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PROPOSAL FOR A CONCEPTUALLY NEW COMPACT COLLECTING OPTICS FOR POWERFUL LIGHT SOURCES

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SUMMARY

Testing of a S/C under simulated outer space conditions is the best guarantee for a successful mission, and for almost all of the parameters a good match (to within a few %) may be reached in relevant test facilities (e.g. I.R. background, earthshine and albedo radiation, residual atmosphere, intensity stability, - distribution and spectrum of the solar radiation).

The collimation angle of the sun (32 arc min.) is, however, a drastic exception, here only ± 1.5 to ± 2° are achieved which means a relative deviation by nearly one order of magnitude.

The main reason for this is the presently used collecting optics having unnecessary large diameters. Here a lens - mirror combination is proposed which allows to reduce the diameter by nearly a factor of two and to achieve with the present Xenon arc lamps a collimation angle of ± 0.8°.

SCOPE

The best guarantee for a successful mission of a S/C project is a careful testing on the ground, and since the S/C's became even more sophisticated requiring more stringent specifications, one must assume that this remains also valid for the future.

The most important tests are the thermal balance tests; however, because of the costly simulation of the solar radiation they are also the most expensive ones.

Present solar simulators show an intensity stability better than 1% and a uniformity of the intensity distribution in the test volume within ± 3 to ± 5%; hence they match in this aspect to a high degree the real solar radiation. The spectral intensity distribution is simulated actually by the Xenon spectrum, sometimes the high Xenon peaks in the range from 0.8 to 1.0μ are filtered to achieve a better match with the solar spectrum. Certainly there are numerous peaks left which do not agree with the solar spectrum but because most materials do not show a great selectivity within these spectral ranges, also this less good simulation of the solar spectrum satisfies most customers so far (Fig. 1).

As for the collimation angle, there was for thermal balance testing neither a serious demand nor is there a technical possibility to match the sun's collimation angle (32 arc min.) to a similar degree as the previous parameters. The solar simulators today have collimation angles of ± 1.5 to ± 2° in the test volume, hence there is a deviation with the real one by a factor of 6 to 8.

For the near future, however, one has to expect a demand for a better simulation of the collimation angle, since on the light weight structures already short shadowing and half shadowing effects will influence considerably temperature, temperature gradient and temperature profile as function of time and hence cause thermal stress and/or degradation on these structures, which are a vital and substantial part of the future S/C generation.

BOUNDARY CONDITIONS

The Light Source

Of course, when using a powerful light source of high plasma temperature, there is no problem anticipated to achieve also a small collimation angle. Considerable effort was spent in the past to develop powerful lamps, and the outcome is the high power Xenon arc lamp with watercooled electrodes allowing an arc power of 25 to 35 kW dependent on the lifetime requirements. This lamp reached technical maturity, is commercially available, and for the near future no other powerful light source is expected to replace this type of lamp.

The radiation intensity distribution of a Xenon arc is typically shown in Fig. 2 and the polar radiation characteristics in Fig. 3 (here a Durotest lamp) [Ref. 1].

Because Xenon and solar spectrum show a fair agreement (Fig. 1), also the plasma temperature of the arc must be approximately the same as at the sun's surface. Therefore, a considerably better match of the collimation angle should be achievable in case the collecting optics is properly adapted; even when considering the light losses due to absorption and/or surface reflections of ~ 12% on each optical element, an improvement by nearly a factor of three is feasible in case the most intense part of the arc is used. The mean arc temperature as function of radius is shown in Fig. 4.

The Projection System

The principle of the projection system is illustrated in Fig. 5. The condensor - or collecting mirror - (C) directs the more or less spherically emitted light of the light source towards the projection lens (F) and the projection lens focusses the condensor plane into the reference plane (P). Optimum performance is obviously achieved in case the condensor is designed such that also the light source is focussed onto the projection lens since then there is no loss of light due to spill over and the lens may have minimum diamter. Naturally one may add in the same way another optical element (e.g. field lens) with the consequence that not the condensor plane but the light source (via an image) is focussed in the reference plane, of course also with the corresponding intensity distribution (Ref. 2, 3, 4).

In order to achieve a high intensity, one should keep the radius (R) of the reference plane (P) as small as possible which requires a small exit angle (α'); this exit angle, however, cannot be made smaller than the entrance angle (α) because then part of the collector would not be covered, hence severe light losses would be the consequence.

On the other hand is the collimation angle (ε) given by the ratio of the projection lens diameter to the distance of the reference plane (D). Thus for a small collimation at a high intensity level ($\hat{=}$ small beam diameter) one should keep both exit (= entrance) angle and the image of the light source as small as possible. The first demand means a small diameter of the collecting optics, the second a small but intense light source (and, as mentioned before, the best one can use is the high power Xenon arc lamp).

When using such a Xenon lamp one could capture and lead the emitted light to the field lens plane e.g. by means of optical fibres, clustered around the Xenon bulb; the spheric light emitting surface ($4 \cdot \pi \cdot R^2$ bulb) is then converted into a circular plane ($\pi \cdot R^2$ plane) with the same exit angle of the light, in other words the smallest achievable diameter of the collecting optics is twice the diamter of the light source:

$$R_{plane} = 2.R_{bulb}$$

The Xenon lamps have a bulb diameter of 13 ÷ 14 cm, therefore it seems likely to reduce the diameter of the collecting optics from presently 56 - 60 cm to 30 cm, which means an improvement by nearly a factor of two.

Since in addition the polar radiation as well as the intensity across the arc is highly non-uniform, a further improvement is feasible when only the most intensive parts are used; of course this will be on account of the overall efficiency.

Review of Presently Used Optics

The parabolic reflector

The well-known and by far mostly used parabolic (or shaped close to a parabola) mirror is mechanically the simplest solution; from the optical point of view it is, however, a bad one. It is actually an optical element where the focal length varies.

Close to the optical axis is the focal length short and increases steadily for larger mouth angles (see Fig. 6). Consequently the rays of small entrance angle (close to the optical axis) produce a large image in the field lens plane and vice versa produce the light rays of large entrance angle ($\hat{=}$ at large mouth angles) small images; thus, in order to capture a high percentage of the emitted light with a parabolic mirror, both a large entrance angle and a large image of the light source in the field lens plane results. In addition the percentage of captured light for large radii is relatively low ($\hat{=}$ per cm radius), see figs. 6, 7.

Of course, one could use a small spherical secondary mirror so that the light leaving the upper part of the bulb (to the anode) will be reflected back through the arc, hence a considerably smaller mouth angle ($\hat{=}$ smaller collector diameter) would result. The efficiency of such a mirror is, however, rather low; according to Kirchhoff's law a good emitter is also a good absorber. We measured at ESTEC on our HBF3 space chamber when operating the solar simulator with a secondary mirror, a contribution of only 15 ÷ 20%.

The Koehler Collector

The less applied Koehler integrator (Ref. 5) is mechanically more complicated, from the optical point of view, however, a better solution; actually two lens + deflecting mirror arrays (2 x 7) are clustered around the light source (Fig. 8). Since the distance to the light source centre is for all lenses the same, all the individual arc images are of the same dimensions. When looking from the field lens plane into the collector along the optical axis, one will see a shining area composed by 2 x 7 circular areas arranged in a circle around the Xenon lamp (Fig. 9).

