DEPLOYMENT OF A SECONDARY CONCENTRATOR TO INCREASE THE INTERCEPT FACTOR OF A DISH WITH LARGE SLOPE ERRORS

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ABSTRACT

We report on the testing of a hyperbolic trumpet non-imaging secondary concentrator with a parabolic dish having slope errors of about 10 mrad. The trumpet, which has a concentration ratio of 2.1, increased the flux through a 141-mm focal aperture by 72%, with an efficiency of 96%, thus demonstrating its potential for use in tandem with cheap dishes having relatively large slope errors.

INTRODUCTION

Recent studies have clearly demonstrated the potential of parabolic dish/receiver/heat engine systems to achieve high solar-to-electricity conversion efficiencies. Part of the reason for this success is the intrinsic ability of parabolic dishes to produce high solar fluxes at a very small focus. A compact receiver and a directly-coupled heat engine located at the focal area form a powerful conversion system with minimal heat losses. Temperatures in the order of 850° - 1200°C are easily generated and maintained. With the advent of modern heat engines and ceramic lined receivers, overall efficiencies higher than 40% are anticipated.

One of the major cost factors in the manufacturing of these systems is the parabolic dish itself. To achieve high concentration levels that can be maintained under heavy windloads the structural requirements on these dishes are very high. In addition, the necessity of a perfectly specular surface and minimum slope errors require very strict manufacturing tolerances and high precision. Obviously the cost of such a concentrator is too high and will always be detrimental to its economic feasibility.

Previous studies by Winston and O'Gallagher (Ref. 1) have demonstrated that a secondary non-imaging concentrator deployed at the focal plane of a parabolic dish can significantly improve the optical performance by increasing the intercept factor. Experiments conducted by the authors of Ref. 1 have shown that a trumpet with a concentration ratio of 2.1 can increase the energy flux into the receiver by more than 30% for a dish of medium quality. Otherwise stated, it is possible to design a trumpet which will increase the compound concentration ratio of a primary dish with given slope errors by a factor of about 2, with an improvement in intercept factor depending on the shape of the actual distribution of slope errors. This means in commercial terms that the dish tolerances normally required to obtain high temperatures may be significantly relaxed, and the cost of the dish reduced. The combination of "sloppy dish" and secondary concentrator has been proposed by SERC (Ref. 2) and a preliminary study of the effects of a secondary concentrator on system efficiency has been made by Jaffe (Ref. 3).

In the light of these findings, the Solar Energy Research Centre (SERC) of the University of Queensland and the Enrico Fermi Institute (EFI) have recently embarked on a joint research programme to further develop the sloppy dish/trumpet combination. This paper reports the beginning of our combined efforts, in which the trumpet built by EFI was tested on SERC's Omnium-G parabolic dish with a focal ratio of $f = 0.67$, located in Brisbane, Australia. The same trumpet tested at JPL was used for this experiment. It is formed from copper with cooling coils brazed around the throat section. The whole trumpet is silver plated and the inside polished.

The trumpet was designed for the Omnium-G parabolic dish at JPL, which concentrates 98% of the reflected energy into a focal aperture of 203 mm. SERC's dish has a broader flux distribution, with a considerable amount of energy arriving outside an aperture of 300 mm.

EXPERIMENTAL PROCEDURE

To best match the trumpet to the dish, the 18 individual petals were realigned to maximise the flux in a 203-mm receiver aperture. This was done using an extension of a diagnostic technique described by Dennison and Argoud (Ref. 4) in which a target of concentric coloured annuli was illuminated at the focus and viewed from a distance. The focus was shifted after alignment to account for the finite viewing distance. In our case, we made a target consisting of a 203-mm bullseye surrounded by four differently coloured quadrants. The dish was viewed through a telescope in daylight from a building 300 m away, and the petals were each adjusted to maximise the area reflecting the colour of the bullseye. The colour coding of the quadrants gave unambiguous information about the adjustments necessary to realign each petal. We estimated from the final image that about 50% of the reflected light would pass through a 203-mm focal aperture.

