solar simulator module for the Solar Dynamic Ground Test Demonstrator Program (SDGTD) at NASA LeRC. In 1993, additional testing of the reduced scale solar simulator was conducted to provide information to refine and improve the design of the full scale solar simulator. This report presents the results of these additional tests.

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SUPPLEMENTARY TEST REPORT

1.0 INTRODUCTION

1.1 BACKGROUND

During the summer of 1992, the Advanced Manufacturing Center at Cleveland State University performed analyses, prepared designs, and conducted evaluation tests of a one third scale solar simulator module for NASA Lewis Research Center. The solar simulator module utilized a unique design collector and lens to concentrate rays from a Xenon lamp in a manner that provided uniform magnification of the rays intensity. The new design was compared to the standard design elliptical collector module and found to provide more power at standardized conditions and the power was distributed more uniformly across the target surface. As a result, the uniform magnification module was selected for the 2 KW Solar Dynamic Ground Test Demonstrator (SDGTD) Program at NASA LeRC.

In 1993, additional testing of the one third scale solar simulator uniform magnification and elliptical modules was conducted per AMC EN-1036 to provide more information to refine and supplement the work done in 1992. This report summarizes the results of these additional tests.

1.2 PURPOSE OF TESTS

The testing conducted in 1993 was to verify previous test results and to evaluate solar simulator module performance at more expanded test conditions. In 1992, the entire program from design, to manufacture of the test components and test stands, and testing of the two modules was completed in approximately four and one half months. Because of this accelerated schedule, only the basic tests needed to evaluate the two modules could be completed. While the information obtained was sufficient to support the choice of the uniform magnification module for SDGTD, additional data were desired to refine the analysis of the simulator. These supplementary tests initially verified previous results to assure that no changes had occurred in test equipment or test setup and then explored new test conditions which could not be completed in 1992.

1.3 TEST OBJECTIVES

The test objectives for both uniform magnification and elliptical solar simulator modules were the same. The tests were divided into three categories; tests with a Xenon lamp, tests with an incandescent lamp, and geometry tests.

The test objectives for tests with the Xenon lamp were as follows:

1. Obtain analytical correlation between the total power measured through various size apertures in the aperture plane and the total power calculated from discrete measurements of power during mapping of the aperture plane.

2. Establish the relationship between power in a ring about the center of the aperture and the radius of the ring.

3. Establish the characteristic of total power versus aperture diameter for apertures from as small as possible to 1.547 inch diameter.

Tests with an incandescent lamp with uniform intensity output were conducted to show the effect of uniform intensity from the lamp source on simulator performance. The objectives were:

1. Determine the uniformity of the incandescent lamp.

2. Measure the uniformity of the solar simulator modules at the target plane using the uniform intensity incandescent lamp.

Several tests of the solar simulator modules were conducted to evaluate geometry features of module components by viewing an illuminated spot from various planes of the modules. The objectives were:

1. With an illuminated spot located at collector focal point, determine the variation in size and shape of the spot along the radii of both collectors when viewed from the plane of the lens.

2. With an illuminated spot located at the aperture plane, determine the variation in size and shape of the spot along the radius of the lens when viewed from the plane of the uniform magnification collector.

3. With an illuminated spot located at collector focal point, determine the variation in size and shape of the spot across the aperture when viewed from the target plane of both modules.

2.0 SUMMARY OF RESULTS

2.1 XENON LAMP TESTS

2.1.1 UNIFORM MAGNIFICATION MODULE

The aperture plane of the uniform magnification module was mapped in two directions by taking readings on a laser power meter in increments of .1 to .2 inches across the diameter of the aperture plane. The orientation of the two directions of the mapping were 90^0 apart and were designated as $+45^0$ and -45^0 indicating plus or minus from the nodule on the Xenon lamp. These planes were chosen so that the nodule would not interfere with the readings of the laser power meter.

The map of the aperture plane for the uniform magnification collector is shown in Figure 2-1 for $+45^0$ orientation and in Figure 2-2 for the -45^0 orientation. As can be seen from these figures, the relationship of flux to radius is nearly identical in each plane indicating that a uniform pattern exists around the circumference of a given radius of the aperture plane. In addition, flux peaks at the center of the aperture and is contained primarily within a one inch radius.

Figure 2-3 is a plot of the total power through various size apertures. Total power as measured with a laser power meter at the aperture is indicated by the test points. The curve designated as calc power was obtained by calculating the total power at different size apertures from Figures 2-1 and 2-2. Excellent agreement was obtained between the two methods with the maximum discrepancy being only 3 percent except at the .4 inch diameter where the discrepancy was 14 percent. This analysis verifies both the test equipment and the design of the uniform magnification module.

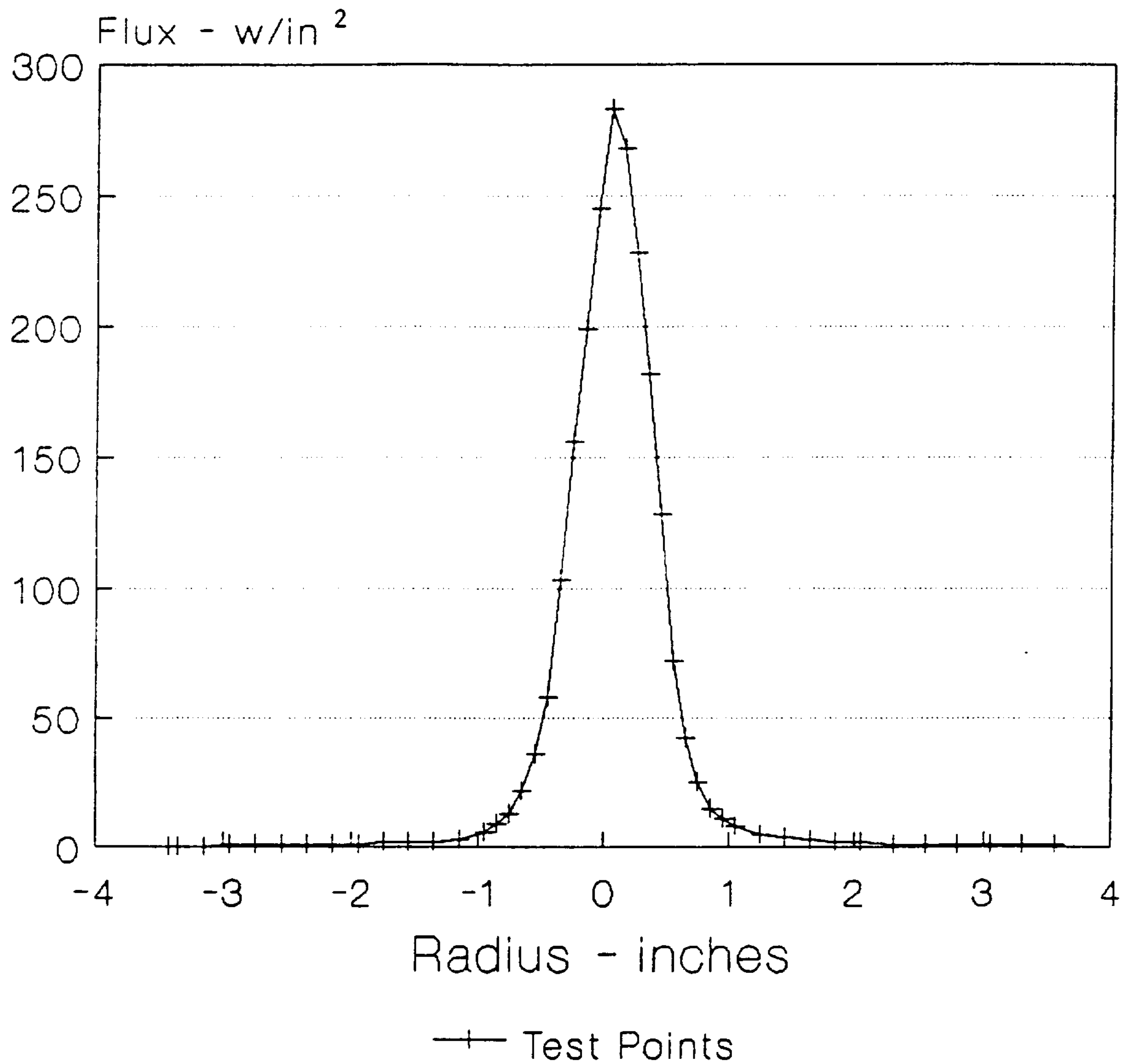
An additional calculation was made from the test data in the aperture plane. The power within a ring of .1 inch width at radii up to .8 inch was calculated and plotted in Figure 2-4. This figure indicates how much each part of the collector and lens assembly is contributing to total power.

2.1.2 ELLIPTICAL MODULE

The aperture plane of the elliptical module was mapped in the same manner as the uniform magnification module. To shield the laser power meter from infra red radiation (IR) from the xenon lamp, a 1/4 inch thick sheet of plexiglas was placed over the sensor. The results of the mapping are shown in Figures 2-5 and 2-6. These results are similar to the results obtained for the uniform magnification module in that the flux is uniform around the circumference of a radius of the aperture plane and that flux peaks at the center and diminishes within a one inch radius.

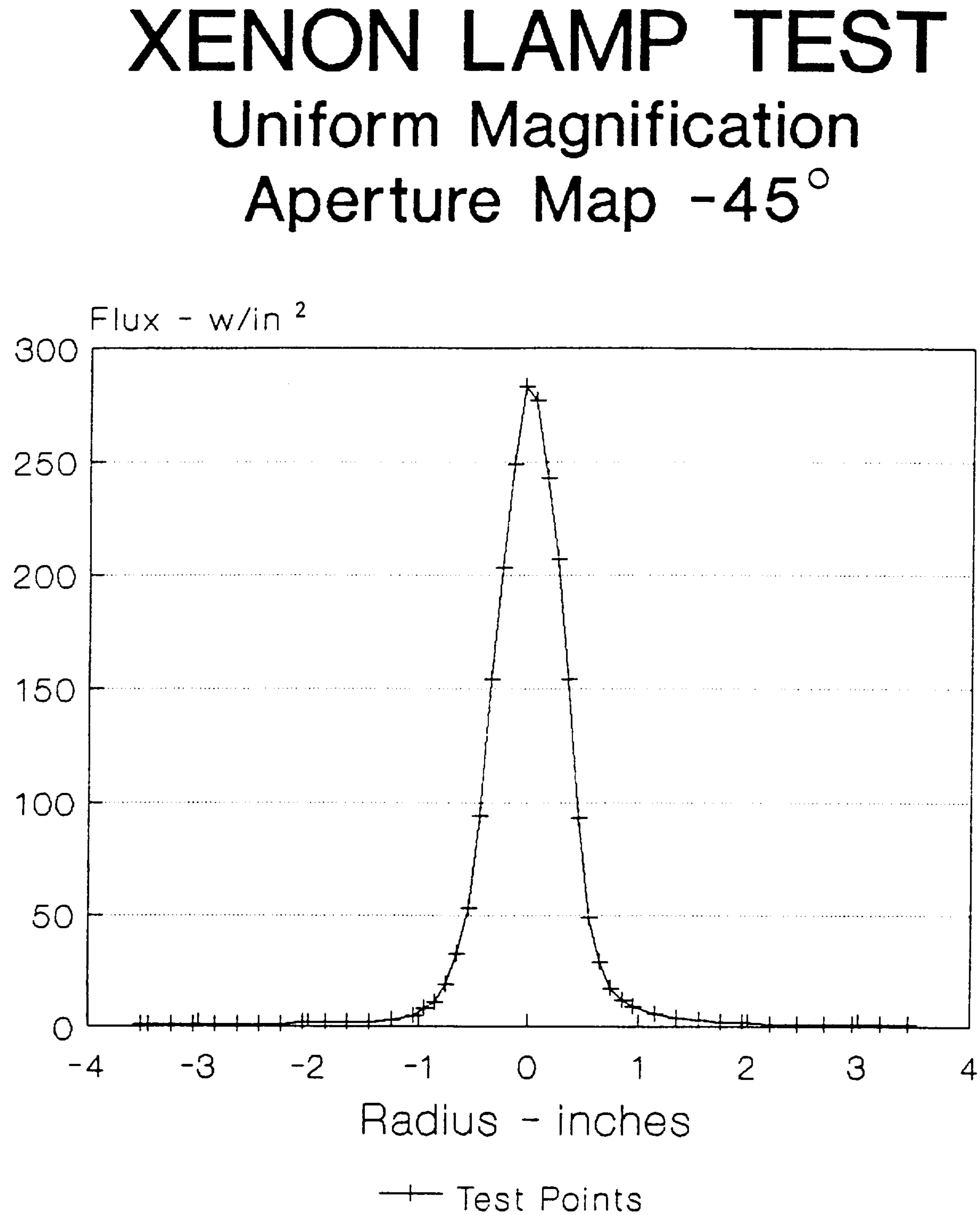
Measurement of total power at the aperture plane was also taken with a 1/4 inch thick sheet of plexiglas over the sensor. Figure

XENON LAMP TEST
Uniform Magnification
Aperture Map +45°



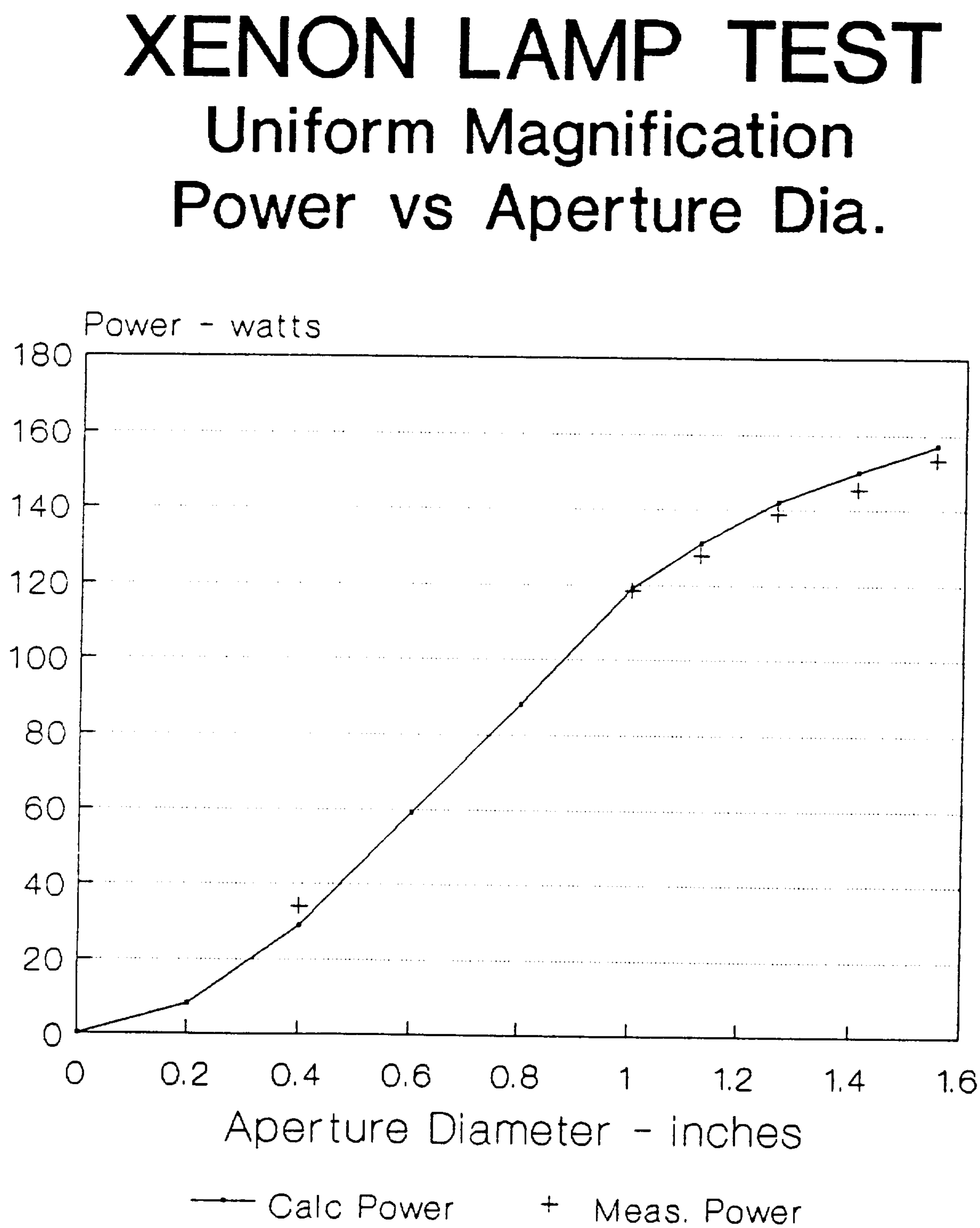
Test U 58
5 mm Pinhole

FIGURE 2-1 Uniform Magnification Module, +45° Aperture Map



Test U 57
5mm Pinhole

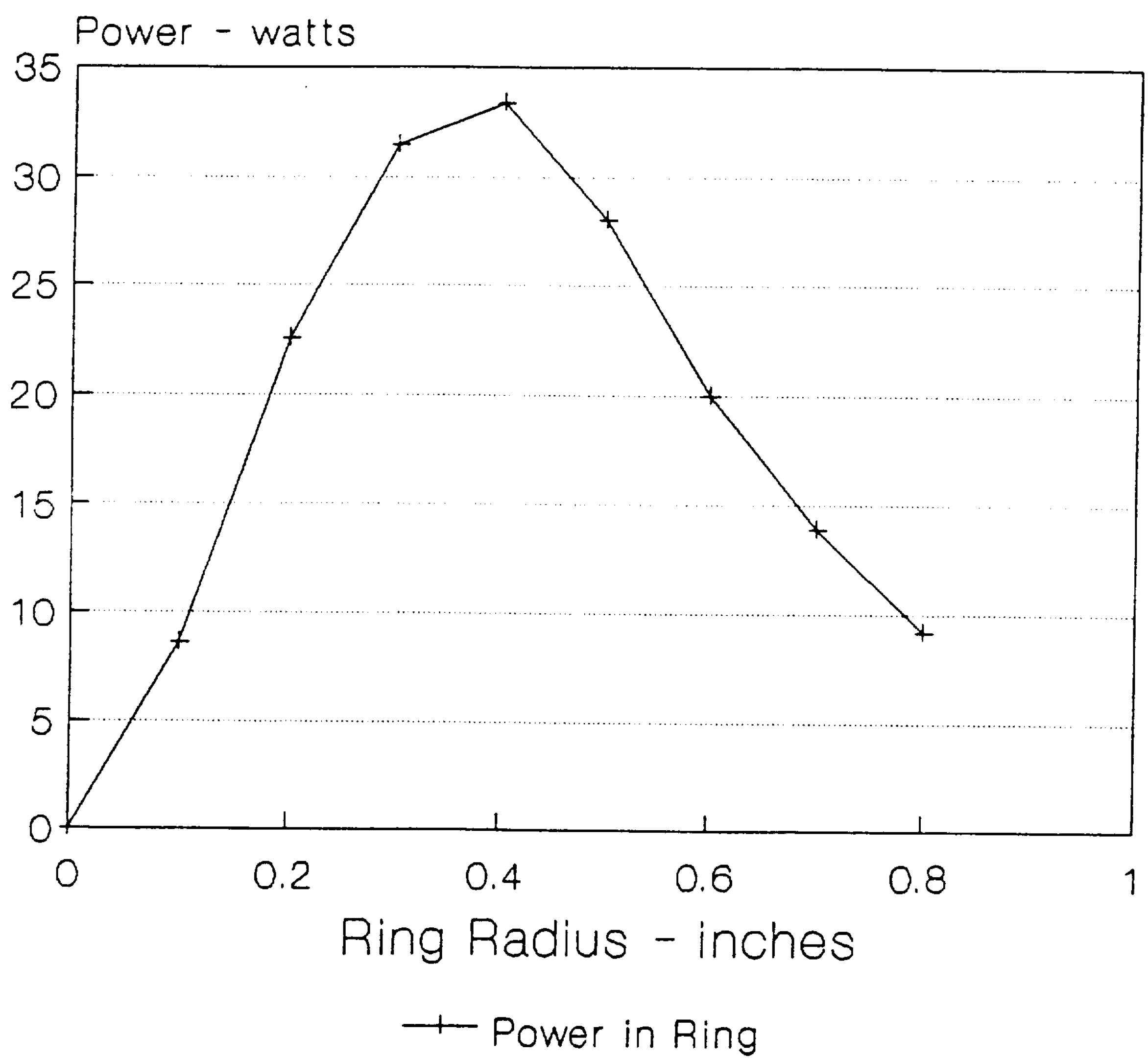
FIGURE 2-2 Uniform Magnification Module, -45° Aperture Map