It is a pity that from the total cross-sectional area only the outer part is used, making the entrance angle unnecessary large. Of course one could place the upper deflecting mirrors closer to the centre, but there is no way to reduce the overall diameter since the lower deflecting mirrors will have to be kept in their position. (When using instead of a 2 x 7 lens array one of 2 x 6 it seems feasible to achieve a hexagon arrangement which would have a higher package density for clustering of lamp units.

Naturally various constructions are possible to fill up the gap in the cross-sectional area using additional deflecting mirrors; however, all these solutions will be highly complex and costly and do not allow standardisation of a lamp module.

COMPACT COLLECTING OPTICS

General Considerations

As outlined in the foregoing paragraph the requirements for achieving a small collimation angle boil down to:

1. To capture the light leaving the light source as soon as possible, that means to align it parallel and avoid further expansion of the light beams.
2. To use optical elements of identical focal length.
3. To convert the spherical light emitting area into a circular or hexagonal plane of preferably the same area.

The Koehler integrator meets only the first two requirements; on account of the third one instead it was designed relatively simple; the lenses are identical, they have both the same focal length and the same diameter, hence also the lens plane may be superimposed and projected into the reference plane because the optical orientation is ruled out, and since the intensity distribution across the lens plane is considerably more uniform than across the arc image one may achieve a fair intensity distribution without integrator or mixer.

The fact that the arc images are of the same dimensions (requirement 2) allows to make effective use of the most intense part of the arc (above the cathode tip, Fig. 2). In Fig. 10 the emitted light is shown as function of the arc diameter used, and obviously it is unfortunate to go for more than ~6 mm arc diameter, since here already ~66% of the emitted light is captured and for larger radii the gain of light is substantially reduced.

Three Lens Array

In order to reduce the overall diameter of the collecting optics one has to disregard the advantages of the simplicity of the Koehler integrator, since only with a third lens array one may make use of the inner parts of the circular plane. The beams of the equatorial lens array (Fig. 11) may be deflected by the inner circle of deflecting mirrors, whilst the beams of the upper (anode) and lower (cathode) lens array will be deflected by mirrors positioned at the same radius, one in the gap of the other, naturally at different height. The diameter of such a collector unit would be ≃ 33 cm and hence only 60% of the parabolic reflector. The amount of captured light is *80%*, which is approximately the same as for the parabolic reflector (Ref. 4). The light losses, however, are higher due to spill over and surface reflections on the lenses. A detailed breakdown of the light losses is given in Table 1, see also Fig. 11 a, b and Fig. 9.

The gaps between the deflecting mirrors of the inner circle may be used for the supporting structure for lenses and mirrors, thus they are not only a disadvantage. Compared with the Koehler integrator this design has considerably more elements and is more complicated. However, the lenses have a smaller opening requiring less refractivity and may therefore be provided with normal spherical surfaces which is substantially cheaper than for parabolic ones.

Considering the arc utilisation, the light losses, the diameter of the collecting optics and the optimum arc image, it should be possible to achieve at 1 S.C. level with a 25 kW lamp a collimation angle of ± 1°.

Four Lens Array

The three lens array leaves mainly two fields open for improvement:

1. the inner part of the light emitting area is not used (smaller than bulb diameter)
2. the spill over losses are relatively high.

Naturally, when more optical elements are used to convert the spherically light emitting surface into a circular plane, also a higher package density is possible. However, when using more optical elements, also the spill over losses will increase, besides the fact that the arrangement will also become more complicated and more costly. A four lens array seems to be sufficient to achieve the desired improvements mentioned without complicating the whole arrangement too much. The main difference compared with the three lens array is that on the top (to the anode) two deflecting mirrors are required (Fig. 12 a, b and Fig. 9).

The breakdown of the light losses and the resulting overall efficiency is given in table 2. For 1 S.C. level this should allow a collimation angle of ± 0.8°, (only the lower intense part of the arc is used) with sufficient margin (Fig. 13).

CONCLUDING REMARKS

In general one may say that the high power Xenon arc lamps allow to achieve a smaller collimation angle in case a properly adapted collecting optics is used. The widely used parabolic reflector is for this purpose not applicable.

Certainly the proposed collecting optics is very expensive due to the high number of optical elements and beyond that it will be a total loss in case of a lamp failure (explosion). On the other hand one should keep in mind that most lamp explosions occur after shutdown (during cooldown of the quartz bulb) and may therefore be avoided in case the Xenon gas is frozen out after operation in a small stainless steel bottle which is cooled down to LN2 temperature and then valved off; thus in case of a thermal crack there is no longer a gas pressure in the quartz bulb (Ref. 1).

Another critical issue is the cooling of the quartz bulb, and the question may come up to mind whether the closely clustered lens arrays are not a serious impedance for the cooling. Considering, however, the fact that most critical for cooling if the upper part of the bulb (above the equator) where turbulent flow dominates, the contrary is to be expected: the lens arrays force the cooling gas to keep in close touch with the quartz bulb and to guarantee a steady and uniform cooling flow also above the equator.

Obviously there is a real possibility to reduce the risk of lamp failure (explosion) drastically and to avoid major damage during operation. Irrespective, such a collecting optics will be a costly investment and will contribute to the besides expensive space simulation facilities. Compared, however, with a single major S/C project the costs are often within the contingency; reliability and accuracy would be considerably improved.

OTHER APPLICATIONS

The proposed collecting optics may of cause be used for any other light source. Compared with the parabolic reflector it is much more complicated; however, the high number of optical elements allow besides the compactness:

1. a better directivity of the beam
2. a better uniformity of the intensity in the reference plane
3. to illuminate an area of special shape by individual adjustment of the deflecting mirrors.

In the car industry there is in recent years a demand for more compact collecting optics; here the high production number would reduce the production costs per unit substantially.

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3. Harrell, J.W. and Argoud, M.J., "The 25-Foot Space Simulator at the Jet Propulsion Laboratory, Pasadena, Calif., Oct. 15, 1969.
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5. P. Dejong, "Les simulateurs Spatiaux", Revue Générale de l'Electricité, October 1966, t. 75, no. 10

TABLE I: III LENS ARRAY, EFFICIENCY OF COLLECTOR

(48% of emitted light, 24.9% of arc power)

	ANGLE °	INTENSITY RANGE %	LOSSES ON LENSES		LOSSES ON MIRRORS		EFFICIENCY PER LENS ARRAY %
			REFLECTION %	OVER-SPILL %	REFLECTION %	OVER-SPILL %	
Lens array I	50- 75	8 - 30	10	3.3	15	25	12.2
Lens array II	75-105	30 - 61	10	3.3	15	5	21.8
Lens array III	105-135	61 - 88	10	3.3	15	30	14

TABLE II: IV LENS ARRAY, EFFICIENCY OF COLLECTOR

(59% of emitted light, 30.6% of arc power)

	ANGLE °	INTENSITY RANGE %	LOSSES ON LENSES		LOSSES ON MIRRORS		EFFICIENCY PER LENS ARRAY %
			REFLECTION %	OVER-SPILL %	REFLECTION %	OVER-SPILL %	
Lens array I	45- 70	5 -22.5	10	3.8	2 x 15	20	10.15
Lens array II	70- 95	22.5-48.5	10	3.3	15	5	20.3
Lens array III	95-120	48.5-75	10	3.3	15	10	17.6
Lens array IV	120-145	75 -93.5	10	3.8	15	20	10.9