Cold-water calorimetry was employed to measure both the distribution of flux in the focal plane and the effectiveness of the trumpet. The calorimeter was a cavity receiver, shown in Figure 2, which was water cooled according to the schematic diagram, Figure 3. The receiver was built at SERC to intercept as much of the beam as possible, and includes a preheating coil of diameter 500 mm on the front face, which was covered throughout the experiment. Water flow was measured by recording the angular speed of a previously-calibrated positive-displacement pump. The temperature rise across the colorimeter was measured by matched deep-insertion platinum resistance thermometers, and flow mixing devices were inserted in the pipes immediately ahead of the measuring points. $T_{out} - T_{in}$ was recorded until it stabilised, a time of about 20 minutes, before the data were accepted.

A water-cooled aperture plate consisting of five removable nesting annuli was used for the measurement of flux distribution. Two of the available apertures, namely 140.7 mm (5.5 inches) and 203.2 mm (8 inches), correspond to the physical exit aperture and the virtual entrance aperture of the trumpet respectively (Ref. 1). The other apertures available are 100 mm, 250 mm and 300 mm.

All the water pipes, including the preheating coil on the face of the SERC receiver, were heavily insulated with an alumina-fibre blanket to prevent stray heat flows. The interspace between the aperture plate and receiver mouth was sealed with the same material to minimise convective losses.

$T_{out}-T_{in}$ was measured with the dish off the sun to account for any differences in the thermometers and direct heating of the receiver by the sun. Direct insolation was measured with an Eppley normal-incidence pyrheliometer calibrated to 1%. All data were recorded as minute by minute averages and then further averaged over periods of up to one hour.

All the measurements were made under very clear skies, with direct insolation from 800 to 1000 W/m². Although the zenith angle varied from 8° to 50° during the measurements, the diffuse radiation was only 8 to 10% of the direct, so no correction for variation in air mass was considered.

The energy collected by the receiver is

$$E = \dot{m}\ C\ \Delta T = I_D\ A\ \eta\ \phi$$

where

$\dot{m}$ = mass flow
C = specific heat
ΔT = $T_{out} - T_{in}$
I_D = direct insolation
A = effective dish area
ϕ = receiver intercept factor

η is an overall efficiency, including dish reflectivity and the effective absorptivity of the receiver cavity, which is assumed constant. Radiation and convection losses are ignored because receiver temperature was limited to about 50°C maximum at the rear surface and 40°C maximum at the front. There must, however, be an increasing convection loss at the larger apertures.

EXPERIMENTAL RESULTS

Values of $\eta\phi$ are given in Table 1 and the derived flux distribution is shown in Figure 4.

APERTURE	$\eta\phi$
100 mm	0.075 ± .005*
140.7 mm (5.5")	0.116 ± .001
203.2 mm (8.0")	0.209 ± .002
250 mm	0.289 ± .002
300 mm	0.351 ± .001
* excluding uncertainty in insolation	

Table 1. Collection efficiency at various receiver apertures

The irregular shape of the flux distribution may be ascribed to the variation in focal length among the 18 separate petals comprising the Omnium-G dish. The large amount of energy captured at diameters between 141 mm and

203 mm is probably due to the method of aligning the dish to maximise throughput in an 8-inch aperture rather than at a central point. The very low values of $\eta\phi$ are due to the poor reflectivity of the dish, whose aluminium ("Alzac") surface has been weathered for 4 years, and to the very broad beam at the receiver.

A preliminary measurement with the bare receiver, including the preheater, gave an overall value for $\eta\phi$ of about 0.5, so assuming $\phi \to 1$ at an aperture of 500 mm, $\eta \cong 0.5$. This suggests a value for ϕ of about 0.42 at an aperture of 203 mm. Using Aparisi's equation (Ref. 5) for slope errors, which is a good approximation at $f = 0.67$, the dish slope error is about 10 mrad. This is a rough estimate since Aparisi's equation assumes a Gaussian distribution of slope errors, whereas the measured distribution is irregular, but it serves to confirm the poor quality of the mirror.