Meas Power Test U-56
Calc Power Ave. Tests U-57 & U-58

FIGURE 2-3 Uniform Magnification Module, Power vs. Aperture Diameter

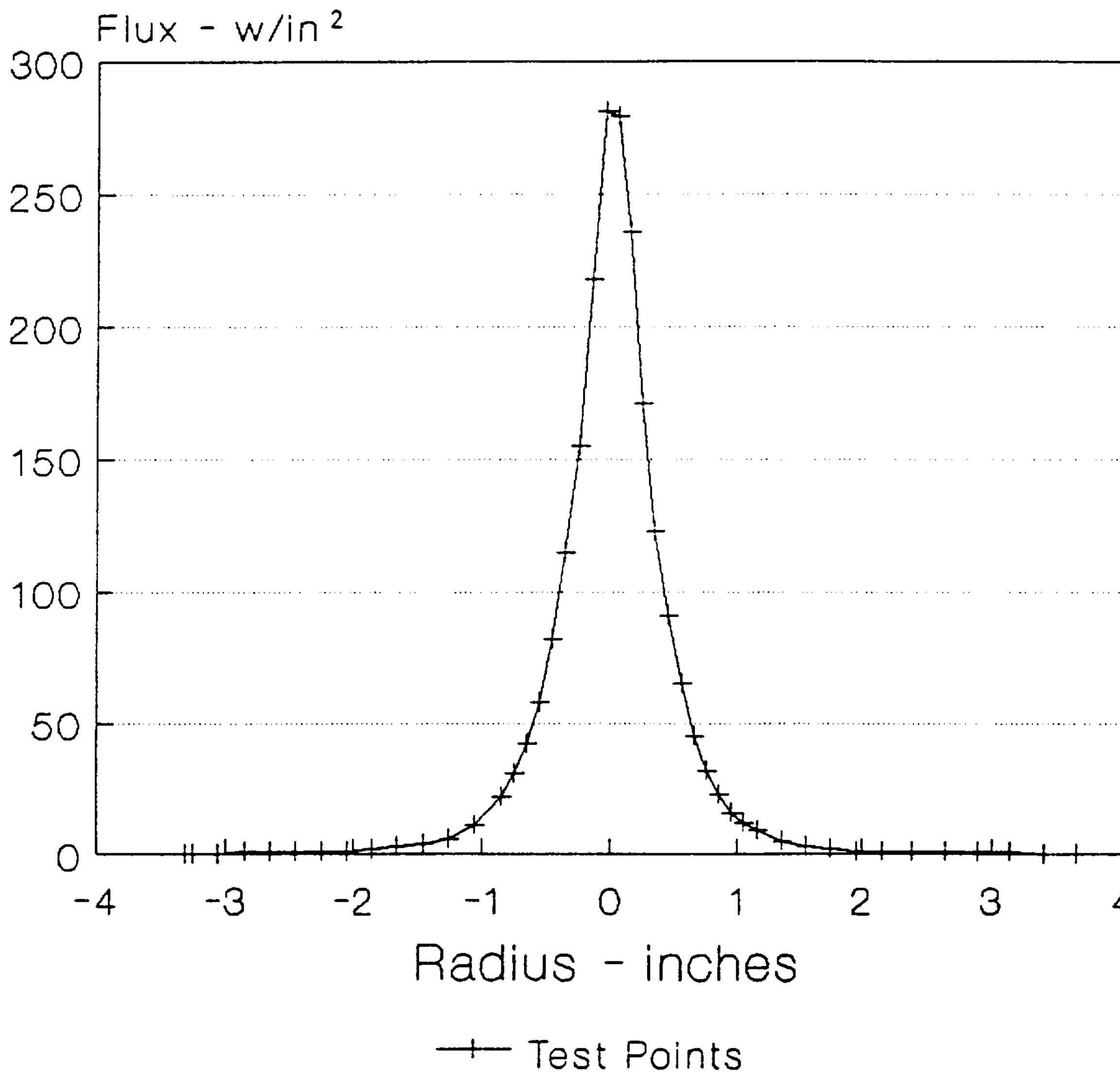
XENON LAMP TEST
Uniform Magnification
Power in Rings



Data is Average of Tests U-57 & U-58
Power Calculated for 0.1 inch Wide Ring
at Noted Radius

FIGURE 2-4 Uniform Magnification Module, Power vs. Ring Radius

XENON LAMP TEST
Elliptical Module
Aperture Map +45°



Test E-55
5 mm Pinhole

FIGURE 2-5 Elliptical Module, +45° Aperture Map

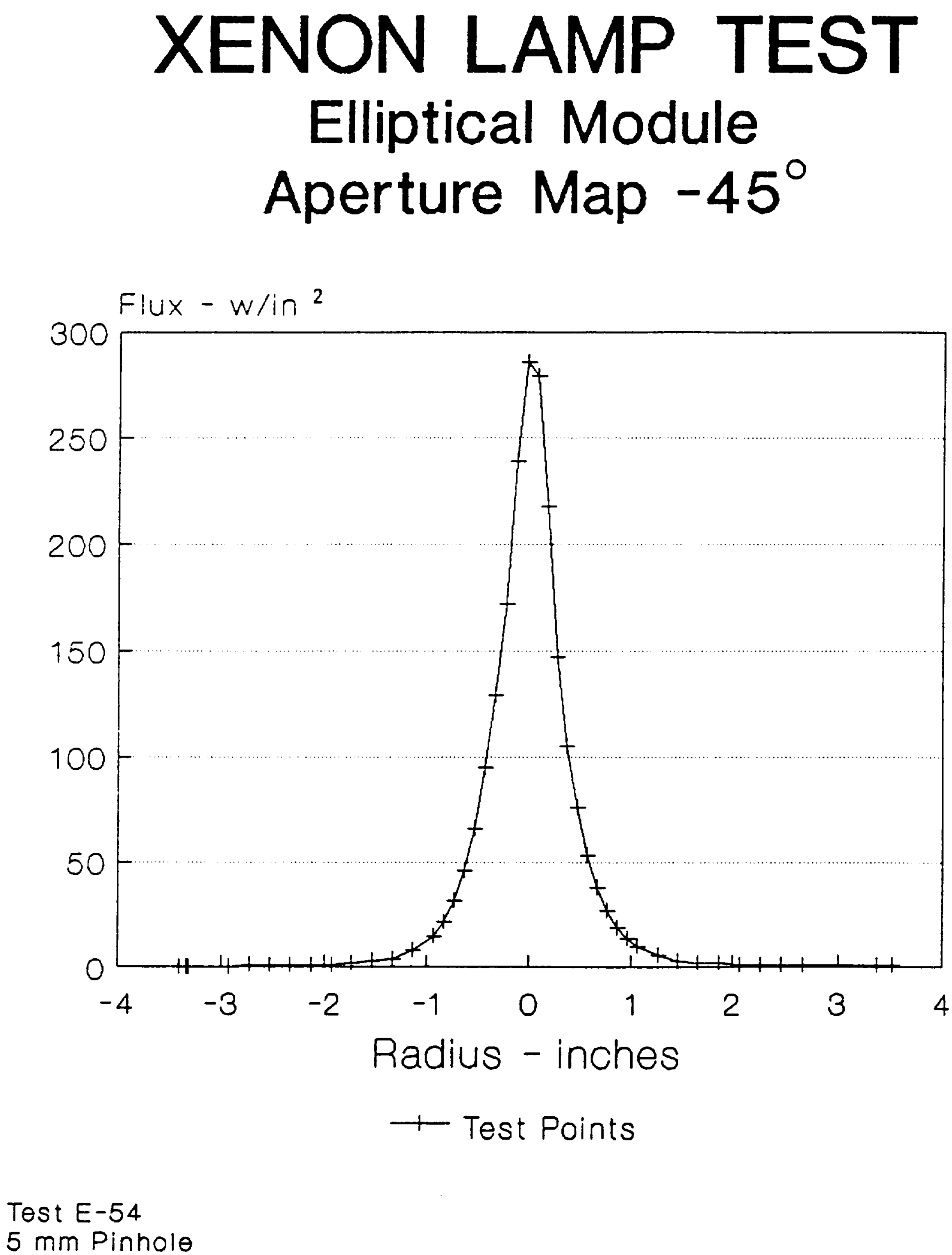


FIGURE 2-6 Elliptical Module, -45° Aperture Map

2-7 shows the total power test point for each aperture size and also shows the total power as calculated from the data obtained by aperture plane mapping. Agreement between these two methods of determining total power is also very good in that the maximum variation is only approximately 5 percent.

The power in a ring .1 inch wide at various radii across the aperture is shown in Figure 2-8. The majority of the power is contained in rings from .2 to .6 inch radii and tapers off at larger radii.

2.2 INCANDESCENT LAMP TESTS

2.2.1 LAMP TESTS

Tests of incandescent lamps were made to establish the uniformity of lamp intensity around the circumference of the lamp in a plane perpendicular to the lamp filament. Two lamps were tested; lamp EL-3B and lamp GE 1004 PL2. The map for lamp EL-3B is shown in Figure 2-9 both with and without a plexiglas shield over the radiometer sensor. Note that a significant amount of flux is due to IR in the lamp. The map for lamp GE 1004 PL2 is shown in Figure 2-10. The effect of IR was not determined for this lamp since it was decided to use lamp EL-3B for the module tests. Also, IR will not impact the results of the incandescent lamp tests since the plastic lens of the uniform magnification module will shield all IR from the radiometer sensor.

2.2.2 UNIFORM MAGNIFICATION MODULE

The target plane was mapped with the radiometer traversing a plane 90^0 to the filament of the lamp and then in line with the filament. The results for the 90^0 plane, Figure 2-11, showed a sharp cut off in flux at the outer radius of the target plane image as expected, but flux was not as uniform as expected from the inner radius to the outer radius of the target plane. On the other hand, the results for the plane in-line with lamp filament, Figure 2-12, showed better uniformity than expected and still had a sharp cut off at the outer radius. This discrepancy was judged to be due to the configuration of the lamp filament. A view perpendicular to the filament is shown in Figure 2-13 and an end view of the filament is shown in Figure 2-14. From these figures, the filament is shown to be .130 inch long and .016 inch in diameter, thus, approximately eight times more circumference of the collector would be viewed in the 90^0 plane than would be viewed in the in line plane. This difference plus the edge effects of the filament are judged to be the cause of the anomaly seen. This was further verified by the images formed by a .15 diameter hole at the target plane when viewed seven inches below the target. As can be seen in Figure 2-15, the image perpendicular to the filament is wide whereas the image for the in-line plane, Figure 2-16, is narrow. Therefore, the width of the filament is the most likely cause of the noted discrepancy in uniformity at the target.

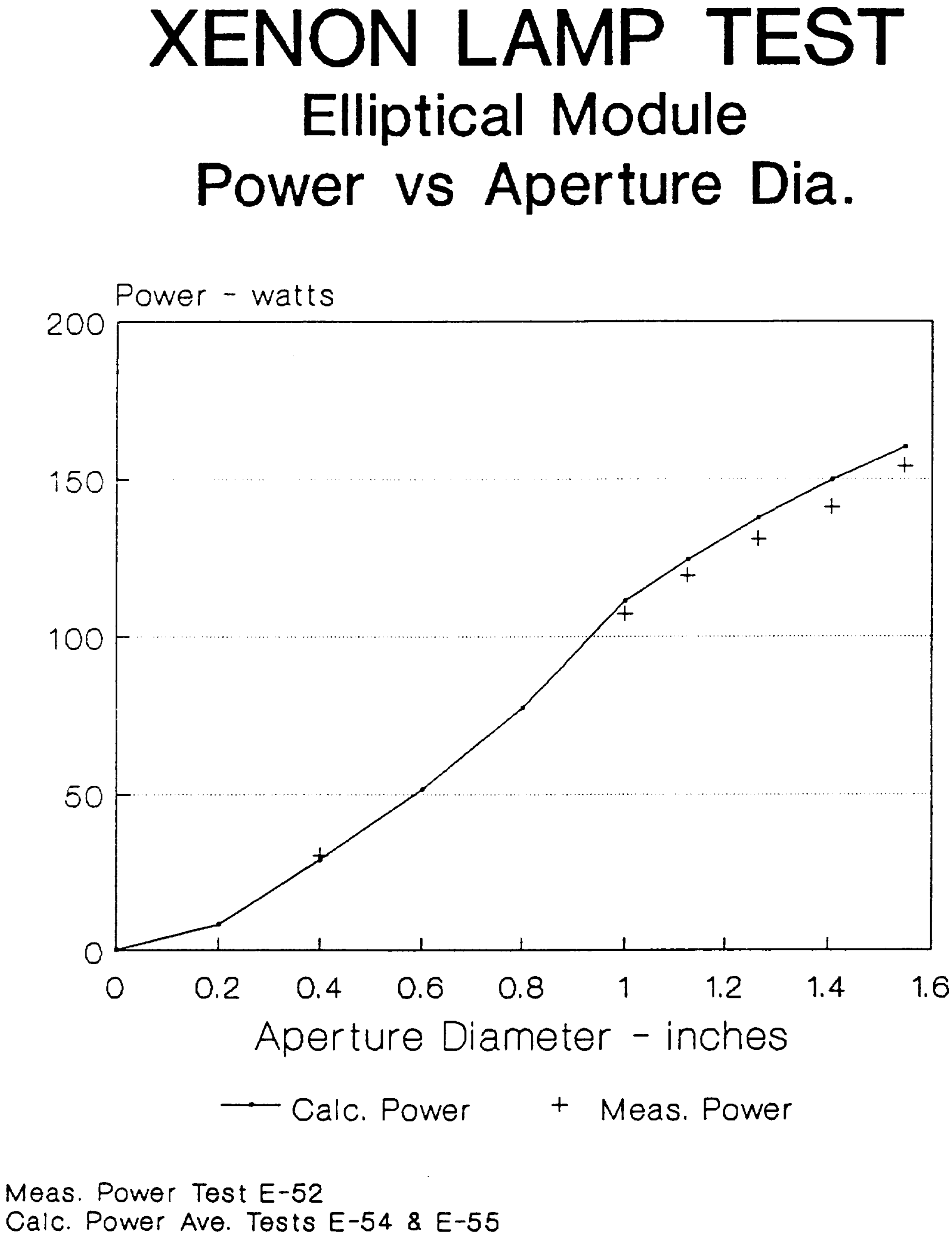


FIGURE 2-7 Elliptical Module, Power vs. Aperture Diameter

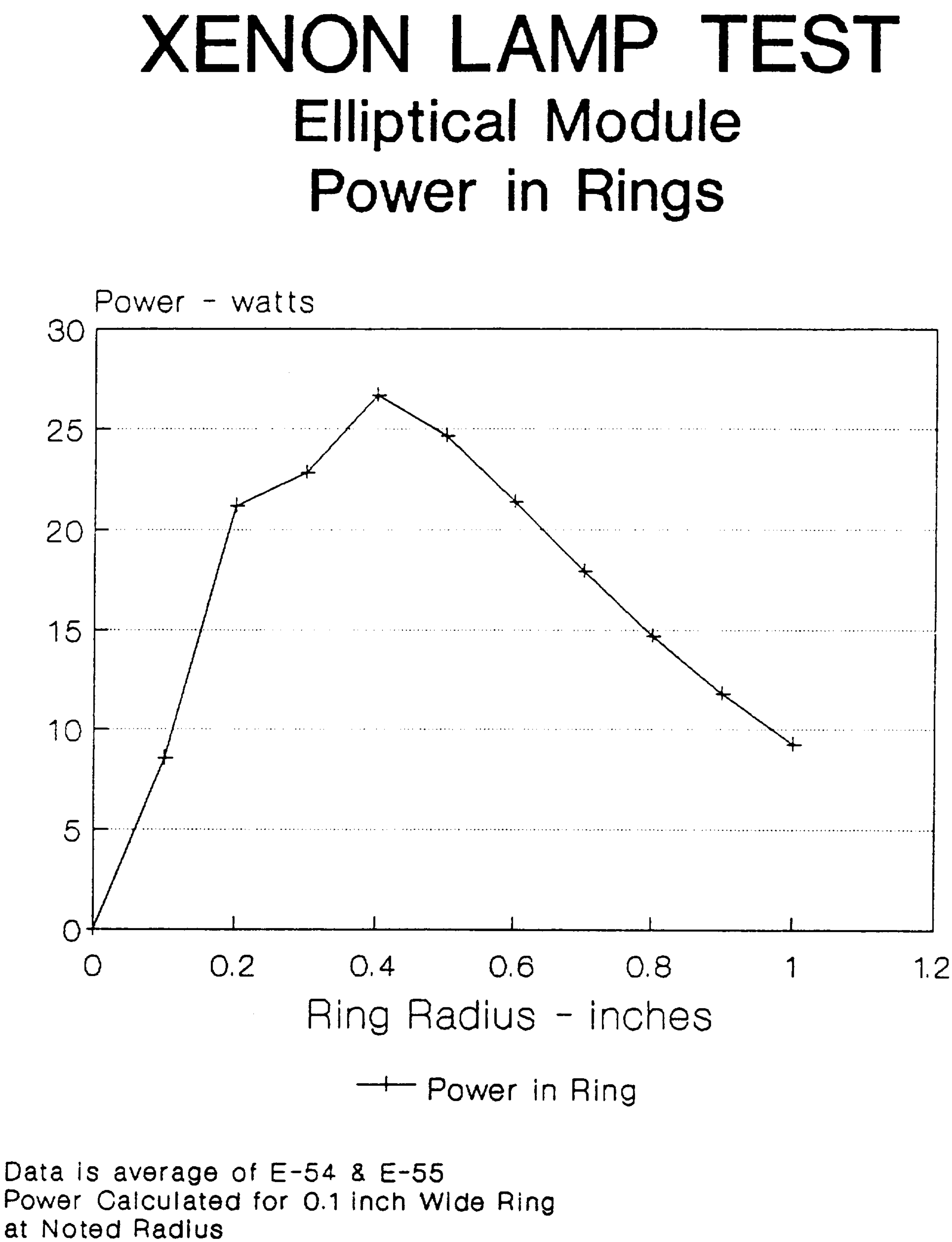
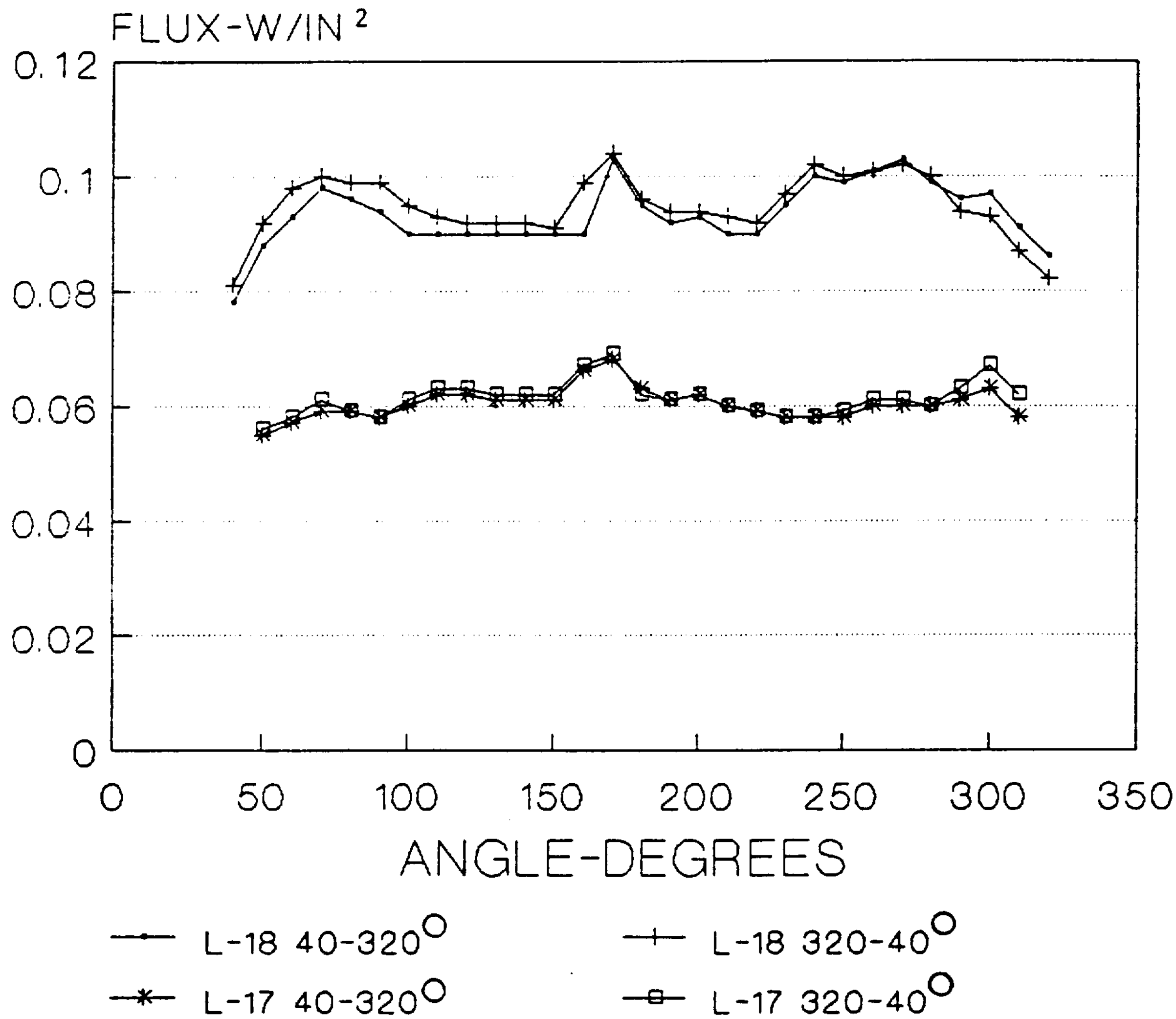