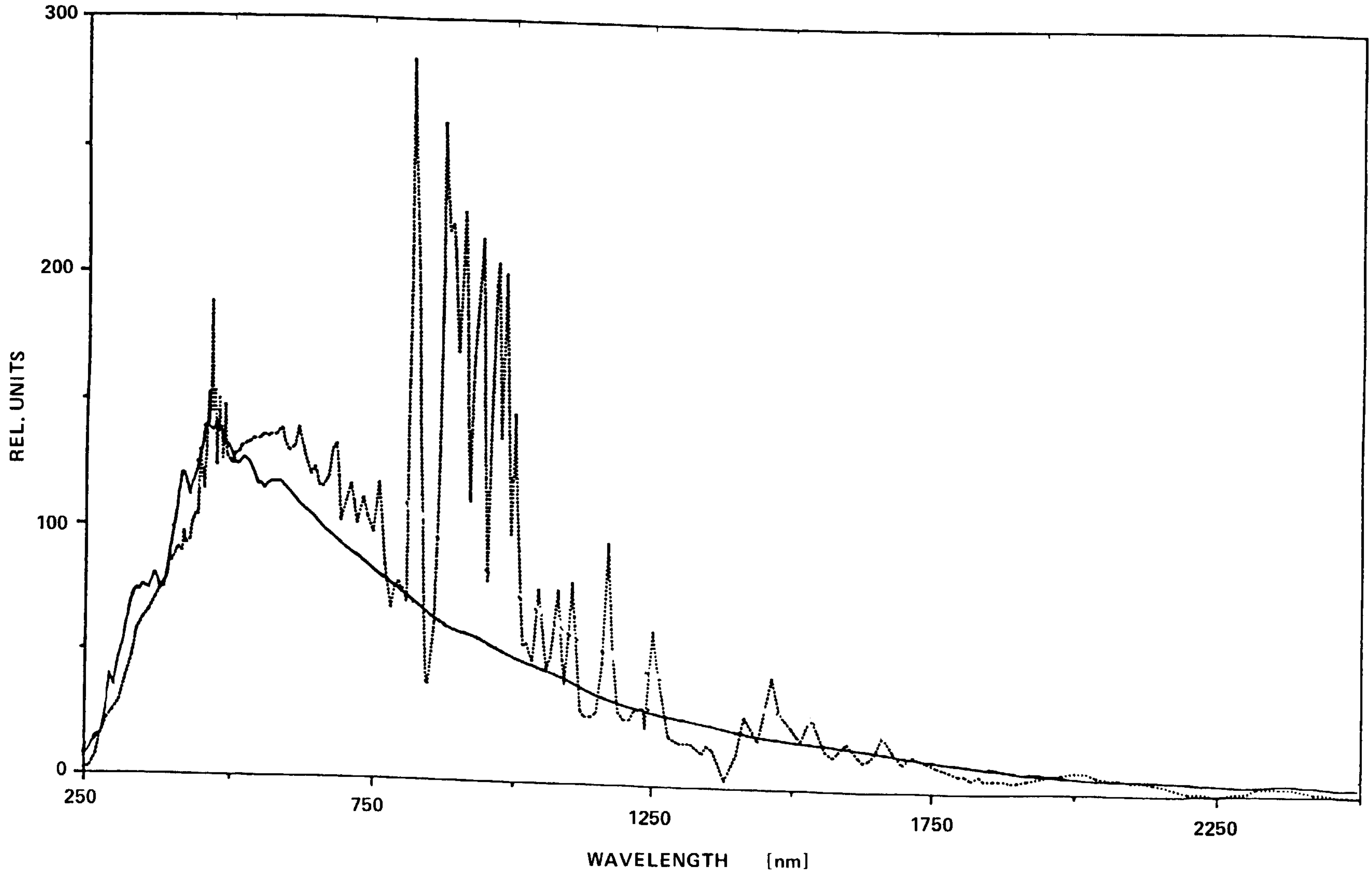

Figure 1. The Continuum of the Xenonspectrum Is in Fair Agreement with the Sun Spectrum