The trumpet concentrator was then mounted and another calorimetric measurement made. The face of the receiver was completely insulated from the outer edge to the trumpet exit. The measured total efficiency was

$$\eta\phi = 0.200 \pm .001$$

excluding the uncertainty of 1% in the absolute value of the direct insolation. The intercept improvement relative to the 141 mm aperture plate is thus (0.200/0.116) - 1, or (72 ± 1)%. The previous measurements by Winston and O'Gallagher (Ref. 1) with this trumpet produced an intercept gain of 33%. The larger improvement with SERC's dish is due to the broad, flat-topped flux distribution. The overall trumpet efficiency is .200/.209, or (96 ± 1)%, in excellent agreement with the value found by Winston and O'Gallagher for the same trumpet.

The high trumpet efficiency is encouraging because in our measurements the trumpet walls reflected a much greater fraction of the total receiver flux than in the previous test. The trumpet throat slightly shades a 141 mm disk at the focal plane, so the energy reflected by its walls is slightly greater than that which would otherwise arrive at the receiver between 141 mm and 203 mm, namely 42% of the total in the 203 mm aperture. The integrated reflectance of the trumpet is thus greater than 90%. Compared to the reflectance of polished silver of about 93%, this indicates that a very high proportion of the energy actually redirected by the trumpet is reflected only once.

CONCLUSION

We have demonstrated the effectiveness of the hyperbolic trumpet secondary concentrator in greatly improving the intercept factor of a dish with slope errors of about 10 mrad. We now propose to investigate the cost/quality tradeoff and design an optimised sloppy dish/secondary trumpet system.

REFERENCES

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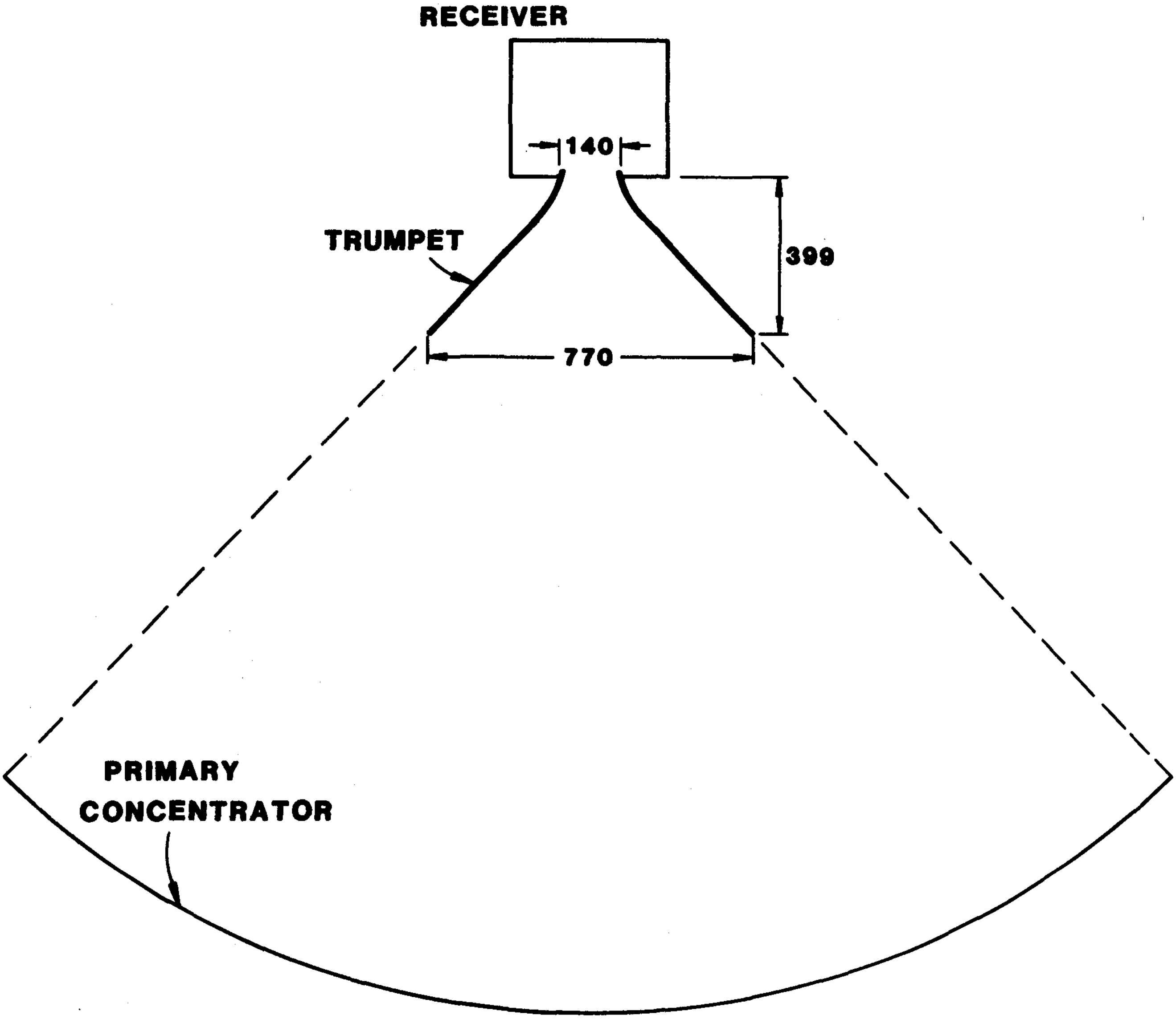