FIGURE 2-8 Elliptical Module, Power vs. Ring Radius

INCANDESCENT LAMP
FLUX VS ANGLE
LAMP EL-3B



L-17 1/4" PLEXIGLAS OVER RADIOMETER
INPUT POWER 2 AMPS, 12 VDC
RADIUS ARM 4.6", PINHOLE 10mm

FIGURE 2-9 Incandescent Lamp Test, Bulb EL-3B

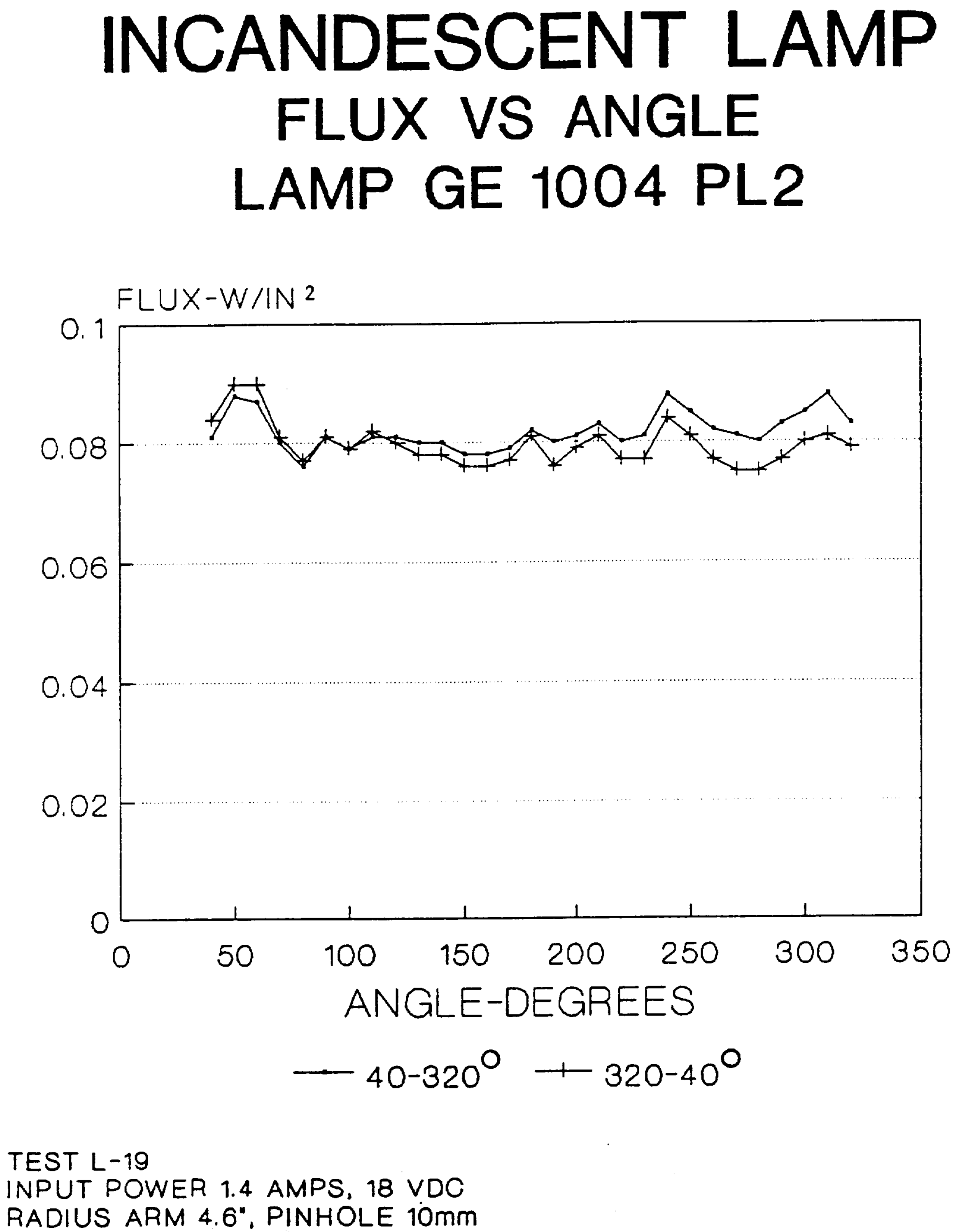
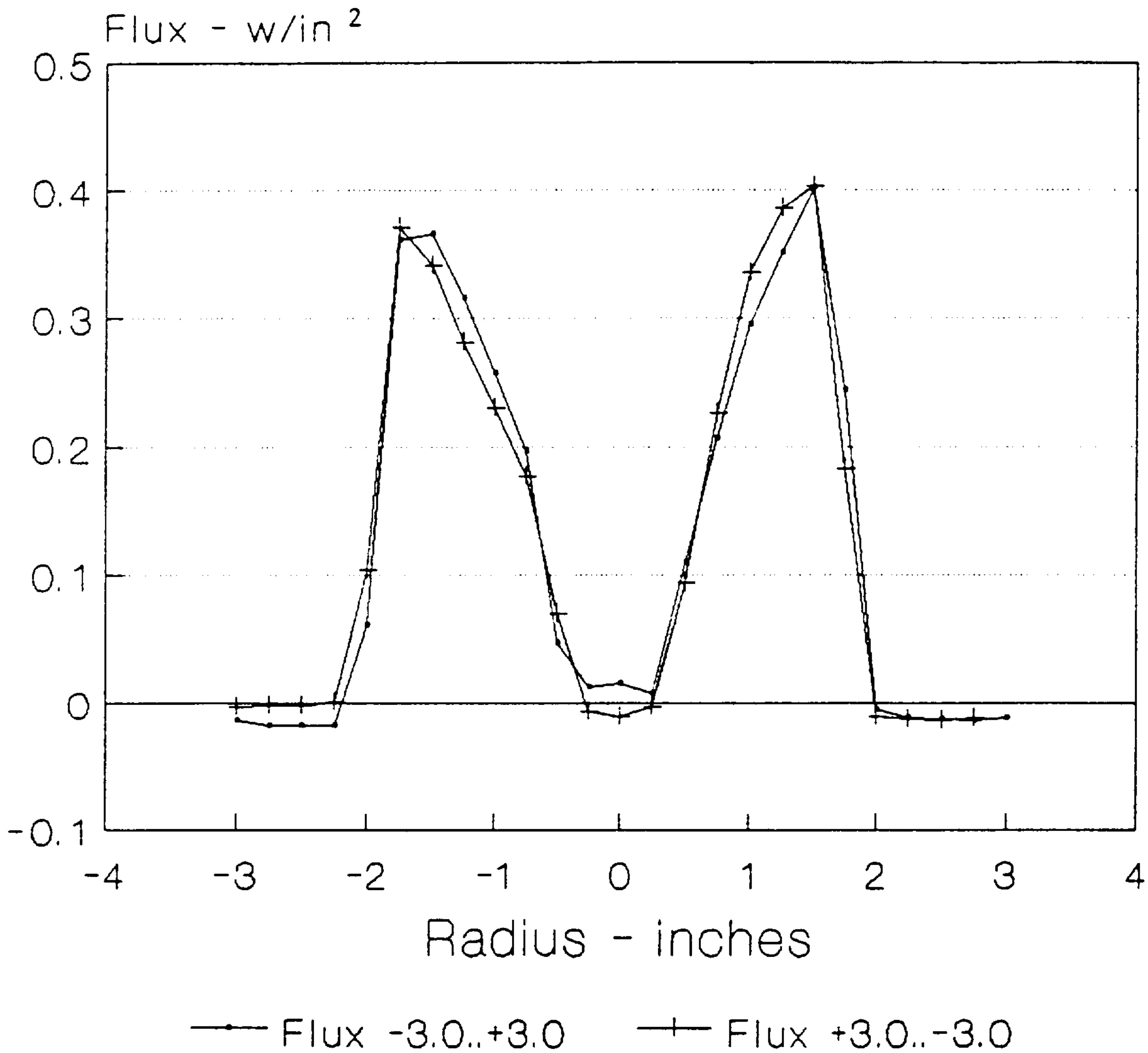


FIGURE 2-10 Incandescent Lamp Test, Bulb GE 1004 PL2

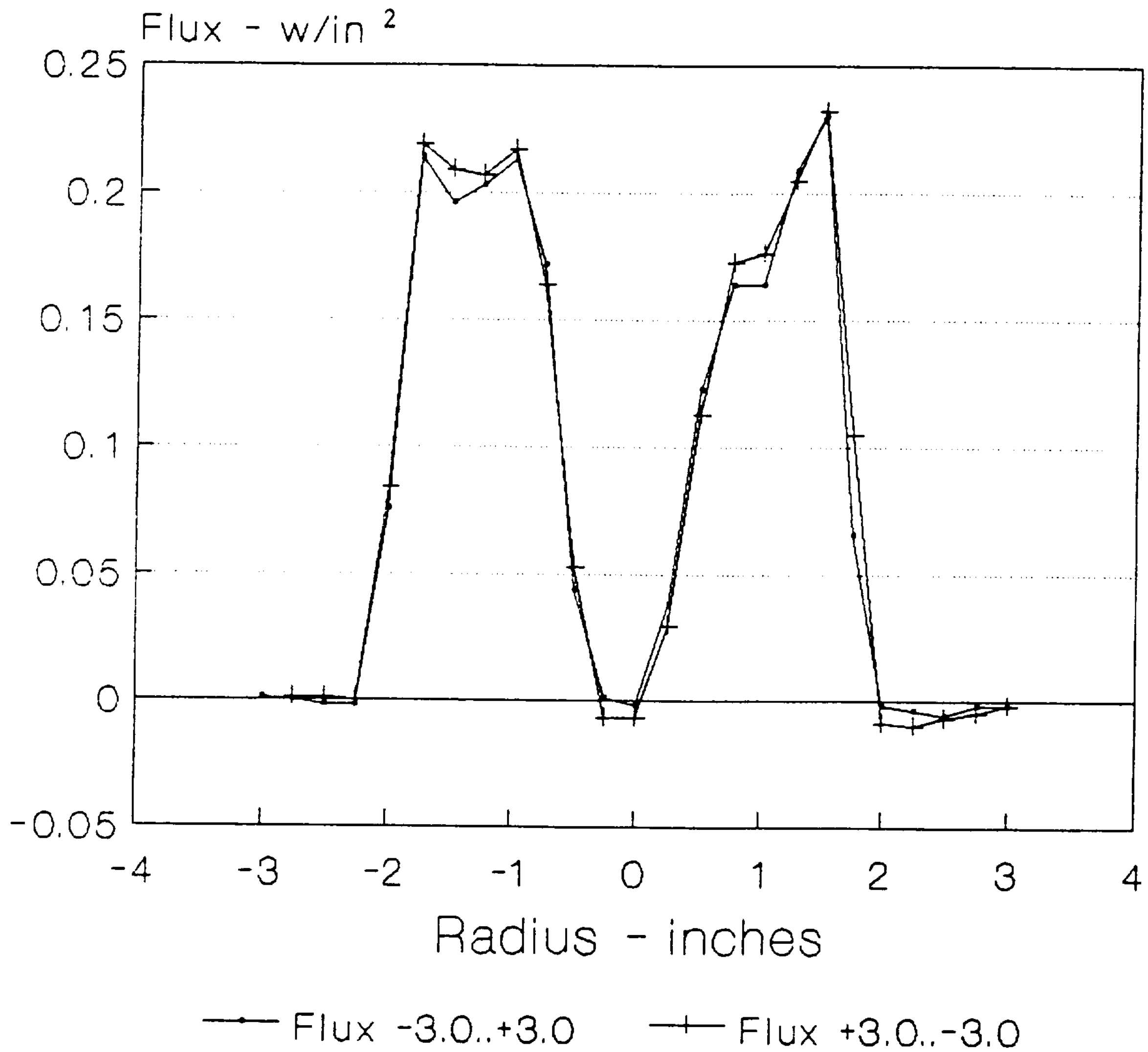
INCANDESCENT LAMP
Uniform Magnification
Target Plane Map



Test U-60 Incandescent Lamp EL-3B #3
Aux. Lens at Aperture, Aper. Dia. 1.125"
Radiometer Motion 90° to Bulb Filament

FIGURE 2-11 Incandescent Lamp, 90° Target Plane Map

INCANDESCENT LAMP
Uniform Magnification
Target Plane Map



Test U-62 Incandescent Lamp EL-3B #4
Aux. Lens at Aperture, Aper. Dia. 1.125"
Radiometer Motion In-line with Filament

FIGURE 2-12 Incandescent Lamp Test, Target Plane Map In-Line with Filament

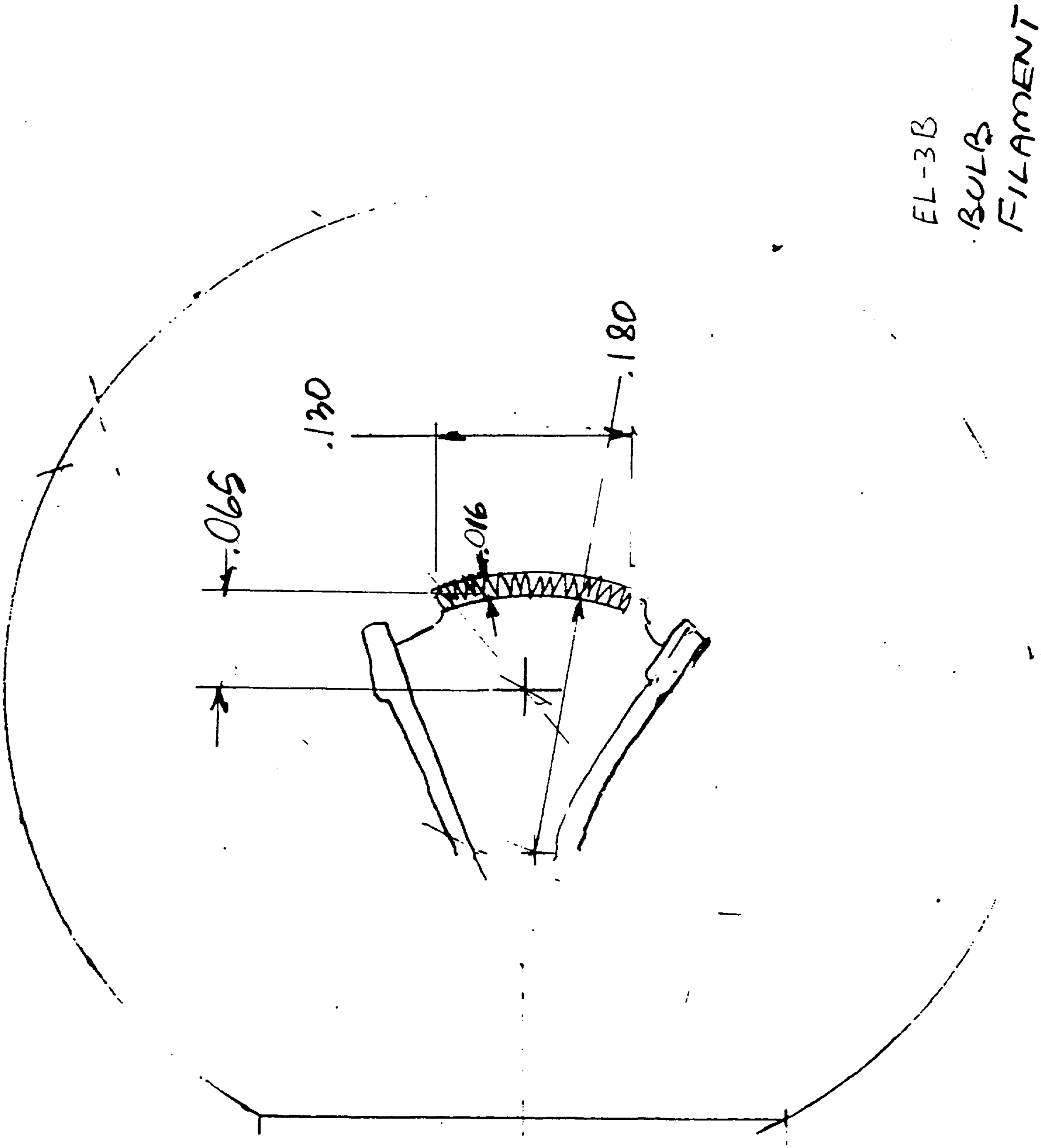


FIGURE 2-13 Bulb EL-3B, View Perpendicular to Filament

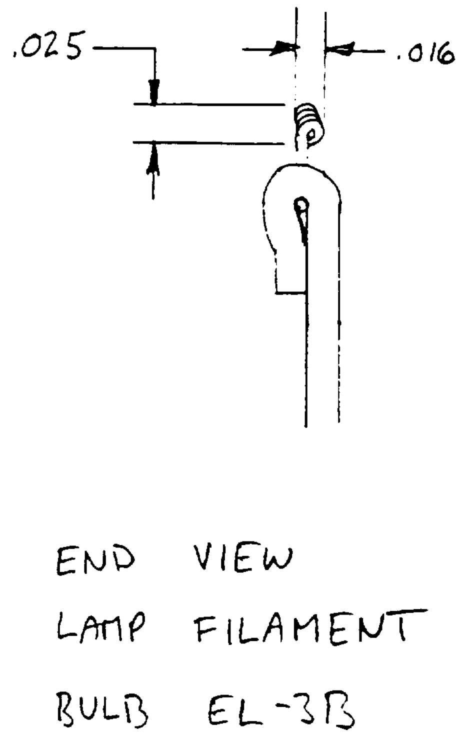


FIGURE 2-14 Bulb EL-3B, End View of Filament

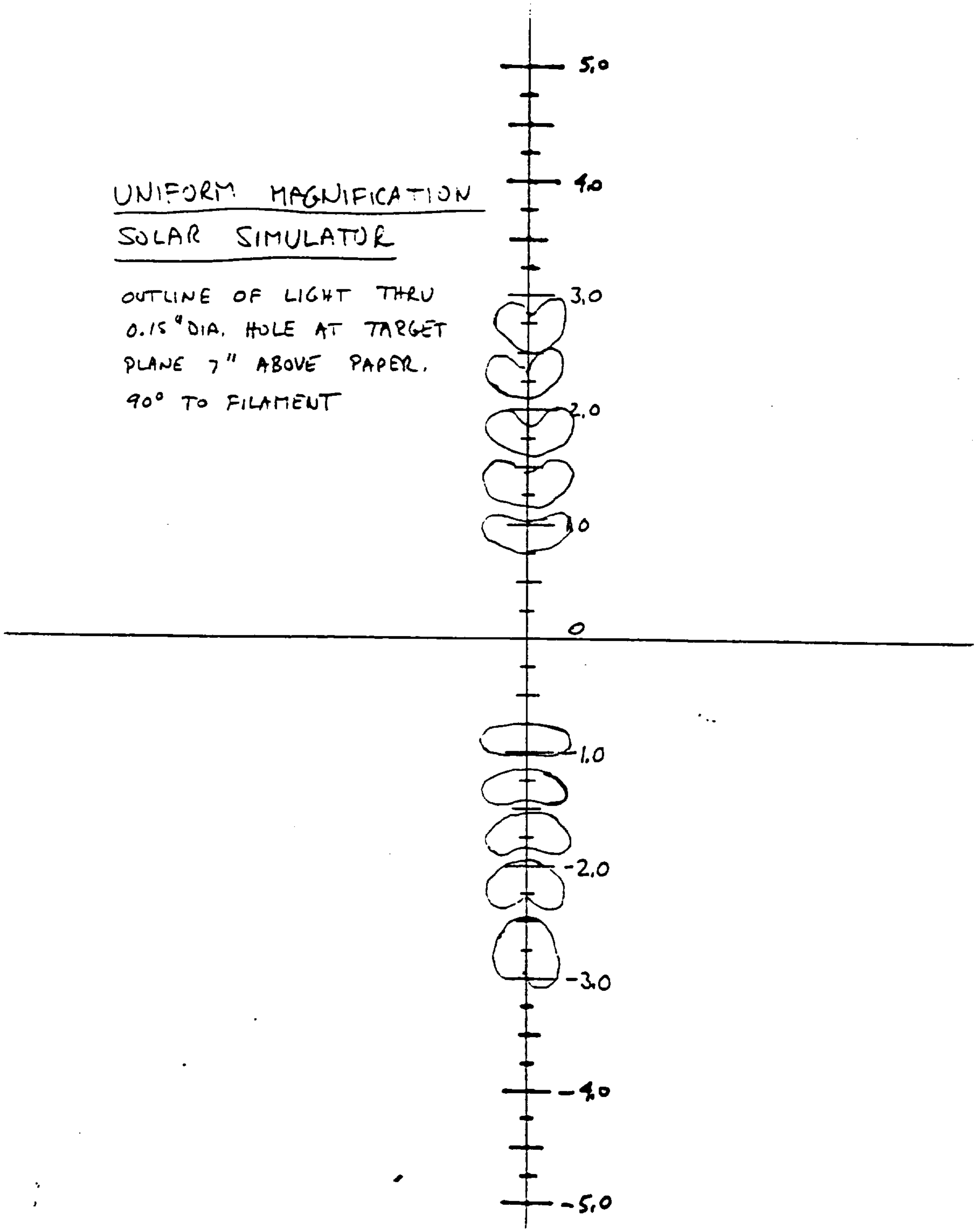


FIGURE 2-15 Light Through 0.15" Diameter Hole at Target Plane, 90° to Filament

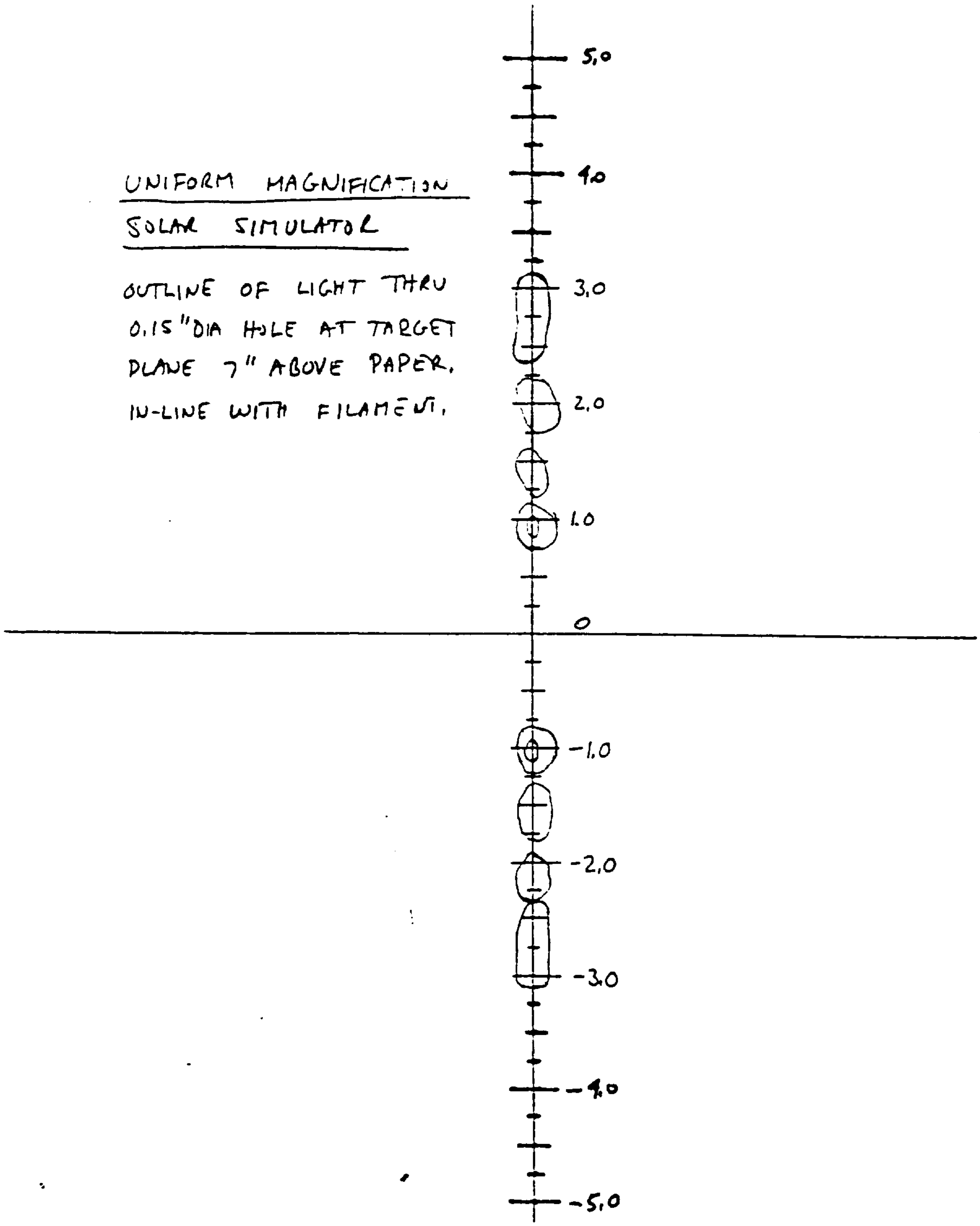


FIGURE 2-16 Light Through 0.15" Diameter Hole at Target Plane, In-Line with Filament