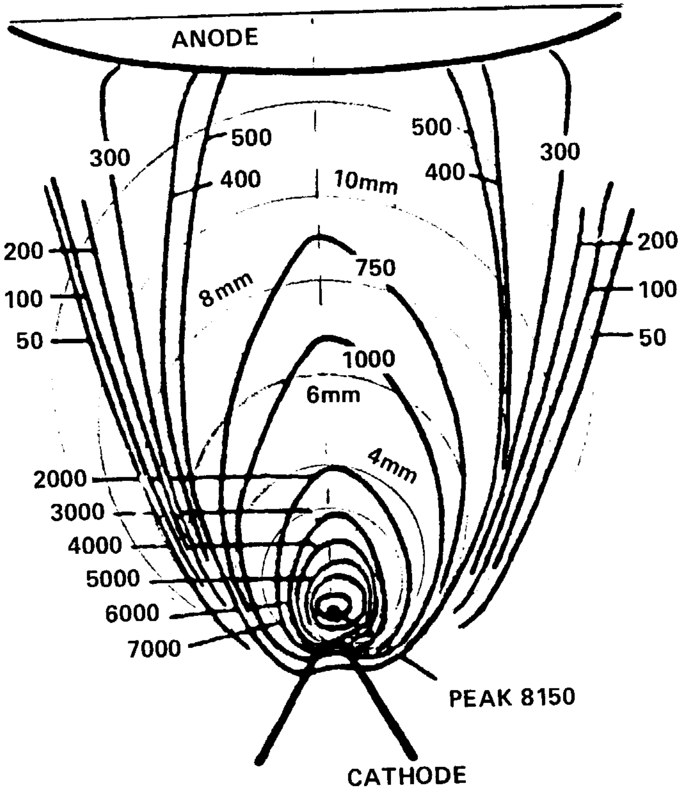

Figure 2. Luminance Distribution of a High Power Xenon Arc

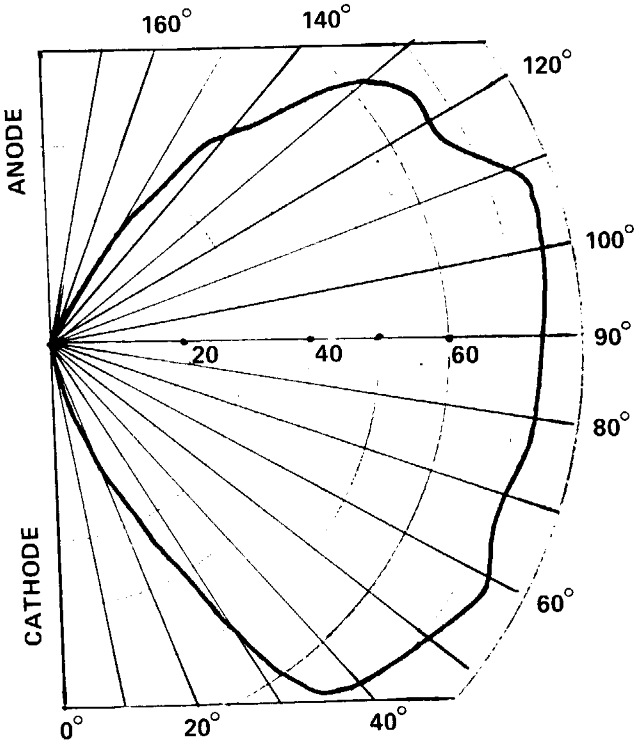

Figure 3. Polar Radiation Distribution of a High Power Xenon Arc Lamp

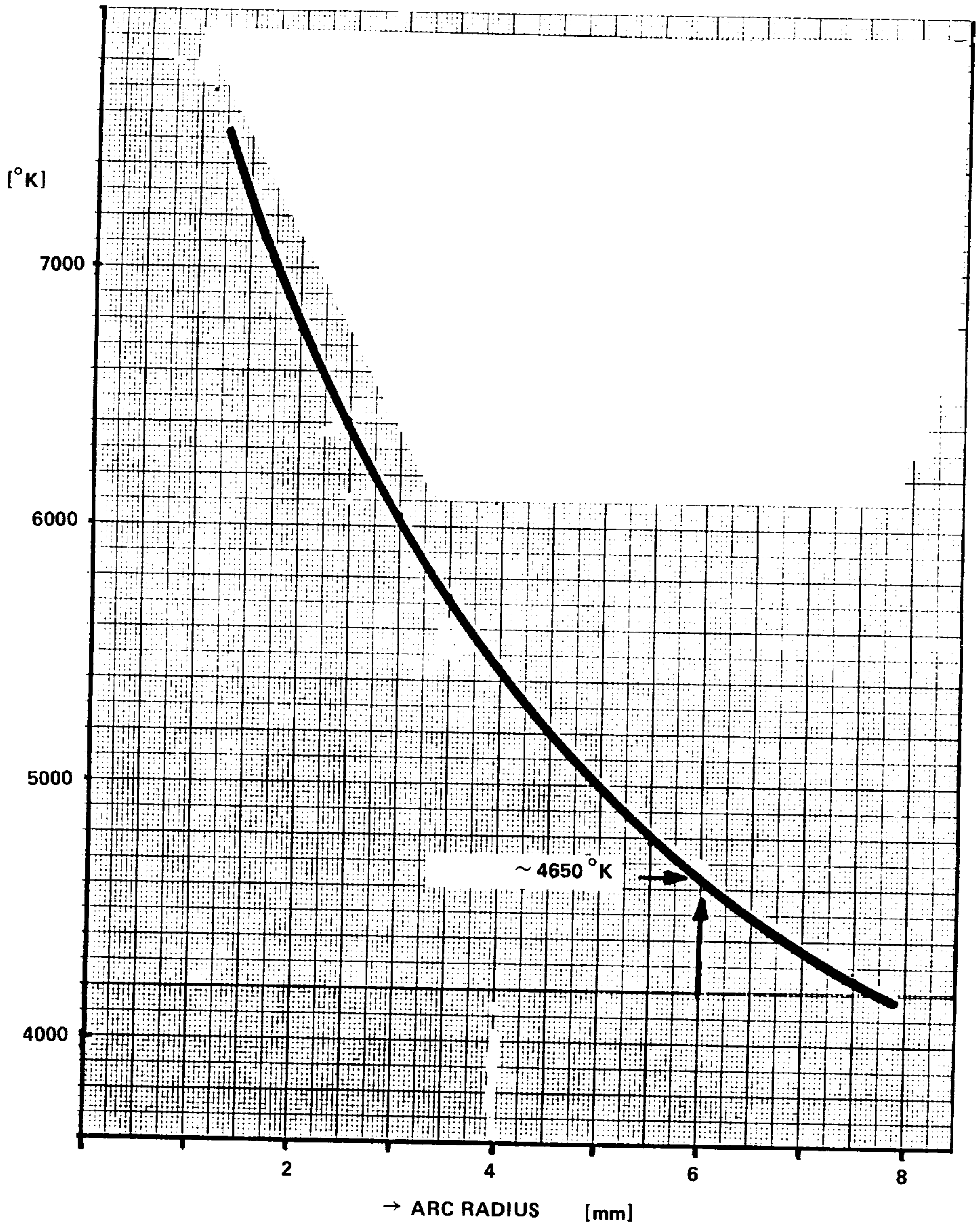

Figure 4. Mean Arc Temperature As Function Radius; 52% of the Arc Power Is Emitted as Light (~ Blackbody Radiation)