Figure 1: Trumpet concentrator configuration. Dimensions in millimetres

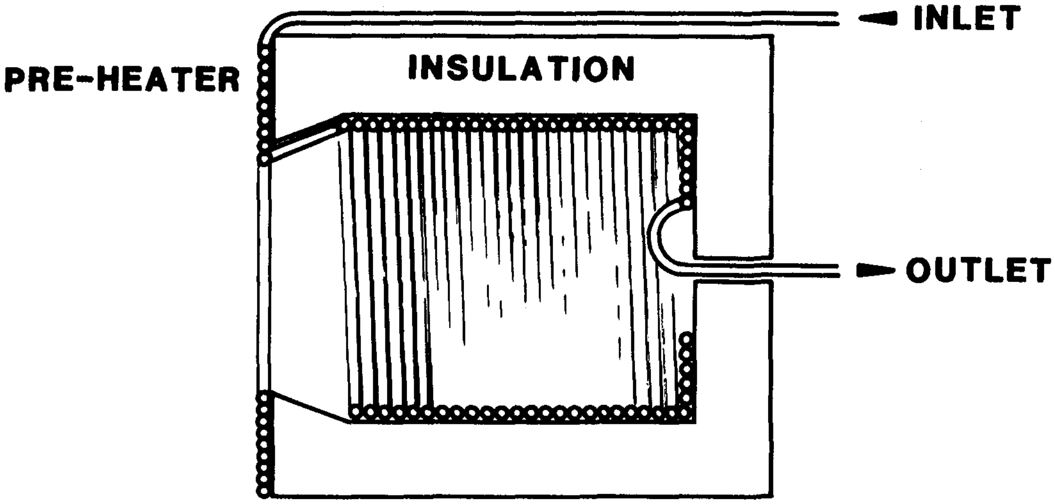