Some additional tests with the incandescent lamp not in the original test plan were conducted to explore aperture plane characteristics. A map of the aperture plane was made at 90^0 to the lamp filament, Figure 2-17. A problem encountered while making the map was a decrease in lamp intensity as the test proceeded. The lamp appeared to have a life of only approximately 10 minutes thus, data points were taken as rapidly as possible. Even so, a decrease in power is evident in Figure 2-17 by noting the flux at zero degrees. At the start of the test, flux was 13.5 w/in^2, in the middle it was 11.7 w/in^2, and at the end was 10.6 w/in^2. Total power measured at the aperture for several size apertures is shown in Figure 2-18. Also noted in Figure 2-18 is power for various size apertures calculated from the aperture map from Figure 2-17. To calculate total power, it was assumed that the map of Figure 2-17 was uniform around the circumference of the uniform magnification module. Even with the decrease in lamp power experienced, reasonably good agreement was obtained between the measured total power and the total power calculated from the aperture map with the maximum discrepancy being only 9 percent.

2.3 GEOMETRY TESTS

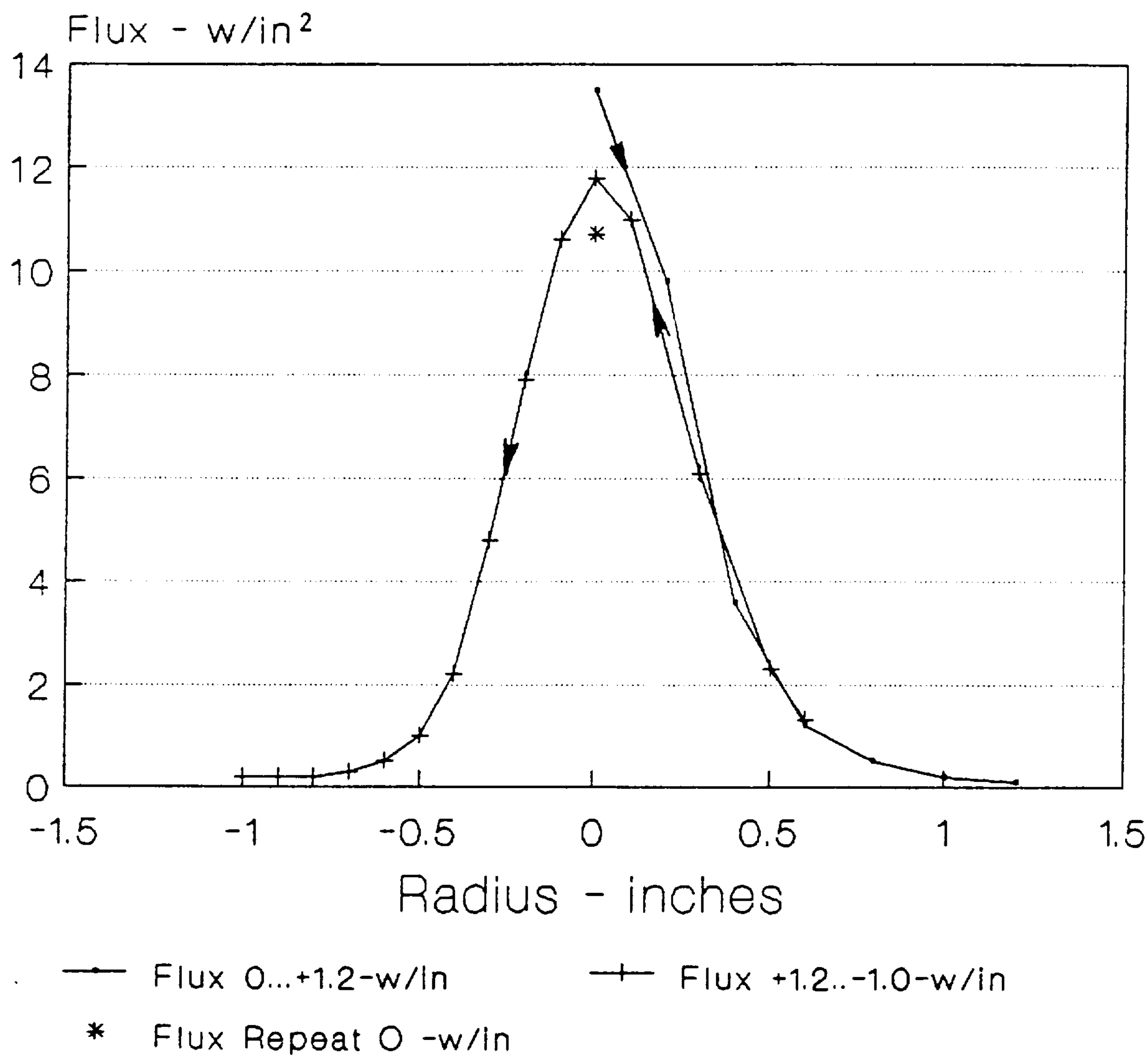
2.3.1 LENS PLANE

The geometry tests at the lens plane were conducted with a 1/16 inch diameter spot located at the collector focus and illuminated by a light external to the collector. Photographs and sketches of the spot were taken when viewed from various positions across a radius at the plane where the lens is normally installed in the test set-up for the uniform magnification module. The lens was not installed for these tests. The test was conducted to observe changes in the spot at various locations across the collector surface.

Figure 2-19 shows photographs of changes in the size and shape of the spot at various positions across a lens plane radius for the uniform magnification collector. Figure 2-20 presents similar photographs for the elliptical collector. Because the photographs were not always able to pick-up a clear image of the spot, sketches were made of the spot for both collectors and are shown in Figure 2-21.

The differences noted between the two collectors were that the spot appeared to be better focused and broader for the uniform magnification module and that the spot separated into two spots when viewed near the outer radius of the elliptical collector. The spot was nearly round near the inner diameter of the uniform magnification collector growing longer, more oval shaped, in the mid-range radii as it separated from the inner radius and long and narrow near the outer radius. The spot was more oval shaped near the inner radius of the elliptical collector and grew long and narrow in the mid-range radii but with one end remaining close to the inner radius. Near the outer radius, the spot remained narrow but finally separated into two spots, one spot near the outer

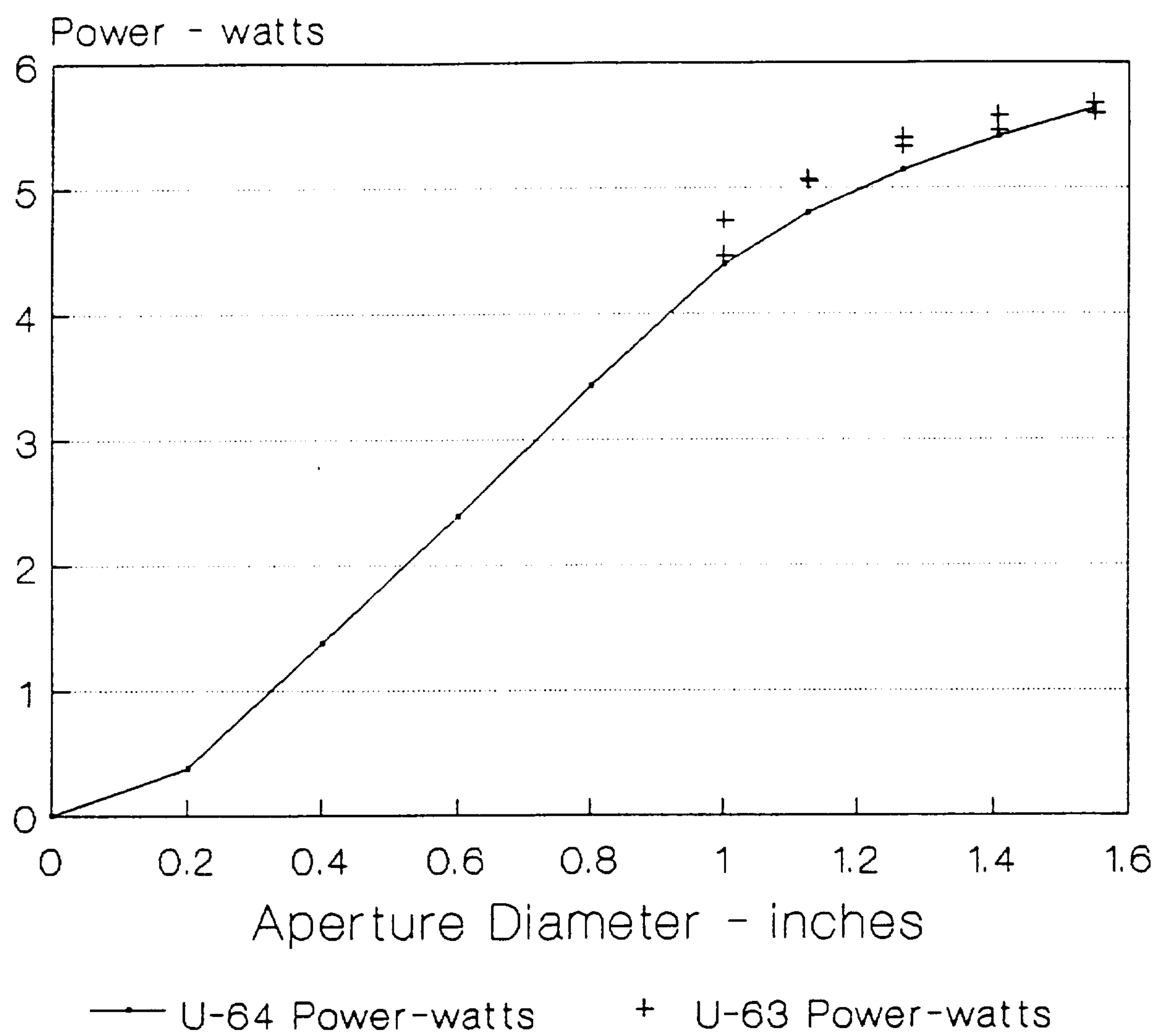
INCANDESCENT LAMP
Uniform Magnification
Aperture Map 90°



Test U-64 10mm Pinhole
Bulb EL-3B #4

FIGURE 2-17 Incandescent Lamp Test, Aperture Plane Map

INCANDESCENT LAMP
Uniform Magnification
Power vs Aperture Dia.



Test U-63 Measured Total Power
Test U-64 Calc Power From Aper. Map
Bulb EL-3B #4

FIGURE 2-18 Incandescent Lamp Test, Power vs. Aperture Diameter

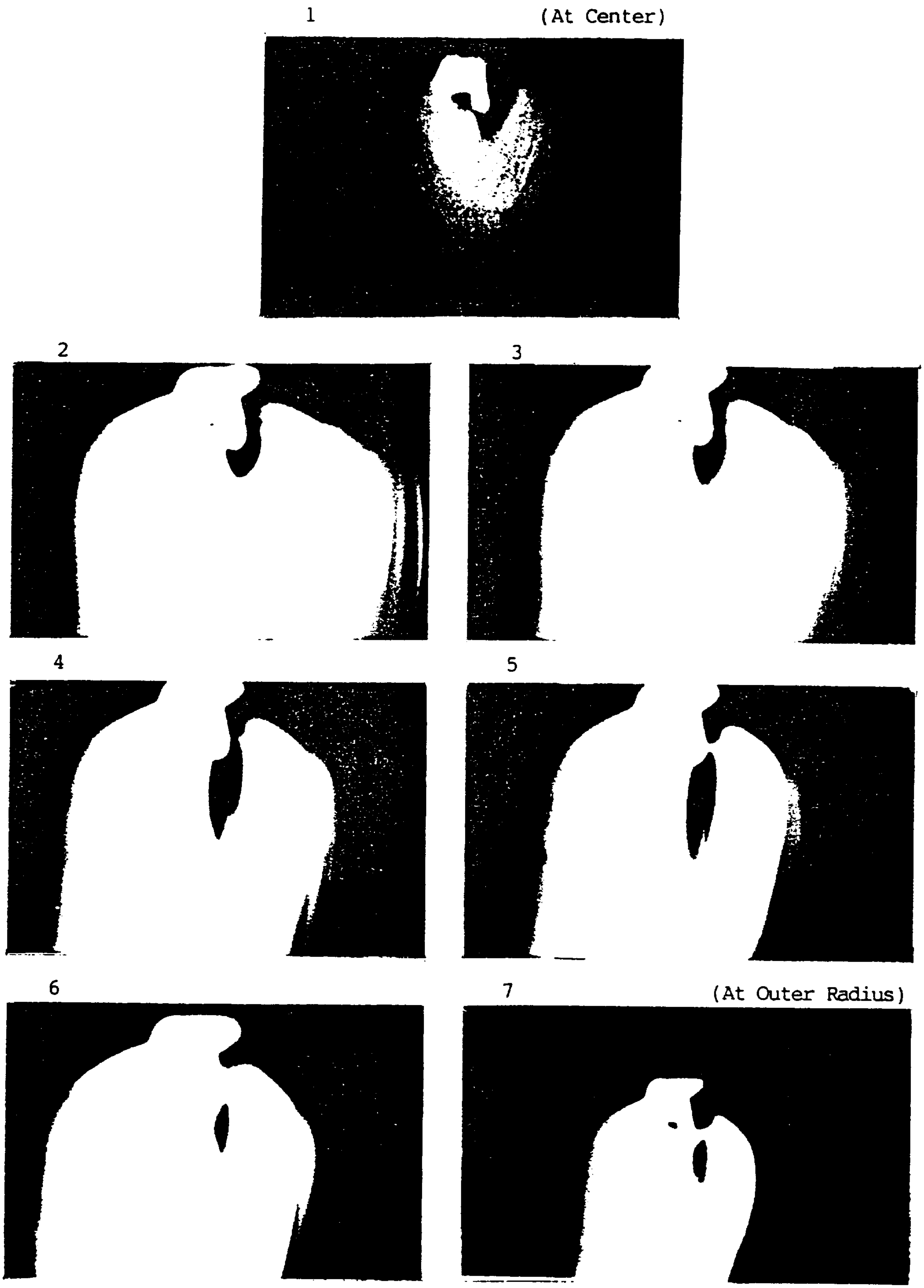


FIGURE 2-19 Photographs of Spot at Collector Focus Viewed Across Radius at Lens Plane of Uniform Magnification Module

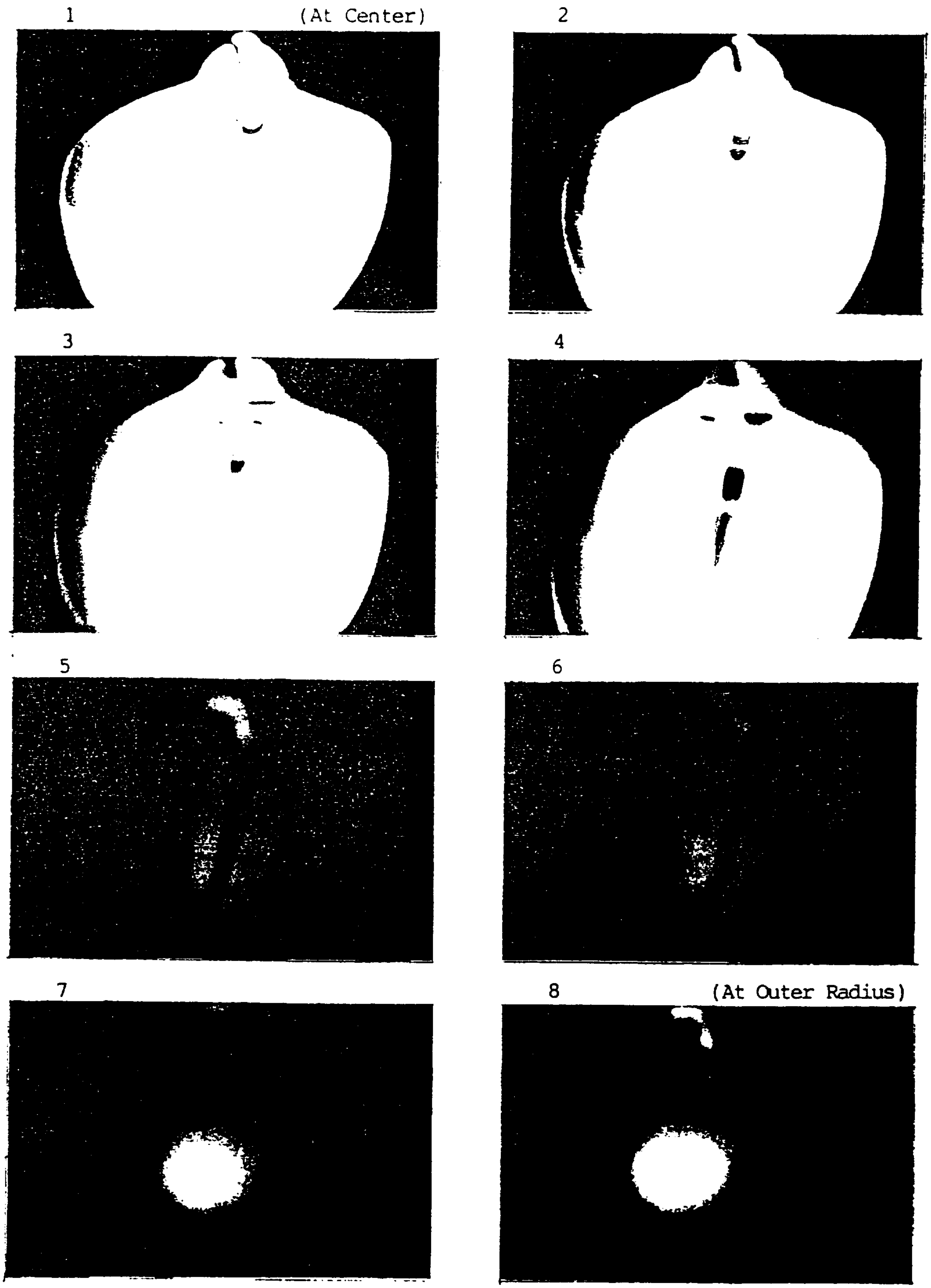


FIGURE 2-20 Photographs of Spot at Elliptical Collector Focus Viewed Across Radius at Lens Plane

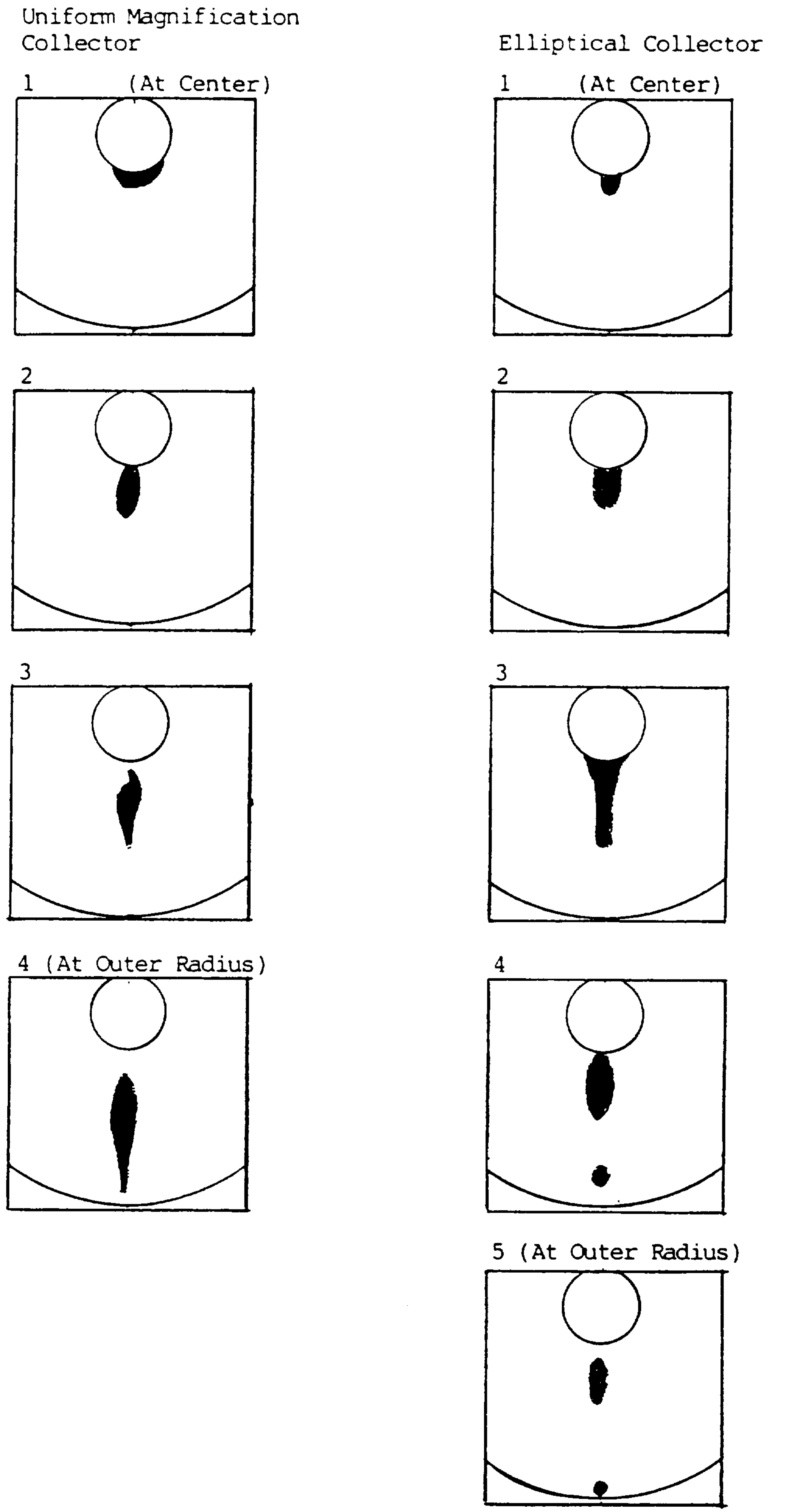


FIGURE 2-21 Sketches of Spot at Collector Focus Viewed Across Radius at Lens Plane

diameter and the other near the inner radius. The significance of this separation is not known as it is possible the spot was being viewed at a radius beyond the normal operating range of the collector. It was not possible with the test equipment available to measure the radius at which the spot was being viewed.