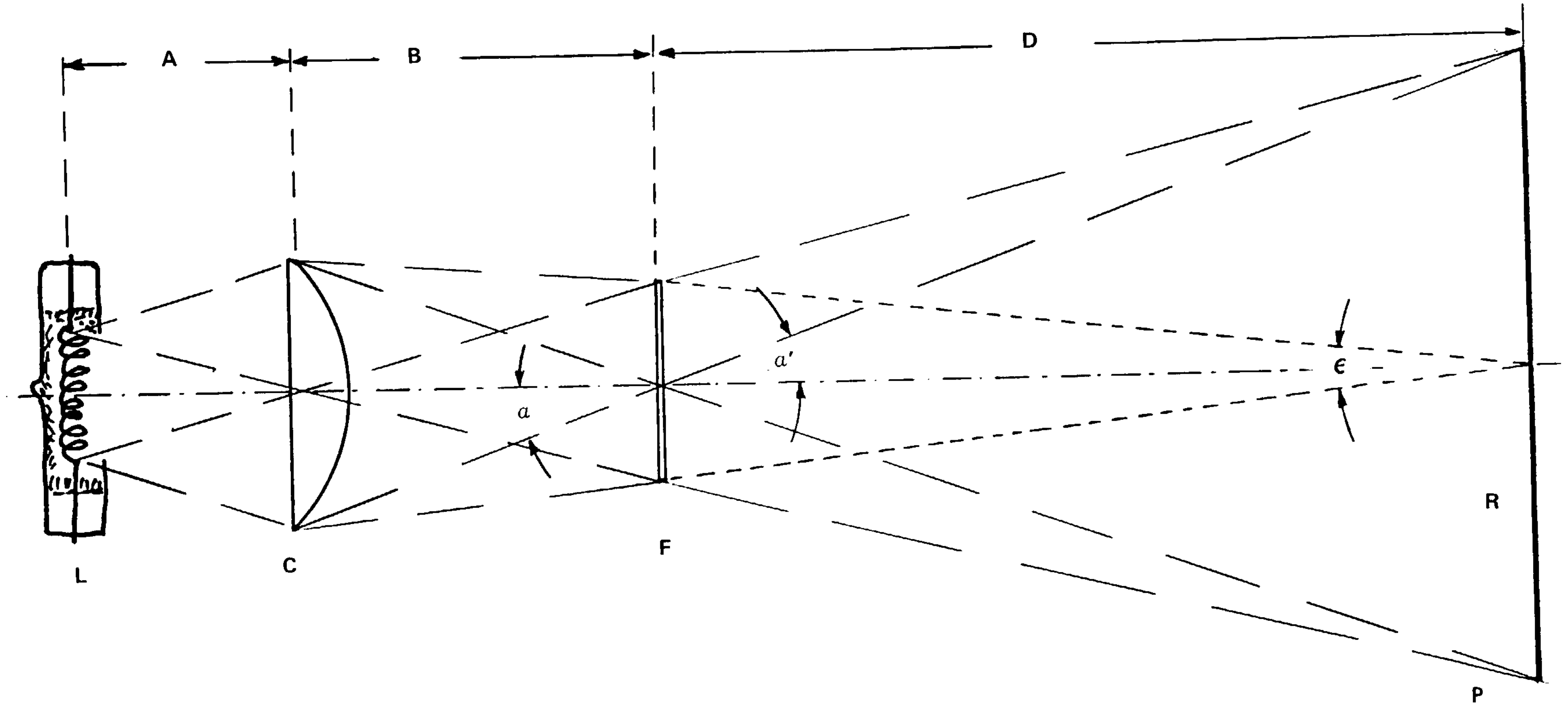

Figure 5. Projection System, Schematic

ϵ = Collimation Angle

a = Entrance Angle; a' = Exit Angle

L = Light Source; C = Collector; F = Projection Lens

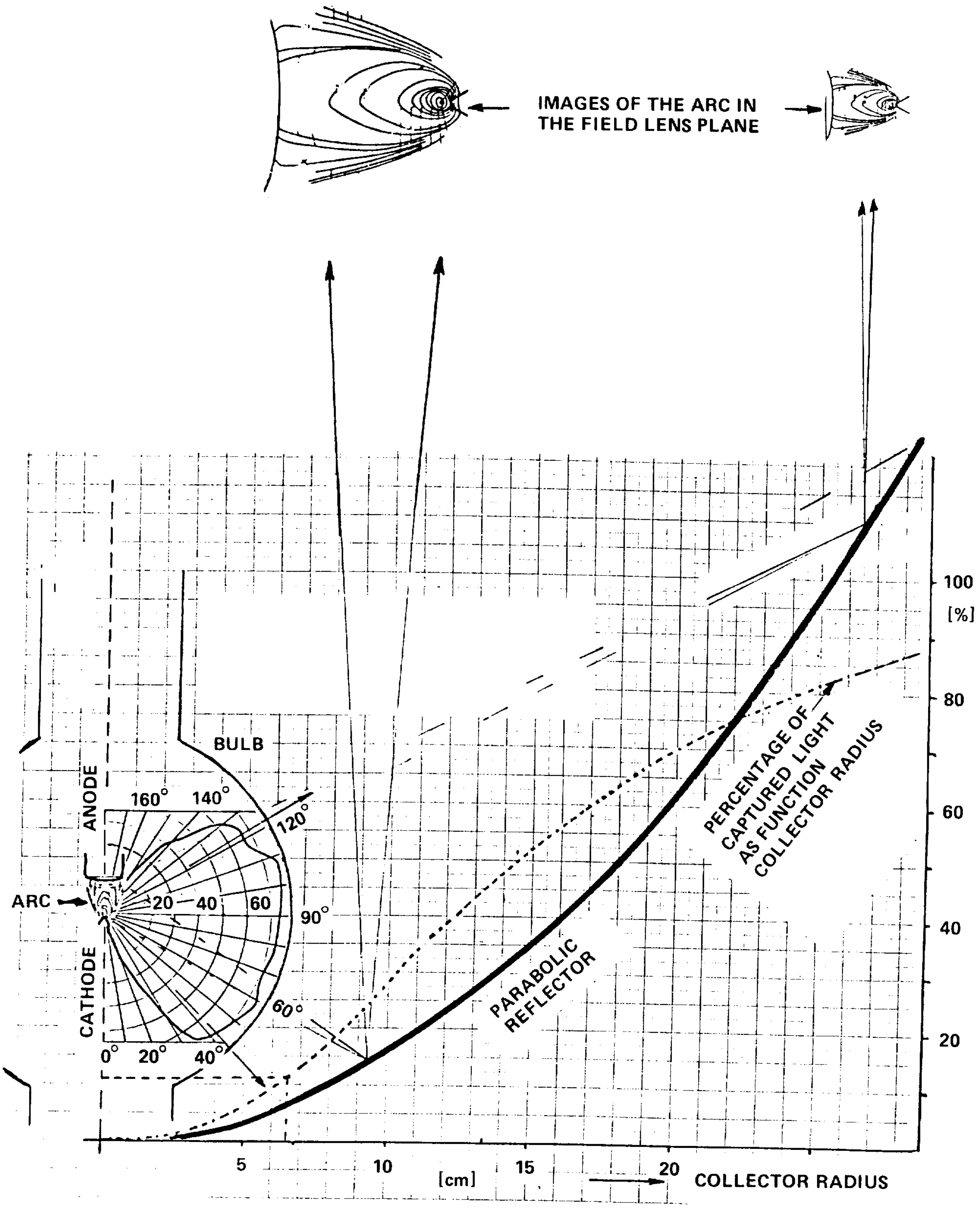

Figure 6. Parabolic Reflector, Schematic

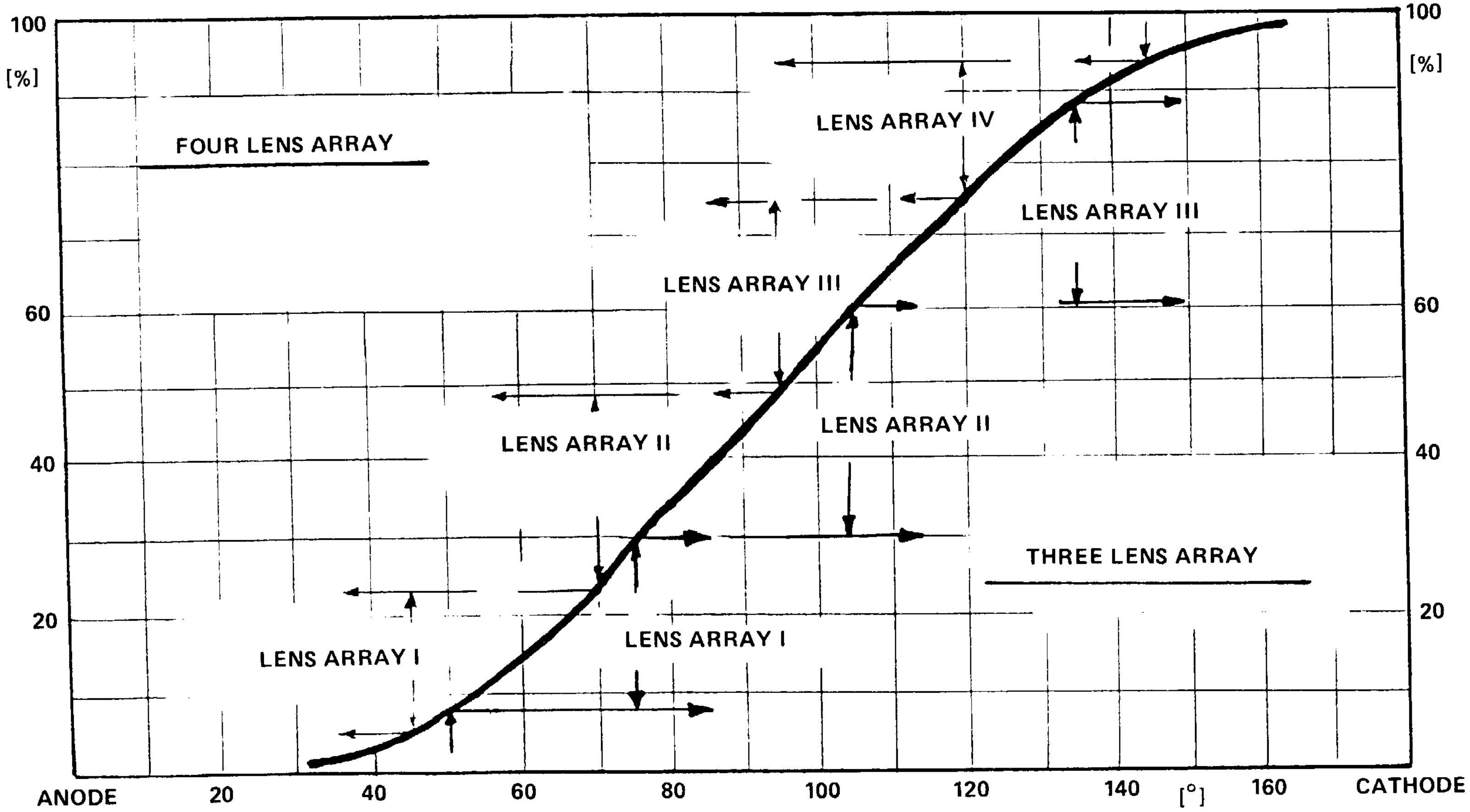

Figure 7. Percentage of Light Intensity Captured by the Collector as Function of Incident Angle