Figure 2: Cavity receiver

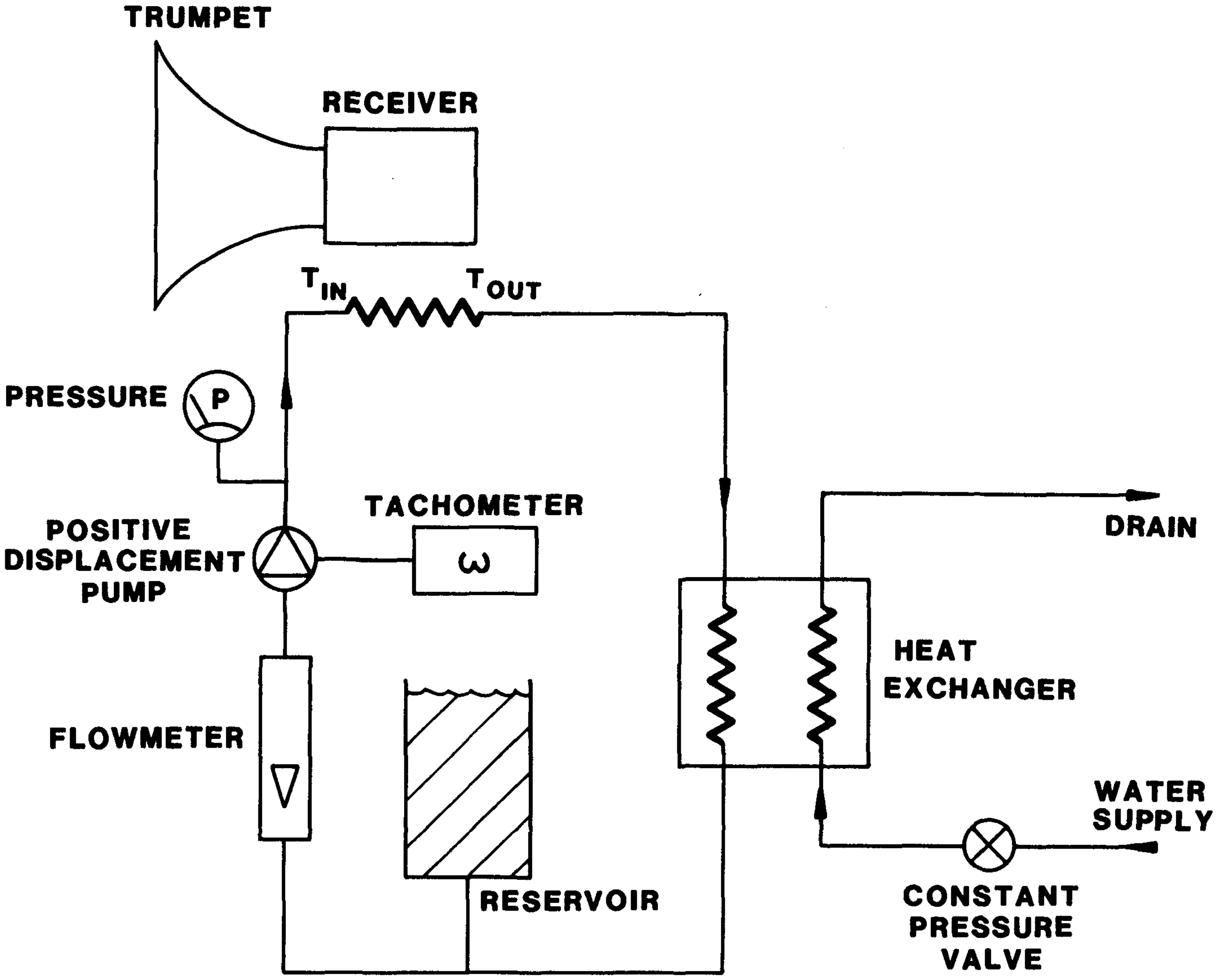

Figure 3: Receiver cooling scheme for cold calorimetry