2.3.2 TARGET PLANE

Testing in the target plane shows how the spot is effected by the complete module assembly. In these tests, the 1/16 inch diameter spot was installed at the focus of the collector and illuminated externally. The complete module assembly was utilized including a 1.125 inch diameter aperture with an auxiliary lens at the aperture plane. Photographs and sketches of the spot were taken at various radii across the target plane.

Figure 2-22 shows photographs of how the spot changed in size and shape for the uniform magnification module. Great difficulty was experienced in attempting to view the spot with the camera for the elliptical module as the detail was washed out when viewed through the auxiliary lens and/or the aperture. As a result, photographs are available only of the images as viewed from the target plane without the auxiliary lens or aperture in place, Figure 2-23. Sketches of the images through the 1.125 inch aperture with and without the lens were made and are contained in Figure 2-24.

The image for the uniform magnification module became somewhat elongated near the center of the target plane but became more rounded towards the outer radius, Figure 2-22. For the elliptical module, the image remained quite broad across the entire radius without the auxiliary lens and 1.125 inch diameter aperture, Figure 2-23. The effect of the auxiliary lens as shown in Figure 2-24, was to reverse and to magnify the image.

2.3.3 APERTURE PLANE

Aperture plane tests were conducted with a 1/2 inch diameter spot installed at the aperture plane and illuminated from behind. The lens for the uniform magnification module was installed and the spot was viewed from the collector position without the collector installed. The purpose was to determine the change in size and shape of the spot due to the lens.

The results are shown in Figure 2-25 which present photographs of the spot as viewed across a diameter at the collector position. The spot appears oval across a lens arc (horizontal in photo) near the outer diameter, round near the mid-point of the lens radius, and oval along a lens radius (vertical in photo) near the center.

UNIFORM MAGNIFICATION MODULE
1/16 inch Spot Illuminated at Focus
of Collector

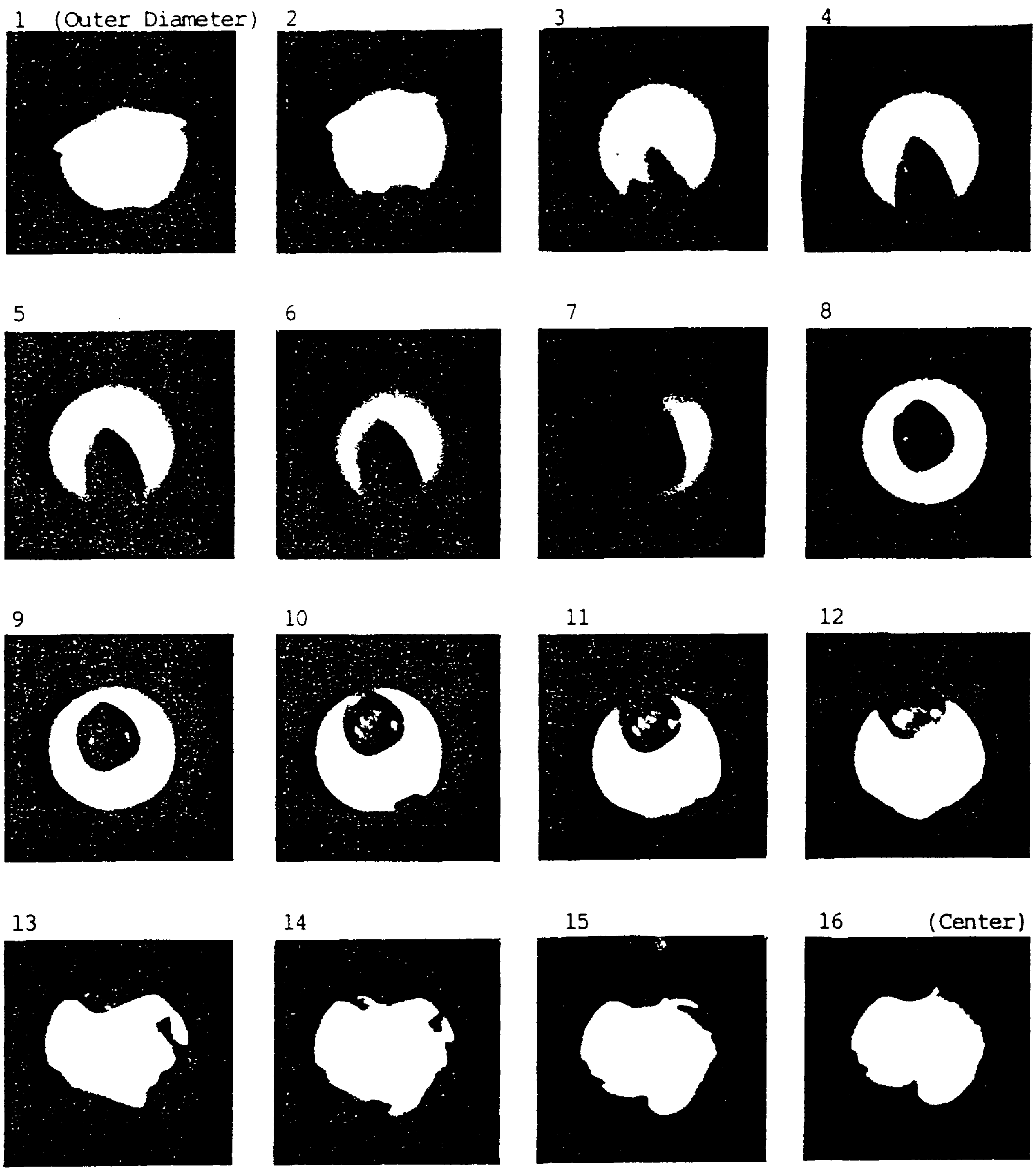


FIGURE 2-22 Image of Spot When Viewed Across a Radius at Target of Uniform Magnification Module

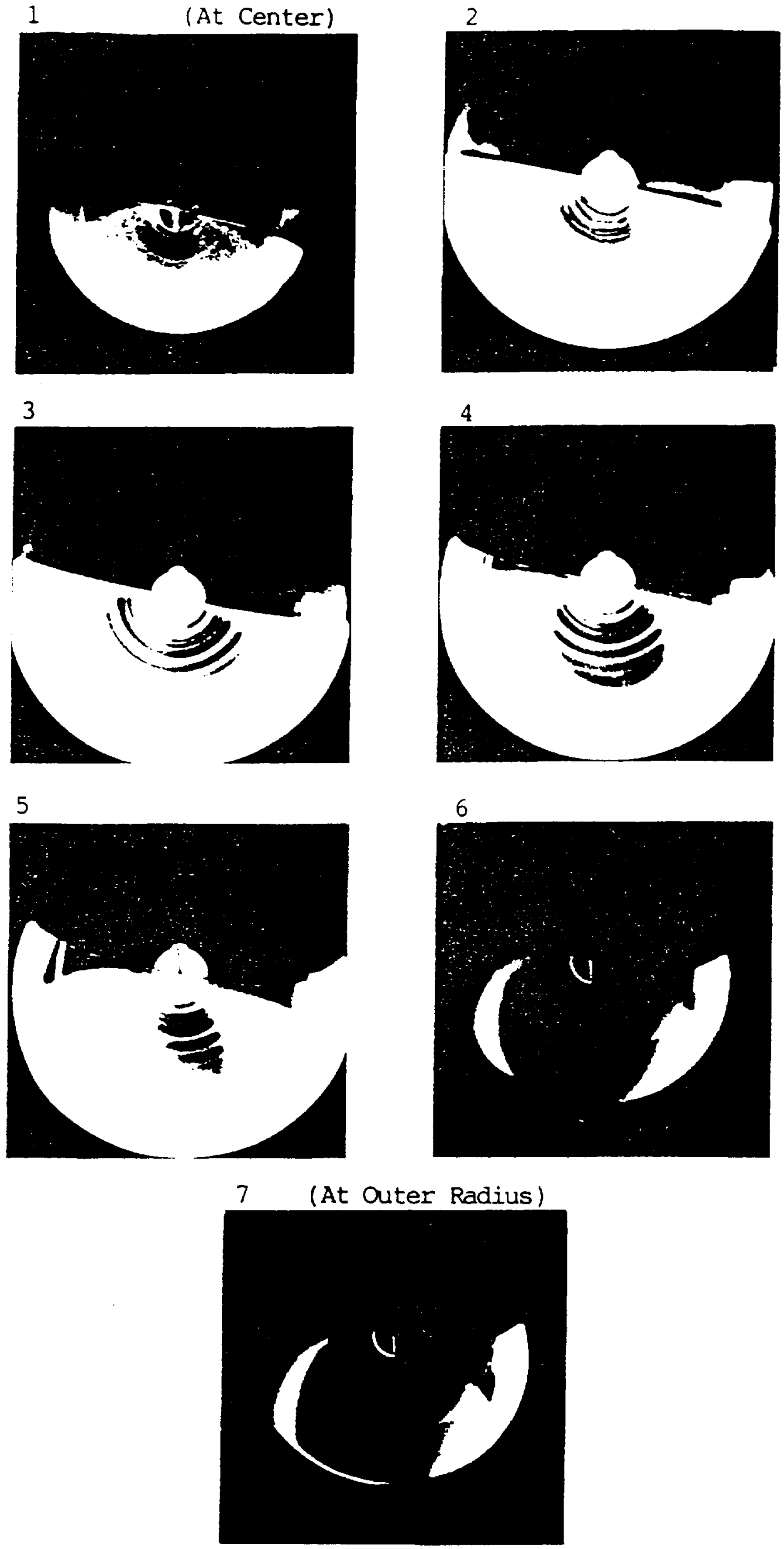


FIGURE 2-23 Photographs of Spot at Collector Focus Viewed Across Radius at Target Plane of Elliptical Module without Auxiliary Lens or Aperture

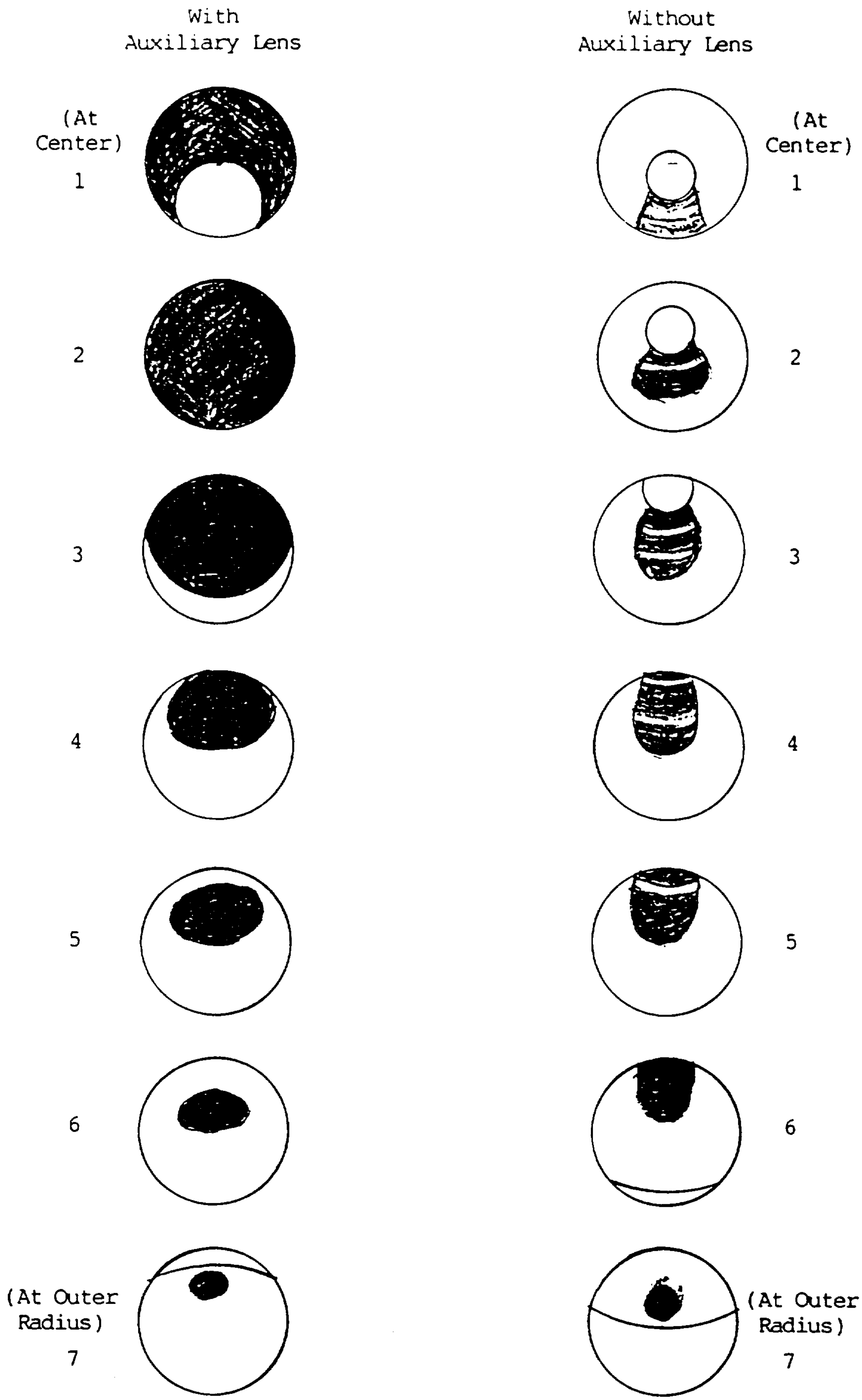


FIGURE 2-24 Spot at Collector Focus Viewed Across Radius at Target Plane of Elliptical Module

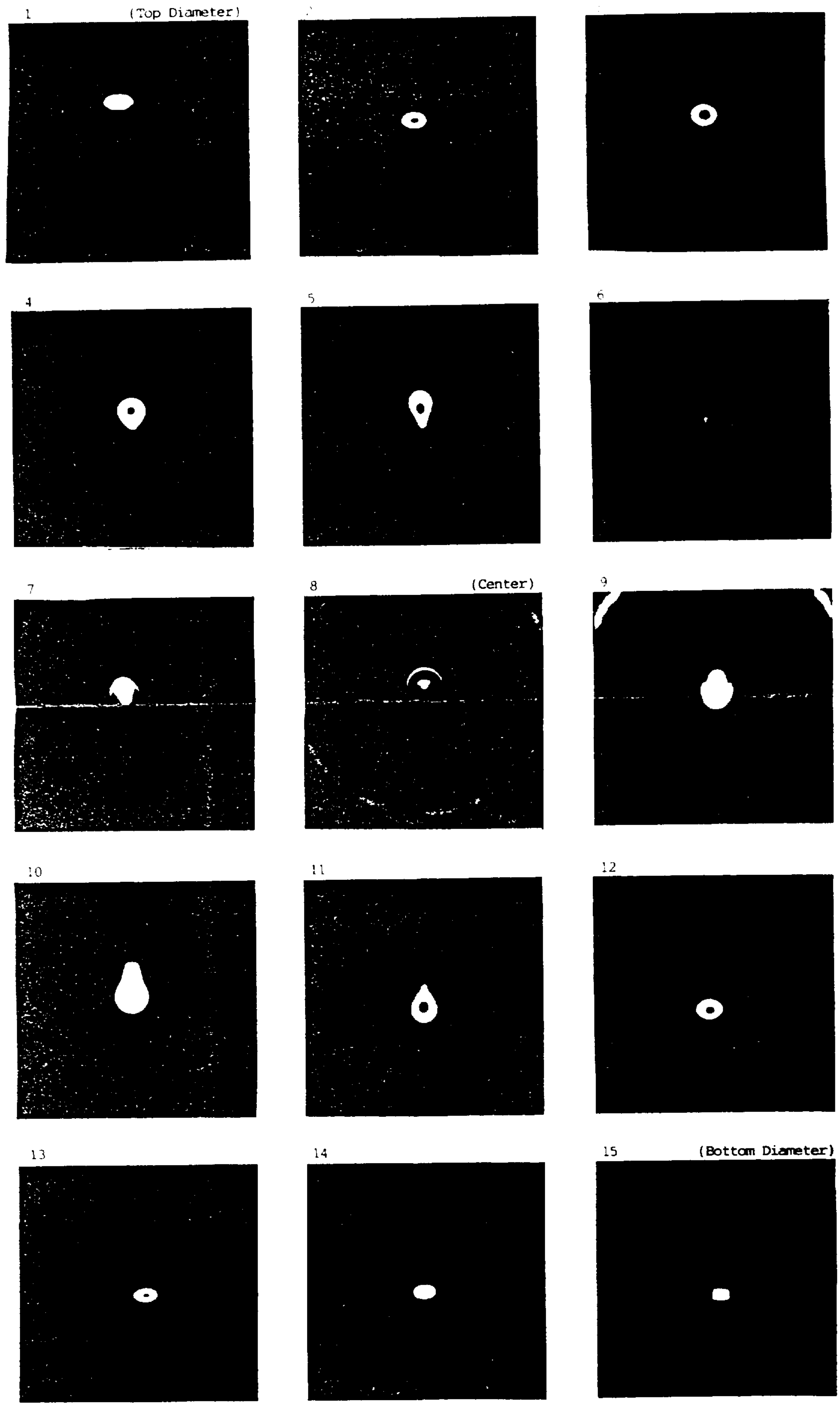


FIGURE 2-25 Photographs of Spot at Aperture Plane Viewed Across a Diameter at the Collector Plane of Uniform Magnitude Module

3.0 DISCUSSION

3.1 XENON LAMP TESTS

Tests with the Xenon lamp utilized the procedures defined in AMC EN-1029, "Solar Simulator Module Evaluation Test Plan". A schematic for aperture plane mapping of the uniform magnification module is shown in Figure 3-1. The schematic for aperture plane mapping of the elliptical module is shown in Figure 3-2. All of the same instrumentation and test equipment including the Xenon lamp was used for both modules. However, because of the effects of IR radiation from the Xenon lamp and to prevent inaccuracies from air currents from lamp cooling air, a 1/4 inch thick sheet of plexiglas was placed over the radiometer sensor during testing of the elliptical module as shown in Figure 3-3. Separation between the plexiglas and the sensor was provided to move the plexiglas away from the focal point of the modules in the aperture plane to prevent over heating of the plexiglas. Even so, slight blistering of the plexiglas was noticed at the end of the testing but previous experience indicated the blisters had no effect on results. Because the lens in the uniform magnification module provides a shield from these effects, the radiometer sensor did not need plexiglas protection during testing of the uniform magnification module.

Total power through the various size apertures was calculated by first converting the power readings obtained from mapping the aperture plane to flux levels and then plotting flux verses radius as shown in Figure 2-1 and 2-2 for the uniform magnification module and Figures 2-5 and 2-6 for the elliptical module. The curve from these figures was then divided into simple geometric shapes and the volume under the curve was calculated for each size aperture. The average of the power from the $+45^0$ and -45^0 planes was calculated and corrected for blockage from the xenon lamp cable to obtain the final calculated power. These calculations are contained in Appendix A for the uniform magnification module and in Appendix B for the elliptical module.