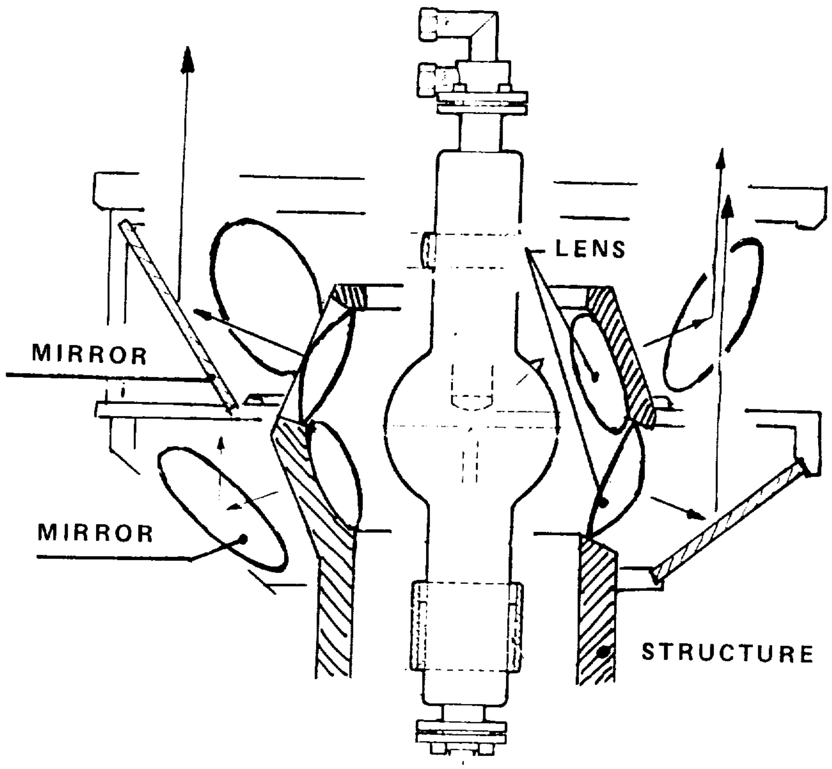

Figure 8. The Koehler Collector of BBT; 2 x 7 Lens-Mirror Combination

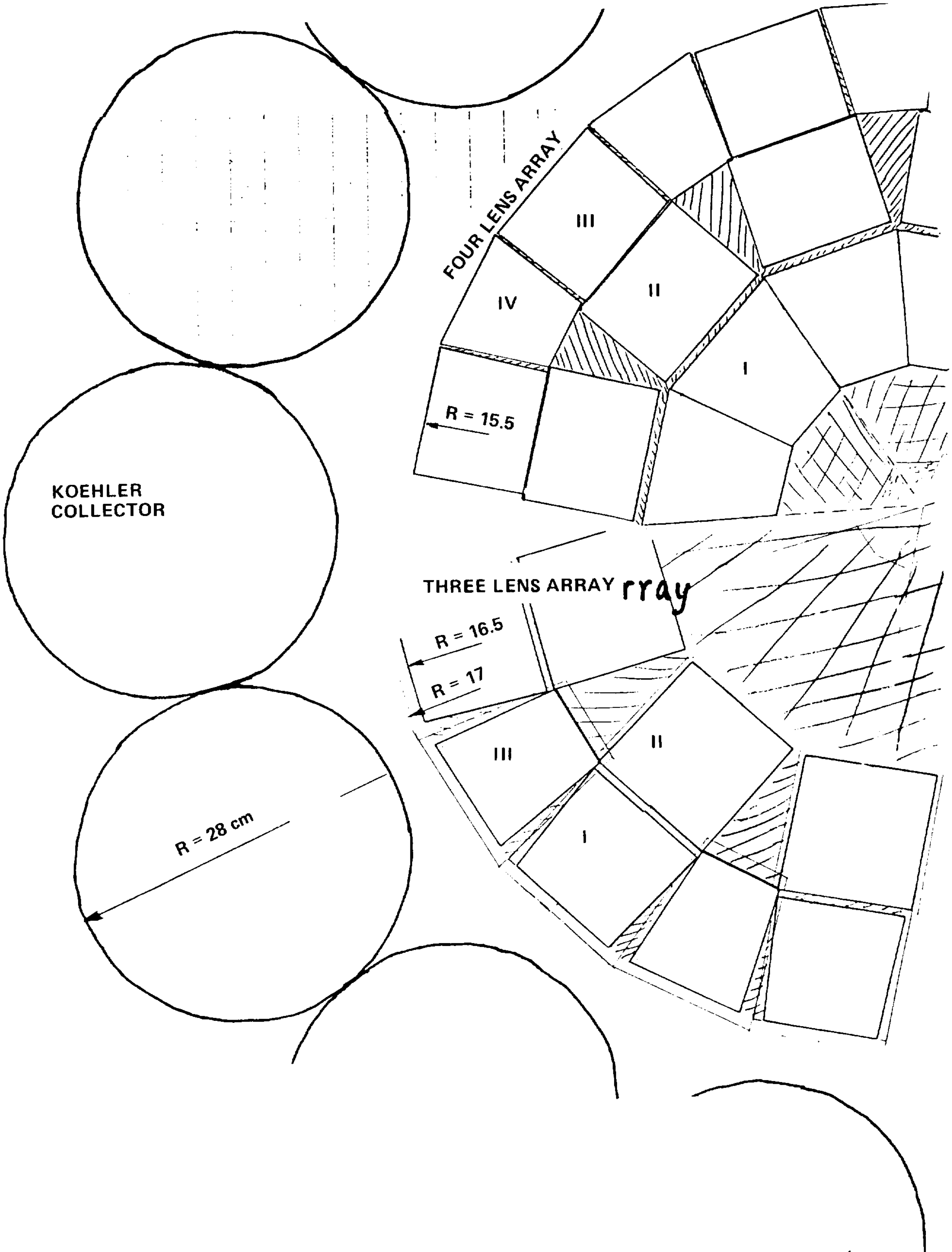

Figure 9. View into Collecting Optics; the Shining Area of the Koehler Collector and the Collectors with Three- and Four-Lens Arrays