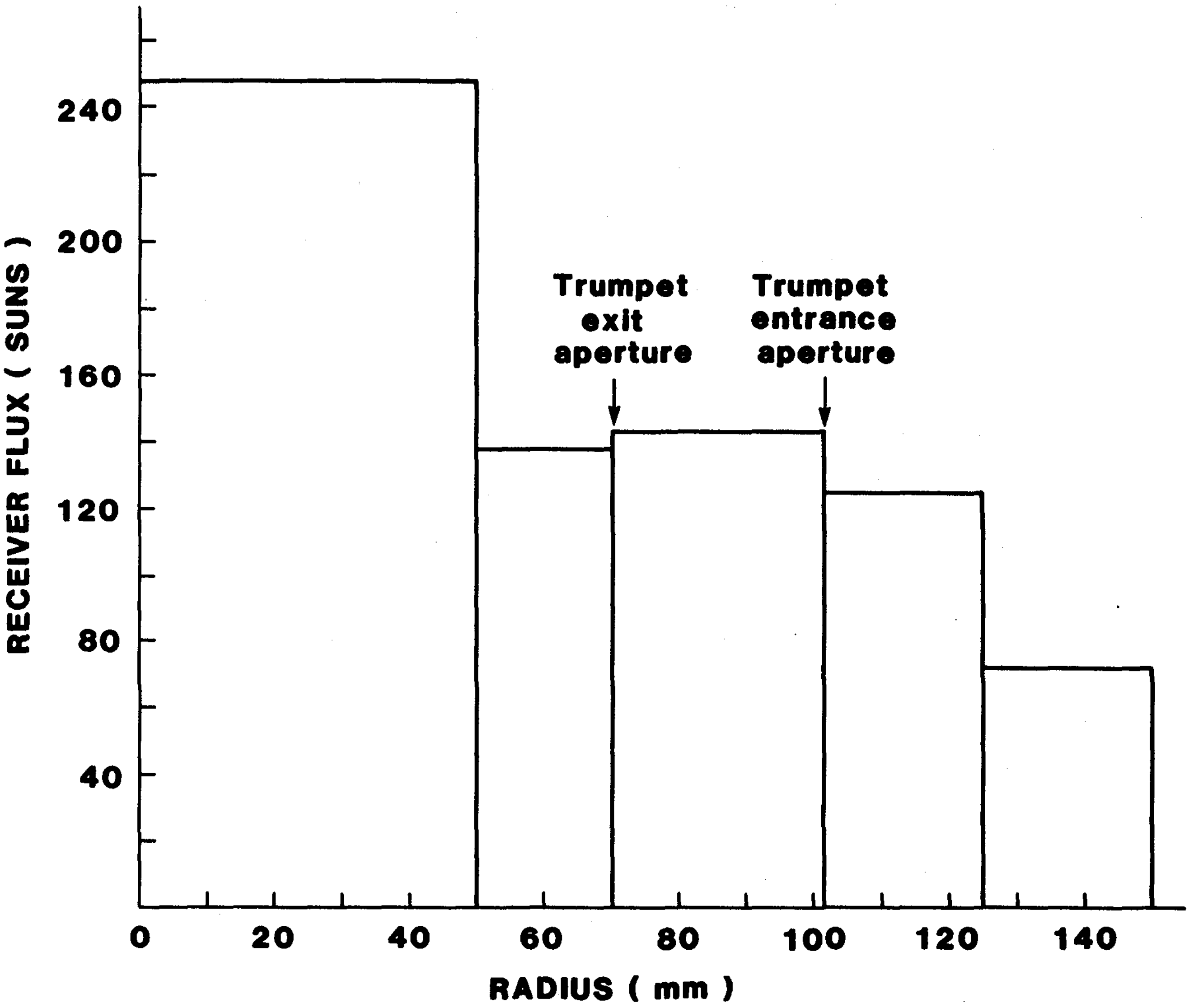

Figure 4: Radially averaged receiver flux distribution, measured by cold calorimetry