The power in rings .1 inch wide was also calculated from the flux versus radius plots discussed above. The method of calculation is shown in Appendix C for the uniform magnification module and in Appendix D for the elliptical module.

3.2 INCANDESCENT LAMP TESTS

The initial goal of the incandescent lamp tests was to find a lamp with a filament approximately the size of the Xenon lamp fireball (0.035 inch diameter) with uniform intensity at least in one plane and with sufficient power output to enable measurement at the target plane. It was soon learned that a lamp that met all those requirements did not exist and that a compromise had to be made. The lamp selected, EL-3B, was satisfactory in power output and uniformity of intensity in one plane, however, the filament was longer than desired even though filament diameter was acceptable,

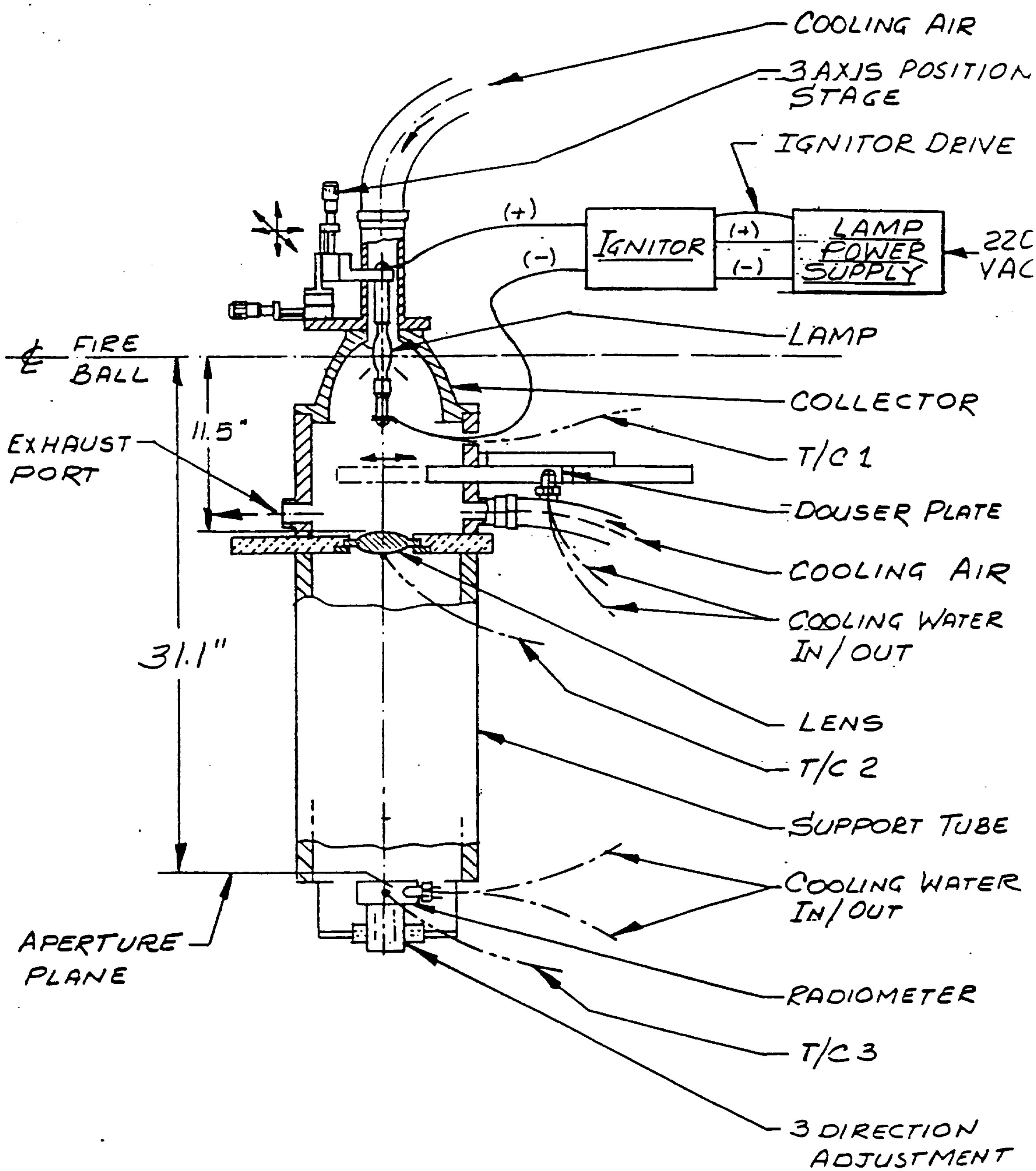


Figure 3-1- Uniform Magnification Module-Aperture Test Plane

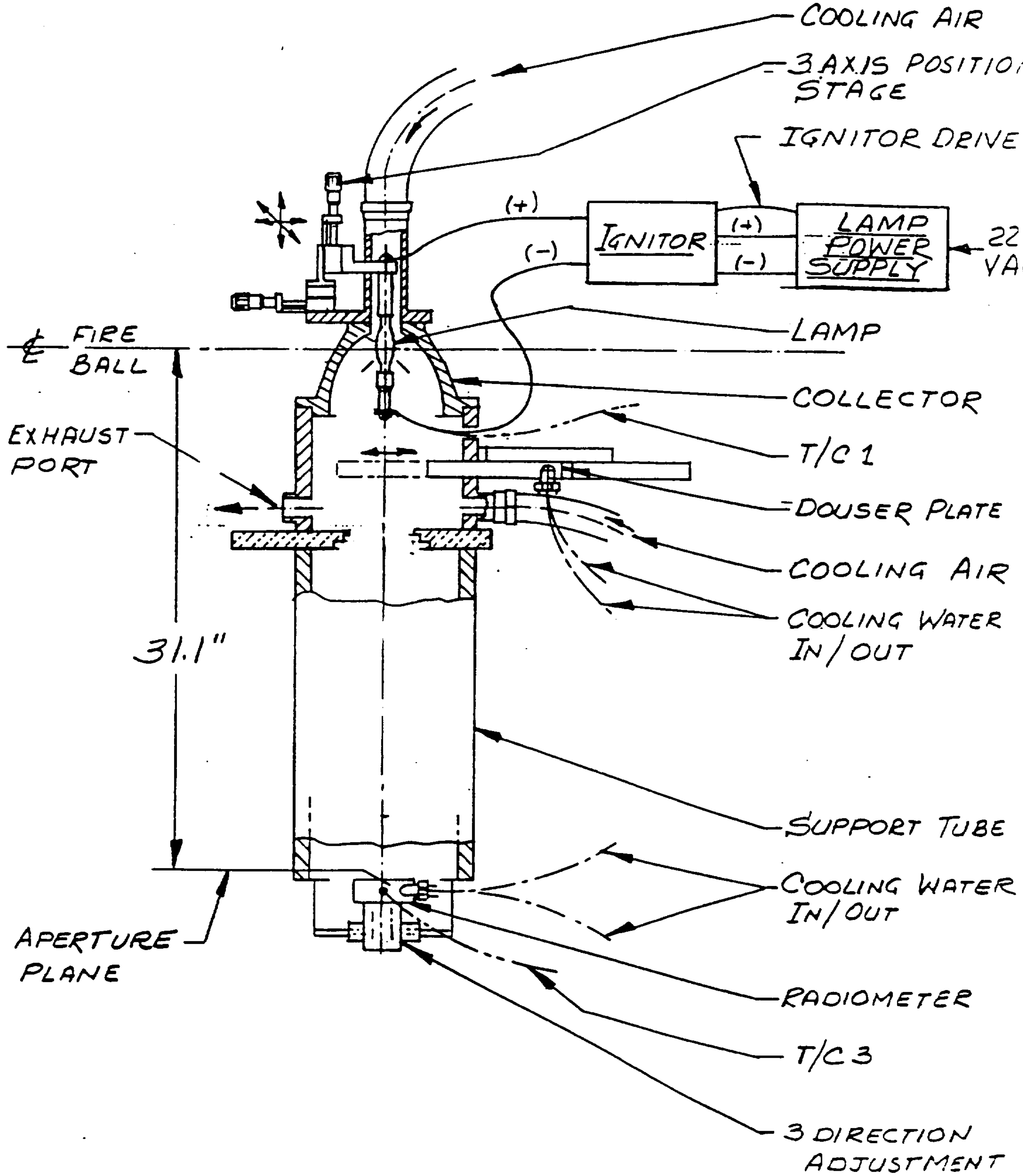
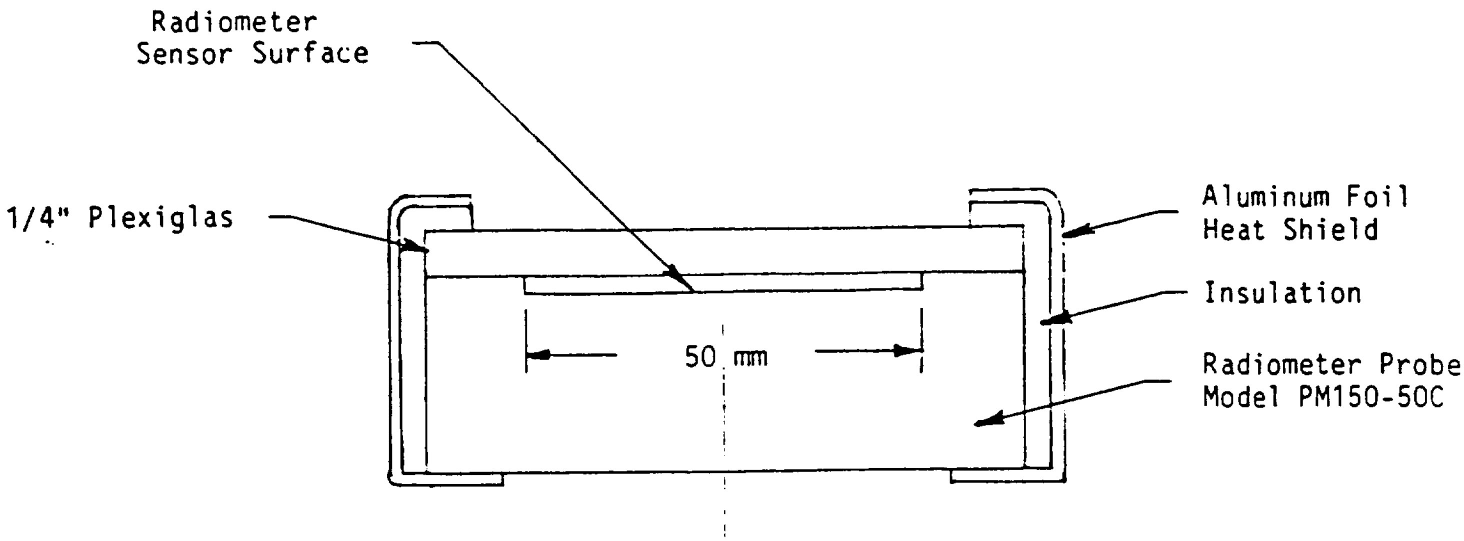
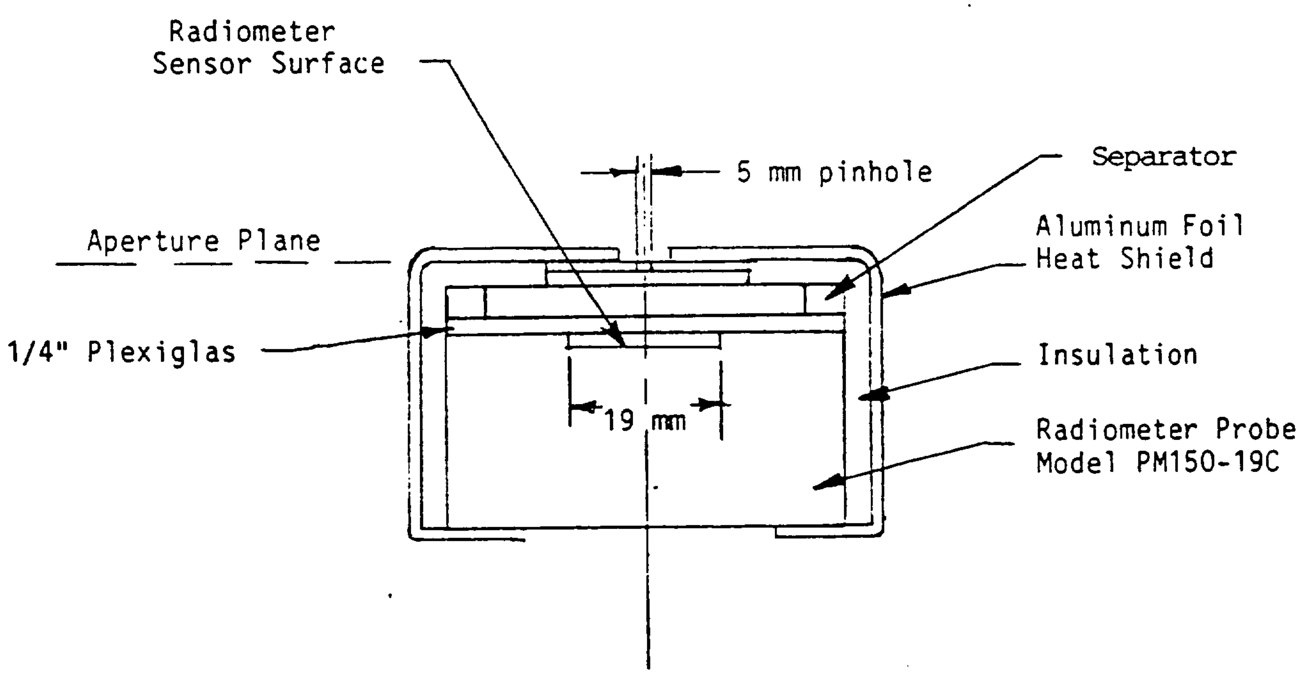


Figure 3-2 - Elliptical Collector - Aperature Test Plane



Total Power Radiometer Probe Set-up



Radiometer Probe Set-up
Aperture Plane Mapping

FIGURE 3-3 Radiometer Probe for Aperature Plane Testing of Elliptical Module note Figure 2-12. The longer filament quite possibly effected the results as discussed in Section 2.2.

Tests of the incandescent lamp were conducted in the test stand used to test Xenon lamps. A schematic of the test setup is shown in Figure 3-4. In this test, the incandescent lamp was mounted at the center of rotation of the rotary stage. The radiometer probe was mounted on an arm attached to the rotary stage and rotated around the lamp. Radiometer readings from a laser power meter were taken at regular intervals around the lamp. The radiometer readings were converted to flux and plotted as shown in Figure 2-8.

A problem encountered with the EL-3B lamp was that the lamp had a relatively short life of approximately 10 minutes at full power. In addition, output from the lamp decreased steadily during the last few minutes of lamp life. As a result, four lamps were used during testing to be able to complete the program and testing had to be curtailed at the end because of lack of replacement lamps. The use of different lamps had no discernable effect on test results.

Testing of the uniform magnification module was done in the same test stand used for testing with the Xenon lamp except that the Xenon lamp was replaced with the incandescent lamp. The test set-up for testing in the aperture plane is shown in Figure 3-5 and the test set-up for testing in the target plane is shown in Figure 3-6. The method used to calculate total power in the aperture plane was the same as used for the Xenon lamp tests. The calculations are shown in Appendix E.

3.3 GEOMETRY TESTS

The geometry tests were conducted using the same test set-up used for testing with the Xenon and incandescent lamps. For tests at the lens plane and the target plane, a 1/16 diameter black spot was installed at the focal point of the collector. The spot was illuminated by shining a light on the spot from outside of the collector. For the aperture plane tests, a .50 inch diameter black spot was installed in the 1.125 diameter aperture and illuminated from the target plane.

To obtain data at the lens plane, the collector was mounted with the center line horizontal and the lens removed. A camera was mounted on a tripod and moved vertically to traverse the lens plane. Photos were taken at regular intervals across the lens plane. Because the spot was difficult to see, hand sketches of the spot were also made. It was interesting to note that for the uniform magnification module when viewed from beyond the lens plane the spot took on a different shape and two spots were visible when looking from near the outer diameter. This was attributed to the collector configuration which causes crossing of the light rays near the outer diameter so that the rays can match the contoured surface of the lens to produce uniform magnification.