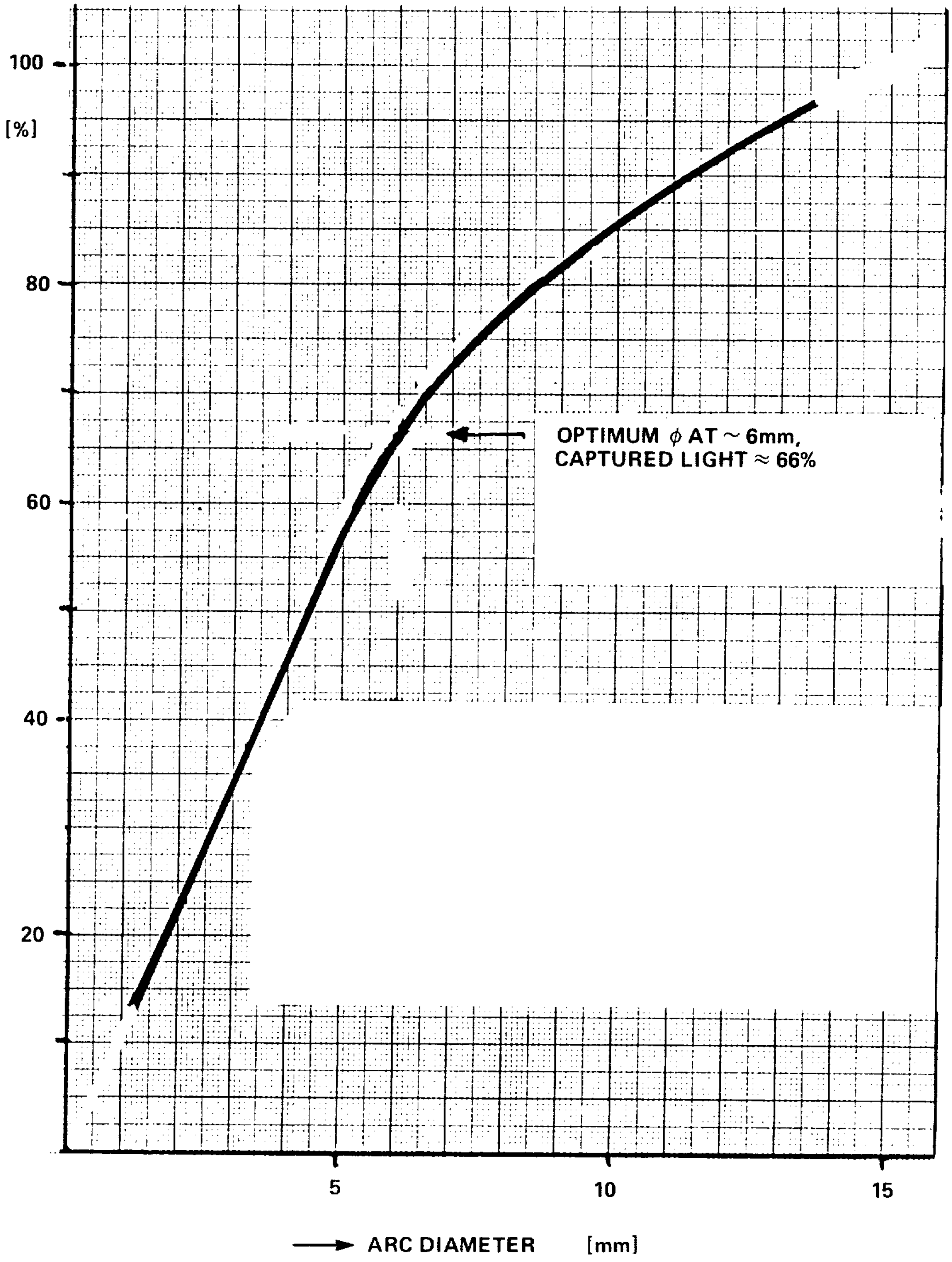

Figure 10. Light Output of a Xenon Lamp a Function of Arc Diameter Used

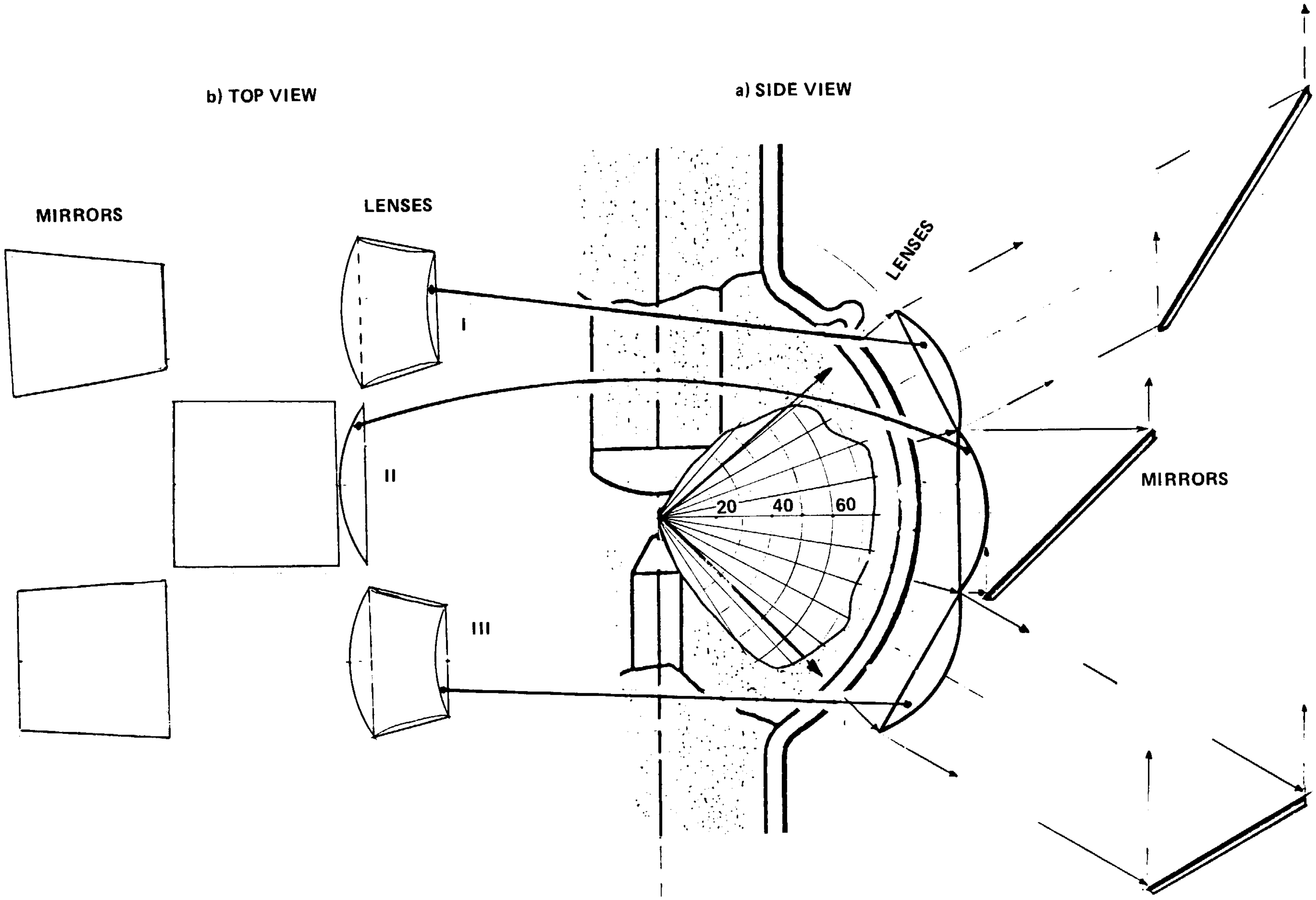

Figure 11. Collecting Optics; Three-Lens Array; Max. Diameter 33 cm; see also Figure 9

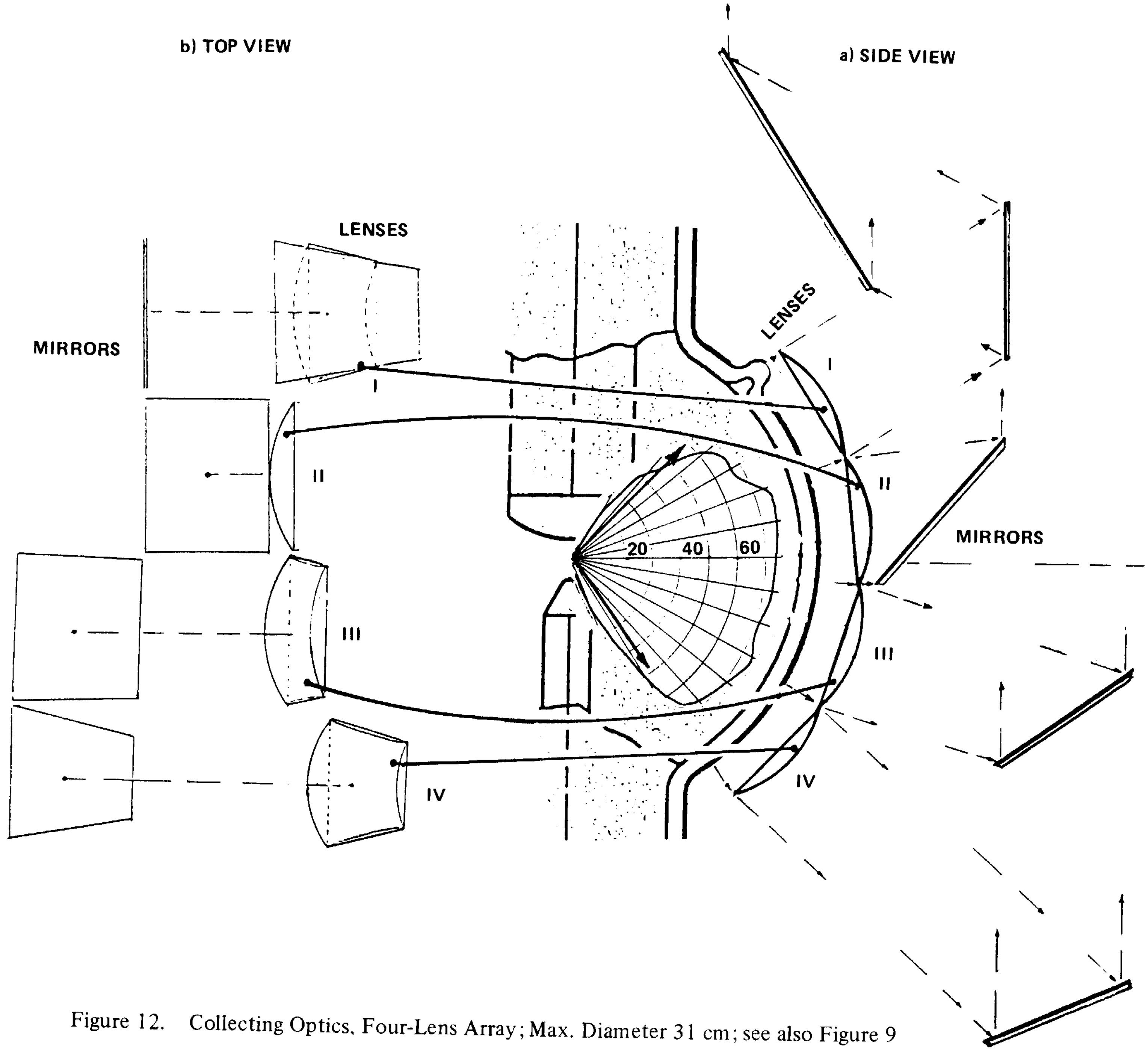

Figure 12. Collecting Optics, Four-Lens Array; Max. Diameter 31 cm; see also Figure 9

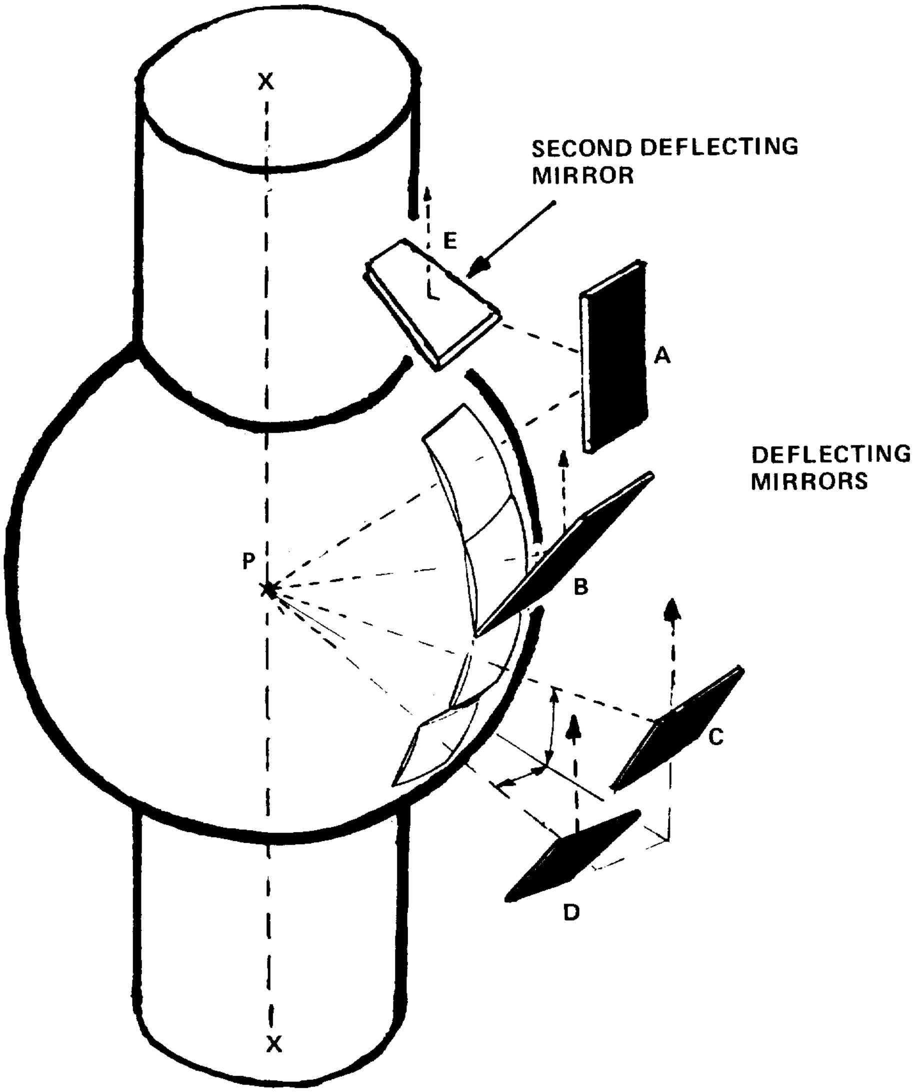

Figure 13. General View of Four-Lens Array Collector

SESSION IX

UNIQUE TESTS AND REQUIREMENTS