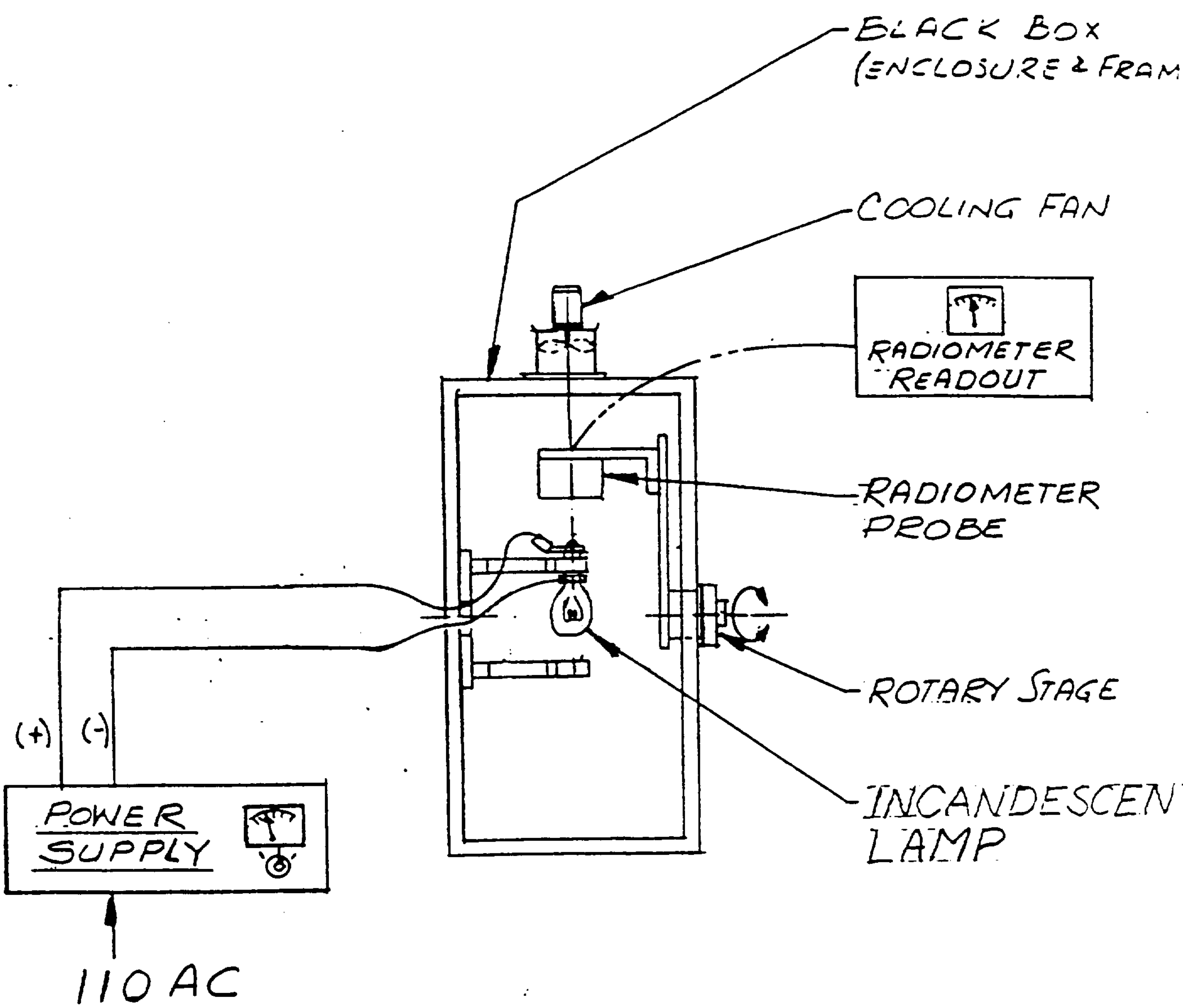


Figure 3-4 Incandescent Lamp Test Set-up
for Bulb Testing

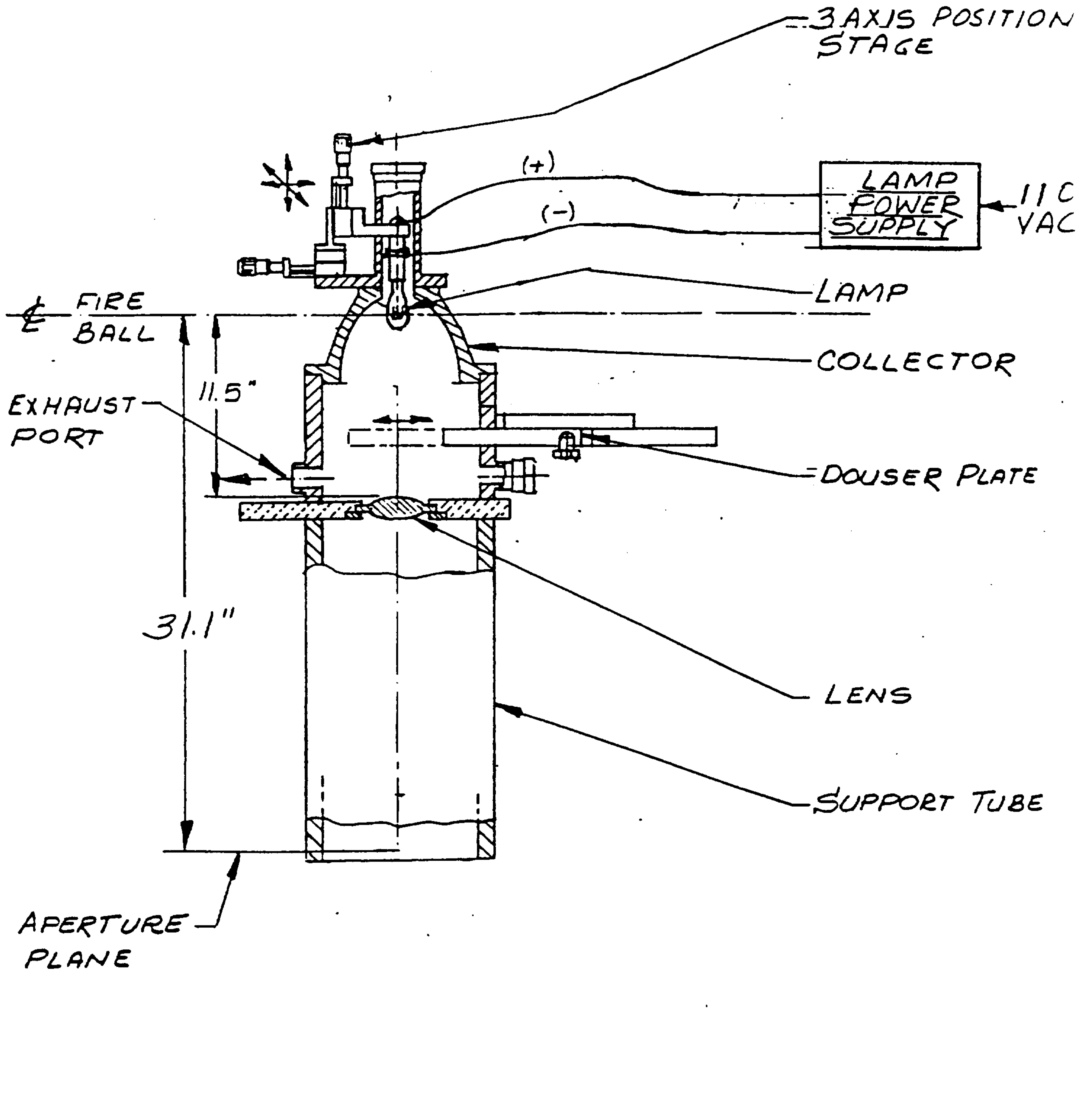


Figure 3-5 - Incandescent Lamp Test Set-up for Aperture Plane Testing

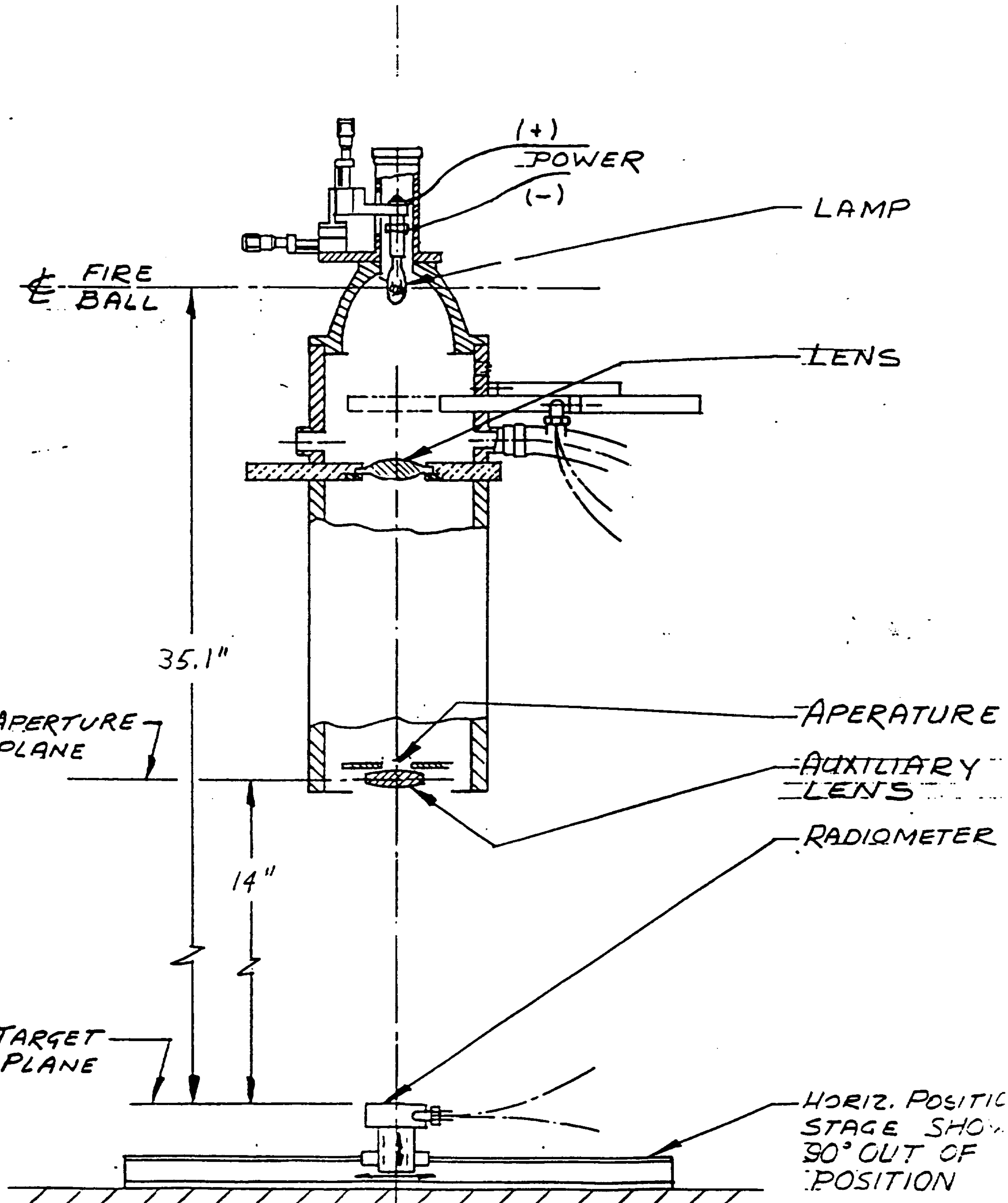


Figure 3-6 - Incandescent Lamp Test Set-up for Target Plane Testing

For the target plane tests, the entire uniform magnification module and elliptical module was mounted horizontally. A camera was mounted on a tripod at the target plane and moved vertically to traverse the plane. While the camera was able to photograph the spot with the uniform magnification module, the spot could not be seen by the camera with the elliptical module. Hand sketches were made for the elliptical module. Because of the difficulty in viewing the spot with the elliptical module, the spot was sketched with and without the auxiliary lens. Note that the lens enlarged the spot and reversed the image.

The uniform magnification module was also installed horizontally for the aperture plane tests. The collector was removed so that the spot could be viewed from the collector plane. Ideally, it would have been best to view the spot from along the contour of the collector but there was no method of accurately measuring the location of the contour with the collector removed. Thus, to compromise, the camera and tripod were set at the approximate axial midpoint of the collector. Because of the brightness of the illumination, the spot was sometimes washed out in the photographs, however, the shape of the aperture is clearly visible in all the photographs. Since this problem was not detected when the photographs were being taken, no hand sketches of the spot were made.

4.0 CONCLUSIONS

The supplementary test program for the reduced scale solar simulator provided additional information for refining the design of the full scale uniform magnification solar simulator for the SDGTD. Original test results were verified and the accuracy for mapping compared to total power measurement was established.

While the tests with the incandescent lamp did not produce the uniformity in the target plane flux expected, the problem is due most likely with the length of the lamp filament. Since better results were obtained with the filament in the in line or narrow position, additional tests with a new lamp with a narrow filament could produce the desired results. Such tests were beyond the scope of this program but could be undertaken if the information is critical to the SDGTD program.

The geometry tests provided information on how the image of the fireball changes shape and size along the contour of the collector and as viewed from the target. In addition, the impact of the lens was shown as seen from the collector.

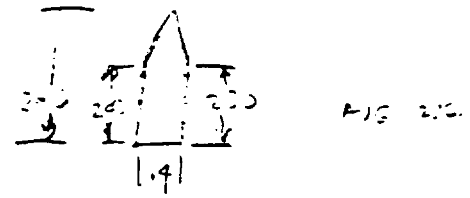
APPENDIX A
UNIFORM MAGNIFICATION MODULE
POWER CALCULATIONS

APPENDIX A

UNIFORM MAGNIFICATION MODULE POWER CALCULATIONS

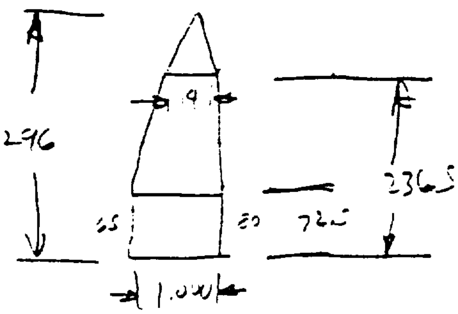
CALCULATED POWER TEST U-57

.400 APERTURE DIA



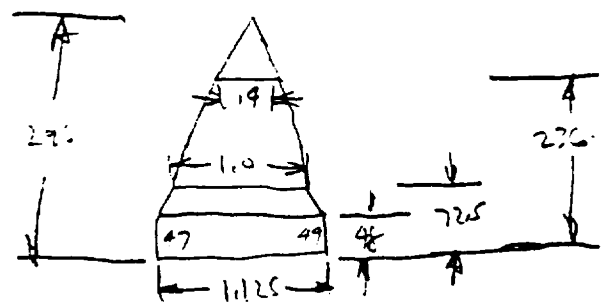
$$P = \frac{\pi}{4}(.4)^2(236.5) + \frac{\pi}{3}(.2)^2(\overset{59.5}{296 - 236.5})$$
$$= 30 + 2 = 32$$

1.000 APERTURE DIA



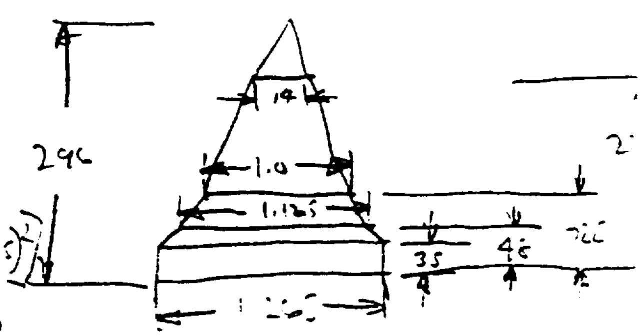
$$P = \frac{\pi}{4}(1)^2(72.5) + \frac{\pi}{3}(.2)^2(59.5)$$
$$+ \frac{\pi}{3}(\overset{164}{236.5 - 72.5})\overset{.39}{\left((.5)^2 + (.5)(.2) + (.2)^2\right)}$$
$$= 57 + 2 + 67 = 126$$

1.125 APERTURE DIA



$$P = 2 + 67 + \frac{\pi}{4}(1.125)^2(48)$$
$$+ \frac{\pi}{3}(72.5 - 48)\left((.5625)^2 + (.5625)(.500) + (.500)^2\right)$$
$$= 2 + 67 + 48 + 22 = 139$$

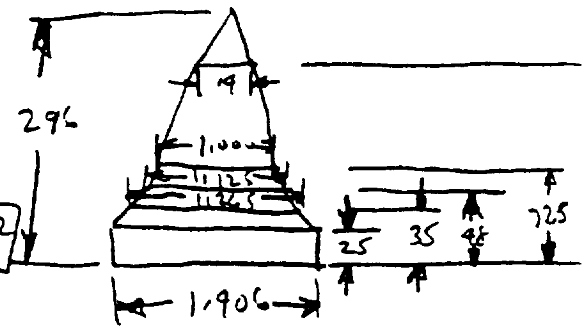
1.265 APERTURE DIA



$$P = 2 + 67 + 22 + \frac{\pi}{4}(1.265)^2(35)$$
$$+ \frac{\pi}{3}(48 - 35)\left((.6325)^2 + (.6325)(.5625) + (.5625)^2\right)$$
$$= 2 + 67 + 22 + 44 + 15 = 150$$

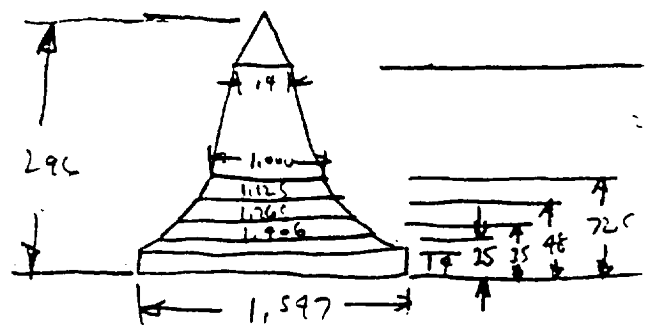
TEST U-57

1,406 APERTURE DIA



$$P = 2+67+22+15+\frac{\pi}{4}(1.406)^2(.25)$$
$$= \frac{\pi}{3}(.35-.25)\left[(.703)^2+(.703)(.6325)+(.6325)^2\right]$$
$$= 2+67+22+15+39+14$$
$$= 159$$

1,597 APERTURE DIA



$$P = 2+67+22+15+14+\frac{\pi}{4}(1.597)^2(.19)$$
$$+\frac{\pi}{3}(.25-.19)\left[(.7735)^2+(.7735)(.703)+(.703)^2\right]$$
$$= 2+67+22+15+14+26+19$$
$$= 165$$

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TOTAL POWER CALCULATION TEST U-58

.400 APERTURE DIA

$$P = \frac{\pi}{4}(.4)^2(217.5) + \frac{\pi}{3}(.2)^2(300-217.5)$$
$$= 27 + 3 = 30 \text{ WATTS}$$

1.000 APERTURE DIA

$$P = \frac{\pi}{4}(1.000)^2(70) + 3 + \frac{\pi}{3}(217.5-70)\left[(.500)^2+(.500)(.200)+(.200)^2\right]$$
$$= 55+3+60 = 118 \text{ WATTS}$$

1.125 APERTURE DIA

$$P = 3+60 + \frac{\pi}{4}(1.125)^2(47.5) + \frac{\pi}{3}(70-47.5)\left[(.5625)^2+(.5625)(.500)+(.500)^2\right]$$
$$= 3+60+47+20 = 130 \text{ WATTS}$$

1.265 APERTURE DIA

$$P = 3+60+20+\frac{\pi}{4}(1.265)^2(39)+\frac{\pi}{3}(47.5-39)\left[(.6325)^2+(.6325)(.5625)+(.5625)^2\right]$$
$$= 3+60+20+43+15 = 141 \text{ WATTS}$$

1.406 APERTURE DIA

$$P = 3+60+20+15+\frac{\pi}{4}(1.406)^2(29)+\frac{\pi}{3}(39-29)\left[(.703)^2+(.703)(.6325)+(.6325)^2\right]$$
$$= 3+60+20+15+37+14 = 149 \text{ WATTS}$$

1.547 APERTURE DIA

$$P = 3+60+20+15+14+\frac{\pi}{4}(1.547)^2(17)+\frac{\pi}{3}(29-17)\left[(.7735)^2+(.7735)(.703)+(.703)^2\right]$$
$$= 3+60+20+15+14+32+12 = \text{[illegible]} \text{ WATTS}$$

POWER VS APERTURE DIAMETER

TEST U-58

DIA = .20 IN.

$$P = \frac{\pi}{3}(.1)^2(42) + \frac{\pi}{4}(.2)^2(258)$$

$$= .4 + 8.1 = 8.5 \text{ WATTS } (.976) = 8.2$$

DIA = .40 IN

$$P = 30 \text{ WATTS } (.976) = 29$$

DIA = .60 IN

$$P = 30 + \frac{\pi}{3}(217.5-167)\left((.3)^2 + (.3)(.2) + (.2)^2\right) + \frac{\pi}{4}(.6)^2(167)$$

$$- \frac{\pi}{4}(.4^2)(217.5)$$

$$= 30 + 10 + 47 - 27 = 60 \text{ WATTS } (.976) = 58$$

DIA = .80 IN

$$P = 60 + \frac{\pi}{3}(167-115)\left((.4)^2 - (.4)(.3) + (.3)^2\right) + \frac{\pi}{4}(.8^2)(115)$$

$$- \frac{\pi}{4}(.6)^2(167)$$

$$= 60 + 19 + 58 - 47 = 90 \text{ WATTS } (.976) = (88.$$

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CALCULATED POWER
AVERAGE OF TEST U-57 (−45°) & U-58 (+45°)

APERTURE DIA	TEST U-57	TEST U-58	AVE	MEASU[RED] TOTAL
.400	32	30	31	34
1.000	126	118	122	118.5
1.125	139	130	134.5	126
1.265	150	141	145.5	139
1.406	159	149	154	145.5
1.547	165	156	160.5	153.5

ADJUST AVE FOR CABLE BLOCKAGE

$$\text{BLOCKAGE} = \text{WIRE AREA} / \text{COLL. AREA}$$

$$= \frac{.3125 \times 4.176}{\pi (4.176)^2} = \frac{1.305}{54.785}$$

$$= .024$$

REVISED CALCULATED POWER

		CALC	MEAS	%
.400	31 X .976 =	30	34	
1.000	122 X .976 =	119	118.5	
1.125	134.5 X .976 =	131	126	
1.265	145.5 X .976 =	142	139	
1.406	154 X .976 =	150	145.5	
1.547	160.5 X .976 =	157	153.5	

APPENDIX B
UNIFORM MAGNIFICATION MODULE
RING POWER CALCULATIONS

APPENDIX B

UNIFORM MAGNIFICATION MODULE RING POWER CALCULATIONS

TEST U-57

POWER IN RINGS VS RING RADIUS

$$P_{r_i} = \overset{P_{TRAP}}{\frac{\pi}{3}\left(\Delta F_{(r_i - r_{i-1})}\right)\left[(r_i)^2 + (r_i)(r_{i-1}) - (r_{i-1})^2\right]} + \overset{P_{CYL}}{\pi (r_i)^2 (F_{r_i})} - \underset{P_{CENTER}}{\pi (r_{i-1})^2 (F_{r_{i-1}})}$$

r_i	r_{i-1}	F_{r_i}	$F_{r_{i-1}}$	P_{TRAP}	P_{CYL}	P_{CENTER}	P_r
.1	0	266	296	.3	8.4	0	8.[illegible]
.2	.1	230	266	2.6	28.9	8.4	23.[illegible]
.3	.2	193	230	7.4	54.6	28.9	33.[illegible]
.4	.3	135	193	22.5	67.9	54.6	35.[illegible]
.5	.4	80	135	35.1	62.8	67.9	30.[illegible]
.6	.5	43	80	35.3	46.6	62.8	21.[illegible]
.7	.6	25	43	23.9	38.5	46.6	13.[illegible]
.8	.7	15	25	17.7	30.2	38.5	9.4
.9	.8	11	15				
1.0	.9	8	11				

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TEST U-58

POWER IN RINGS VS RING RADIUS

$$P_{r_i} = \overbrace{\frac{\pi}{3}\left(\Delta F_{(r_i - r_{i-1})}\right)\left[(r_i)^2 + (r_i)(r_{i-1}) + (r_{i-1})^2\right]}^{P_{TRAP}} + \overbrace{\pi (r_i)^2 (F_{r_i})}^{P_{CYL}} - \underbrace{\pi (r_{i-1})^2 (F_{r_{i-1}})}_{P_{CENTER}}$$

r_i	r_{i-1}	F_{r_i}	$F_{r_{i-1}}$	P_{TRAP}	P_{CYL}	P_{CENTER}	P_{r_i}
.1	0	258	300	.4	8.1	0	8.
.2	.1	217.5	258	3	27	8	22
.3	.2	167	217.5	10	47	27	3[illegible]
.4	.3	115	167	20	58	47	31
.5	.4	70	115	29	55	58	26
.6	.5	41	70	28	46	55	19
.7	.6	24	41	23	37	46	1[illegible]
.8	.7	15	24	16	30	37	9
.9	.8						
1.0	.9						

TEST U-57 & U-58 AVERAGE

POWER IN RINGS VS RING RADIUS

$$P_{ri} = \overset{P_{TRAP}}{\frac{\pi}{3}\left(\Delta F_{(r_i - r_{i-1})}\right)\left[(r_i)^2 + (r_i)(r_{i-1}) + (r_{i-1})^2\right]} + \overset{P_{CYL}}{\pi (r_i)^2 (F_{ri})} - \underset{P_{CENTR}}{\pi (r_{i-1})^2 (F_{ri-1})}$$

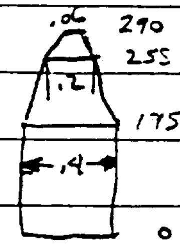
r_i	r_{i-1}	F_{ri}	F_{ri-1}	U-57 ~~P_{TRAP}~~	U-58 ~~P_{CYL}~~	AVE ~~P~~	~~P~~
.1	0			8.7	8.5	8.6	
.2	.1			23.1	22.0	22.6	
.3	.2			33.1	30.0	31.5	
.4	.3			35.8	31.0	33.4	
.5	.4			30.0	26.0	28.0	
.6	.5			21.1	19.0	20.0	
.7	.6			13.8	14.0	13.9	
.8	.7			9.4	9.0	9.2	
.9	.8						
1.0	.9						

APPENDIX C
ELLIPTICAL MODULE
POWER CALCULATIONS

APPENDIX C
ELLIPTICAL MODULE
POWER CALCULATIONS

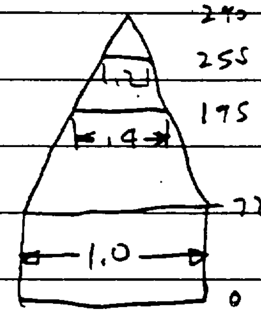
CALCULATED POWER TEST E-59

.400 APERTURE DIA



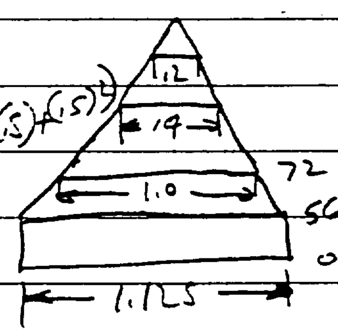
$$P = \frac{\pi}{3}\overset{35}{(290-255)}\overset{.0139}{\left((.1)^2+(.1)(.08)+(.08)^2\right)} + \frac{\pi}{3}(255-195)\overset{.07}{\left((.2)^2+(.2)(.1)+(.1)^2\right)}$$
$$+ \frac{\pi}{4}(.4)^2(195)$$
$$= .5 + 4.40 + 24.5 = 29.4 \quad \text{WATTS}$$

1.00 APERTURE DIA



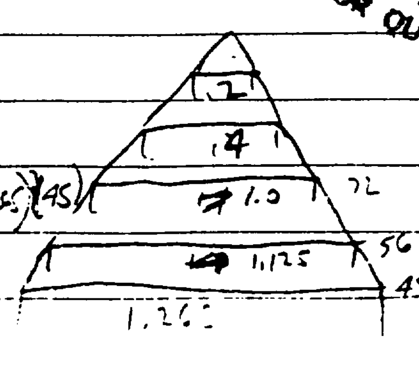
$$P = .5 + 4.4 + \frac{\pi}{3}(195-72)\overset{.39}{\left((.5)^2+(.5)(.2)+(.2)^2\right)}$$
$$+ \frac{\pi}{4}(1.0)^2(72)$$
$$= .5 + 4.4 + 50.2 + 56.5 = 111.6 \quad \text{WATTS}$$

1.125 APERTURE DIA



$$P = .5 + 4.4 + 50.2 + \frac{\pi}{3}(72-56)\overset{.846}{\left((.5625)^2+(.5625)(.5)+(.5)^2\right)}$$
$$+ \frac{\pi}{4}(1.125)^2(56)$$
$$= .5 + 4.4 + 50.2 + 14.2 + 55.7$$
$$= 125 \quad \text{WATTS}$$

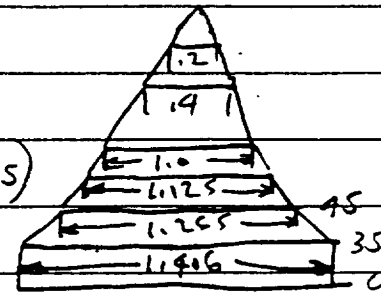
1.265 APERTURE DIA



$$P = .5 + 4.4 + 50.2 + 14.2$$
$$+ \frac{\pi}{3}(56-45)\overset{1.073}{\left((.6325)^2+(.6325)(.5625)+(.5625)^2\right)} + \frac{\pi}{4}(1.265)^2(45)$$
$$= .5 + 4.4 + 50.2 + 14.2 + 12.4 + 56.6$$

TEST E-54

1.406 APERTURE DIA

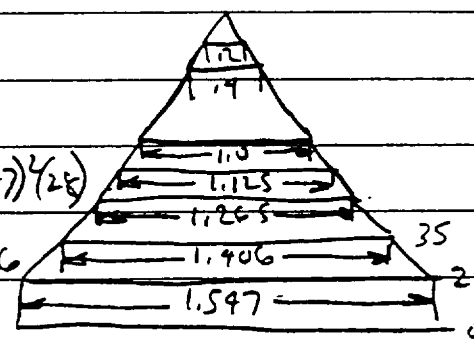


$P = .5 + 4.4 + 50.2 + 14.2 + 12.4$
$+ \frac{\pi}{3}(45-35)\left((.703)^2 + (.703)(.6325) + (.6325)^2\right) + \frac{\pi}{4}(1.406)^2(35)$

$= .5 + 4.4 + 50.2 + 14.2 + 12.4 + 14.0 + 54.3$

$P = 150.0$ WATTS

1.547 APERTURE DIA



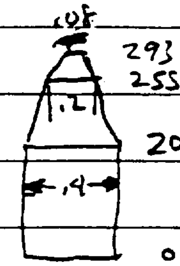
$P = .5 + 4.4 + 50.2 + 14.2 + 12.4 + 14.0$
$+ \frac{\pi}{3}(35-28)\left((.7735)^2 + (.7735)(.703) + (.703)^2\right) + \frac{\pi}{4}(1.547)^2(28)$

$= .5 + 4.4 + 50.2 + 14.2 + 12.4 + 14.0 + 12.0 + 52.6$

$P = 160.3$ WATTS

CALCULATED POWER TEST E - 55

.400 APERTURE DIA

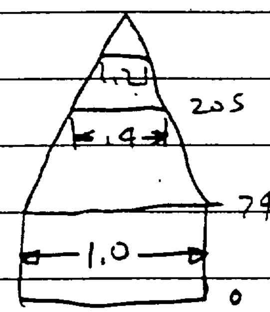


$$P = \frac{\pi}{3}(293-255)\left((.1)^2+(.1)(.04)+(.04)^2\right)+\frac{\pi}{3}\overset{107}{(255-205)}\left((.2)^2+(.2)(.1)+(.1)^2\right)$$

$$+\ \frac{\pi}{4}(.4)^2(205)$$

$$= .67 + 3.7 + 25.8 = 30.0 \quad \text{WATTS}$$

1.00 APERTURE DIA

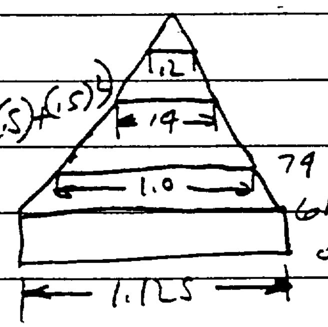


$$P = 4.3 \quad + \frac{\pi}{3}\overset{.39}{(205-74)}\left((.5)^2+(.5)(.2)+(.2)^2\right)$$

$$+\ \frac{\pi}{4}(1.0)^2(74)$$

$$= 4.3 + 53.5 + 58.1 = 115.9 \quad \text{WATTS}$$

1.125 APERTURE DIA



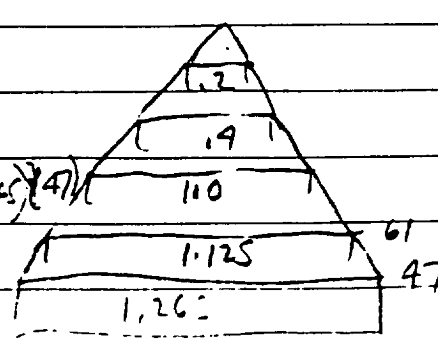
$$P = 57.8 \quad + \frac{\pi}{3}\overset{.848}{(74-61)}\left((.5625)^2+(.5625)(.5)+(.5)^2\right)$$

$$+\ \frac{\pi}{4}(1.125)^2(61)$$

$$= 57.8 + 11.5 + 60.6$$

$$= 129.9 \quad \text{WATTS}$$

1.265 APERTURE DIA



$$P = 69.3$$

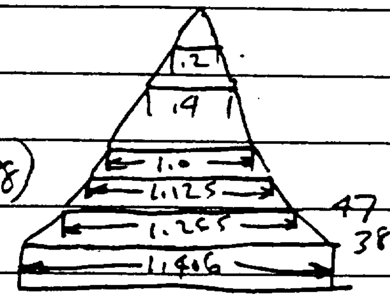
$$+\ \frac{\pi}{3}\overset{1.072}{(61-47)}\left((.6325)^2+(.6325)(.5625)+(.5625)^2\right)+\frac{\pi}{4}(1.265)^2(47)$$

$$= 69.3 + 15.7 + 59$$

$$= 144$$

TEST E-55

1.406 APERTURE DIA



$P = 85.0$

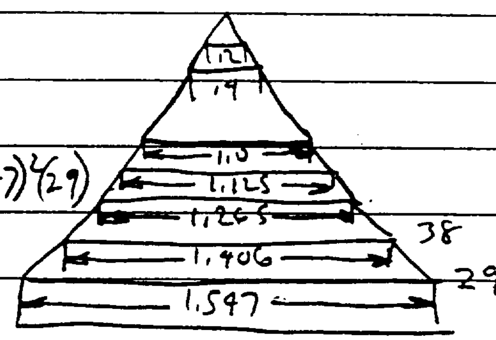
$$+ \frac{\pi}{3}(47-38)\left[(.703)^2 + (.703)(.6325) + (.6325)^2\right] + \frac{\pi}{4}(1.406)^2(38)$$

1.339

$= 85.0 + 12.6 + 59.0$

$P = 156.6$ WATTS

1.547 APERTURE DIA



$P = 97.6$

$$+ \frac{\pi}{3}(38-29)\left[(.7735)^2 + (.7735)(.703) + (.703)^2\right] + \frac{\pi}{4}(1.547)^2(29)$$

1.636

$= 97.6 + 15.4 + 54.5$

$P = 167.5$ WATTS

POWER VS. APERTURE DIA

TEST E-54

DIA = .20 IN

$$P = \frac{\pi}{3}(\overset{35}{290-255})\left[(.1)^2 + \overset{.0139}{(.1)(.03) + (.03)^2}\right] + \frac{\pi}{4}(.2)^2(255)$$

$$= .5 + 8 = 8.5 \text{ WATTS}$$

DIA = .60 IN

$$P = .5 + 4.40 + \frac{\pi}{3}(195-140)\left(\overset{.13}{(.3)^2 + (.3)(.2) + (.2)^2}\right) + \frac{\pi}{4}(.6)^2(140)$$

$$= 4.90 + 7.5 + 39.6 = 520 \text{ WATTS}$$

DIA = .80 IN

$$P = 4.90 + 7.5 + \frac{\pi}{3}(140-103)\left(\overset{.37}{(.4)^2 + (.4)(.3) + (.3)^2}\right) + \frac{\pi}{4}(.8)^2(103)$$

$$= 12.4 + 14.3 + 51.8 = 78.5 \text{ WATTS}$$

TEST E-55

DIA = .20 IN

$$P = \frac{\pi}{3}(\overset{38}{293-255})\left((.1)^2 + (.1)(.03) + (.03)^2\right) + \frac{\pi}{4}(.2)^2(255)$$

$$= .6 + 8.0 = 8.6 \text{ WATTS}$$

DIA = .60 IN

$$P = .6 + 3.7 + \frac{\pi}{3}(205-143)\left((.3)^2 + (.3)(.2) + (.2)^2\right) + \frac{\pi}{4}(.6)^2(143)$$

$$= 4.3 + 8.4 + 40.4 = 53.1 \text{ WATTS}$$

DIA = .80 IN

$$P = 4.3 + 8.4 + \frac{\pi}{3}(143-103)\left((.4)^2 + (.4)(.3) + (.3)^2\right) + \frac{\pi}{4}(.8)^2(103)$$

$$= 12.7 + 15.5 + 51.8 = 80.0 \text{ WATTS}$$

ORIGINAL PAGE IS
OF POOR QUALITY

CALCULATED POWER

AVERAGE OF TEST E-54 (-45°) & E-55 (+45°)

APERTURE DIA	TEST E-54	TEST E-55	AVE	MEASURED TOTAL E-52
.400	29.4	30.0	29.7	30.5
1.000	111.6	115.9	113.8	107
1.125	125.0	129.9	127.5	119.5
1.265	138.3	144	141.2	131
1.406	150.0	156.6	153.3	142.5
1.547	160.3	167.5	163.9	154
.200	8.5	8.6	8.55	
.600	52.0	53.1	52.55	
.800	78.5	80.0	79.3	

ADJUST FOR WIRE BLOCKAGE 2.4 %

ADJUSTED POWER			% DIFF E-52
.400	29.7 x .976 =	29.0	-4.9
1.000	113.8 x .976 =	111.1	+3.8
1.125	127.5 x .976 =	124.4	+4.1
1.265	141.2 x .976 =	137.8	+5.2
1.406	153.3 x .976 =	149.6	+5.0
1.547	163.9 x .976 =	160.0	+4.9
.200	8.6 x .976 =	8.4	
.600	52.6 x .976 =	51.3	
.800	79.2 x .976 =	77.3	

APPENDIX D
ELLIPTICAL MODULE
RING POWER CALCULATIONS

APPENDIX D
ELLIPTICAL MODULE
RING POWER CALCULATIONS
TEST E-54

POWER IN RINGS VS RING RADIUS

$$P_{ri} = \overset{P_{TRAP}}{\frac{\pi}{3}\left(\Delta F_{(r_i - r_{i-1})}\right)\left[(r_i)^2 + (r_i)(r_{i-1}) + (r_{i-1})^2\right]} + \overset{P_{CYL}}{\pi (r_i)^2 (F_{ri})} - \underset{P_{CENTER}}{\pi (r_{i-1})^2 (F_{ri-1})}$$

	r_i	r_{i-1}	F_{ri}	F_{ri-1}	P_{TRAP}	P_{CYL}	P_{CENTER}	P_{ri}
	.1	0	255	290	.5	8.0	0	8.[illegible]
	.2	.1	195	255	4.4	24.5	8.0	20.[illegible]
	.3	.2	140	195	7.5	39.6	24.5	22.[illegible]
	.4	.3	103	140	14.3	51.8	39.6	26.5
[illegible]	.5	.4	72	103	19.8	56.5	51.8	29.[illegible]
.91	.6	.5	50	72	21.0	56.5	56.5	21.0
1.27	.7	.6	35	50	19.9	53.9	56.5	17.3
1.69	.8	.7	25	35	17.7	50.3	53.9	14.1
2.17	.9	.8	18	25	15.9	45.8	50.3	11.4
2.71	1.0	.9	13	18	14.2	40.8	45.8	9.2

ORIGINAL PAGE IS
OF POOR QUALITY

TEST E-55

POWER IN RINGS VS RING RADIUS

$$P_{r_i} = \overset{P_{TRAP}}{\frac{\pi}{3}\left(\Delta F_{(r_i - r_{i-1})}\right)\left[(r_i)^2 + (r_i)(r_{i-1}) + (r_{i-1})^2\right]} + \overset{P_{CYL}}{\pi (r_i)^2 (F_{r_i})} - \underset{P_{CENTER}}{\pi (r_{i-1})^2 (F_{r_{i-1}})}$$

r_i	r_{i-1}	F_{r_i}	$F_{r_{i-1}}$	P_{TRAP}	P_{CYL}	P_{CENTER}	P_{r_i}
.1	0	255	293	.6	8.0	0	8.[illegible]
.2	.1	205	255	3.7	25.8	8.0	21.[illegible]
.3	.2	143	205	8.4	40.4	25.8	2[illegible]
.4	.3	103	143	15.5	51.8	40.4	26.[illegible]
.5	.4	74	103	18.5	58.1	51.8	29.[illegible]
.6	.5	53	74	20.0	59.9	58.1	21.[illegible]
.7	.6	38	53	19.9	58.5	59.9	[illegible]
.8	.7	27	38	19.5	54.3	58.5	15.[illegible]
.9	.8	19	27	18.2	48.3	54.3	12.[illegible]
1.0	.9	12	19	19.9	37.7	48.3	9.[illegible]

TEST E-54 & E-55 AVERAGE

POWER IN RINGS VS RING RADIUS

$$P_{ri} = \overbrace{\frac{\pi}{3}\left(\Delta F_{(ri-ri-1)}\right)\left[(ri)^2 + (ri)(ri-1) - (ri-1)^2\right]}^{P_{TRAP}} + \overbrace{\pi (ri)^2 (F_{ri})}^{P_{CYL}} - \underbrace{\pi (r_{i-1})^2 (F_{ri-1})}_{P_{CENTER}}$$

r_i	r_{i-1}	F_{ri}	F_{ri-1}	E-54	E-55	AVE
.1	0			8.5	8.6	8.55
.2	.1			20.9	21.5	21.2
.3	.2			22.6	23.0	22.8
.4	.3			26.5	26.9	26.7
.5	.4			24.5	24.8	24.65
.6	.5			21.0	21.8	21.4
.7	.6			17.3	18.5	17.9
.8	.7			14.1	15.3	14.7
.9	.8			11.4	12.2	11.8
1.0	.9			9.2	9.3	9.25

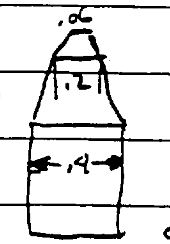
APPENDIX E
INCANDESCENT LAMP
POWER CALCULATIONS

APPENDIX E

INCANDESCENT LAMP POWER CALCULATIONS

CALCULATED POWER TEST U-69

.400 APERTURE DIA

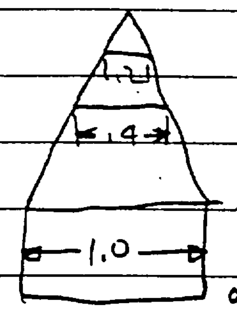


$$P = \frac{\pi}{3}(.2^2)(13.5 - 9.8) + \frac{\pi}{3}(0)\left((.2)^2 + (.2)(.1) + (.1)^2\right) + \frac{\pi}{4}(.4)^2(9.8)$$

.07

$= .155 + 1.23 = 1.387$ WATTS

1.00 APERTURE DIA

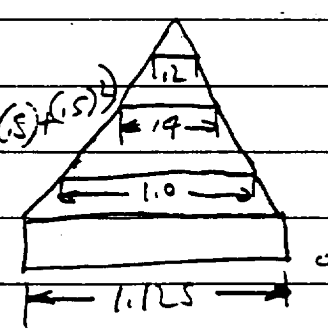


6.2 .4 .28

$$P = .155 + \frac{\pi}{3}(9.8 - 3.6)\left((.8)^2 + (.8)(.2) + (.2)^2\right) + \frac{\pi}{4}(1.0)^2(2.3) + \frac{\pi}{3}(3.6 - 2.3)\left((.5)^2 + (.5)(.4) + (.4)^2\right)$$

$= .155 + 1.818 + 1.806 + .623 = 4.40$ WATTS

1.125 APERTURE DIA



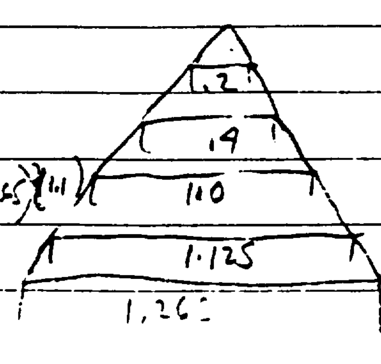
1.648

$$P = .155 + 1.818 + .623 + \frac{\pi}{3}(2.3 - 1.5)\left((.5625)^2 + (.5625)(.5) + (.5)^2\right) + \frac{\pi}{4}(1.125)^2(1.5)$$

$= .155 + 1.818 + .623 + .710 + 1.491$

$= 4.797$ WATTS

1.265 APERTURE DIA



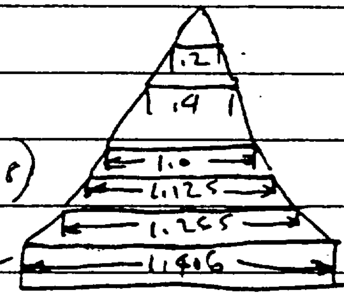
1.07

$$P = .155 + 1.818 + .623 + .710 + \frac{\pi}{3}(1.5 - 1.1)\left((.6325)^2 + (.6325)(.5625) + (.5625)^2\right) + \frac{\pi}{4}(1.265)^2(1.1)$$

$= .155 + 1.818 + .623 + .710 + .449 + 1.382$

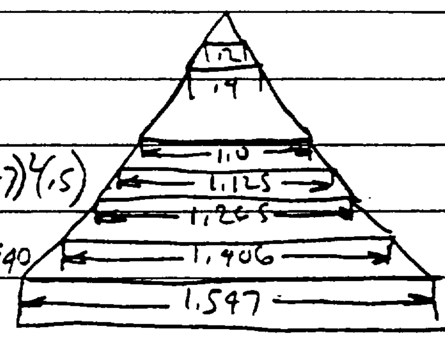
TEST ~~8~~-U-64

1.406 APERTURE DIA



$$P = .155 + 1.818 + .623 + .710 + .449$$
$$+ \frac{\pi}{3}(1.1-.8)\left((.703)^2+(.703)(.6325)+(.6325)^2\right) + \frac{\pi}{4}(1.406)^2(.8)$$
$$= .155 + 1.818 + .623 + .710 + .449 + .421 + 1.242$$
$$P = 5.41 \text{ WATTS}$$

1.547 APERTURE DIA



$$P = .155 + 1.818 + .623 + .710 + .449 + .421$$
$$+ \frac{\pi}{3}(.8-.5)\left((.7735)^2+(.7735)(.703)+(.703)^2\right) + \frac{\pi}{4}(1.547)^2(.5)$$
$$= .155 + 1.818 + .623 + .710 + .449 + .421 + .514 + .940$$
$$P = 5.630 \text{ WATTS}$$

POWER VS. APERTURE DIA

TEST U-64

DIA = .20 IN

$$P = \frac{\pi}{3}(13.5 - 11.5)(.1)^2 + \frac{\pi}{4}(.2)^2(11.5)$$

$$P = .021 + .361 = .382 \text{ W.}$$

DIA = .60 IN

$$P = .155 + \frac{\pi}{3}(9.8 - 6.1)\left((.3)^2 + (.3)(.2) + (.2)^2\right) + \frac{\pi}{4}(.6)^2(6.1)$$

$$= .155 + .504 + 1.725 = 2.384 \text{ W}$$

DIA = .80 IN

$$P = .155 + .504 + \frac{\pi}{3}(6.1 - 3.6)\left((.4)^2 + (.4)(.3) + (.3)^2\right) + \frac{\pi}{4}(.8)^2(3.6)$$

$$= .155 + .504 + .969 + 1.801 = 3.429 \text{ W.}$$