PERFORMANCE OF AN EXPANDABLE WHIRLING MEMBRANE

SOLAR ENERGY CONCENTRATOR

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ABSTRACT

The whirling membrane solar energy concentrator is a preformed approximate paraboloid constructed of an aluminized plastic film which is attached to a fixed hub. The concentrator is deployed by rotation about the optical axis, and the membrane assumes the desired paraboloidal shape under the stresses imposed by centrifugal and axial loading. The concentrating ability of three whirling membrane models was determined by optical ray trace methods and the results of the investigation are presented. The three models of 13-μm-thick aluminized plastic film were 3.05 meters in diameter with ratios of fixed hub to concentrator diameters of 0.20, 0.35, and 0.50. The investigations were conducted in an 18-m-diameter vacuum sphere at approximately 130 N/m^2 pressure.

Dispersion of the reflected optical image in the focal plane occurred for all three models. This undesirable energy spread probably resulted from circumferential wrinkles and a deviation in the circular shape of the membrane similar to cusping or scalloping. Comparison of data for the models shows that the two larger hub models developed considerably less circumferential wrinkling than the smallest hub model. A parabolic radial cross section was generally attained for each model, but with focal distances slightly less than the design value. Estimation of the geometric efficiency indicates that the whirling membrane concentrator is applicable for relatively low-temperature space power conversion systems.

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INTRODUCTION

Solar energy concentrators used in conjunction with electrical conversion devices are being considered for space power systems. Most of these concentrators are reflecting paraboloidal mirrors that concentrate solar energy on a heat receiver in the focal region. The method of conversion of heat to electrical power, required power output, weight, and payload packaging influence the basic materials and type of construction used in fabricating the concentrator. As a result, concentrators ranging from lightweight inflatable plastic mirrors to relatively heavy one-piece nickel mirrors have been built and quantitative data on their ground test performance are available.[1]

Expandable concentrators are of interest for large power systems that require concentrators much larger than launch vehicle diameters since they can be compactly packaged for launch and then deployed for use in space. Although expandable concentrators have not been fabricated with highly accurate surface geometry, most have optical accuracies capable of attaining temperatures suitable for dynamic conversion systems. One of the expandable types that has been proposed is the whirling membrane concentrator.[2] The whirling membrane concentrator is a thin aluminized plastic membrane that has been preformed to an approximate paraboloid and is rotated about the optical axis to maintain the desired paraboloidal shape. The centrifugal loading, plus axial loading applied at the rim, stretch the approximate paraboloid into the desired paraboloid. The results of an experimental investigation to determine the feasibility of this concept and to measure the concentrating ability are presented in this paper.

The units used for the physical quantities defined in this paper are given in the International System of Units (SI). Factors relating this system to U.S. Customary Units are presented in reference 3.

DESCRIPTION OF TEST MODEL

A sketch of the whirling membrane solar concentrator model is shown in figure 1. The model consists of a shaft, metal hub, aluminized plastic paraboloid, cables, and cable hub. The paraboloid design diameter is 3.05 meters, the design rim angle is 60°, and the design focal length is 132.1 centimeters.

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The membrane is constructed of 13-μm-thick aluminized polyethylene terephthalate plastic and is formed of 45 gores assembled on a convex mold. The reflective gores are attached to the edge of the metal hub and, by means of plastic tabs, to the cables at the concentrator rim. There are seventy-two 0.8-mm-diameter steel cables which extend from the cable hub mounted on the shaft to the plastic tabs in which they are embedded. Three 3.05-m-diameter models with ratios of metal hub to concentrator diameters of 0.20, 0.35, and 0.50 were tested. The metal hubs are flat disks and are mounted on the shaft below the cable hub.

The models were tested at a rotational speed of 71 rad/sec in an 18-m-diameter vacuum sphere at approximately 130 N/m^2[*] pressure. The angular velocity was chosen in order to have membrane maximum stress well below the material yield stress of about 100 MN/m^2. The vacuum condition was necessary in order to eliminate undesirable aerodynamic forces which would cause membrane flutter.

DESIGN CONCEPT

The membrane for the whirling concentrator was preformed as an approximate paraboloid so that the desired paraboloidal shape would be obtained under the stresses imposed by centrifugal and axial loading. In order to construct the proper preformed membrane, it was necessary to know the stress distribution of the spinning paraboloid. This stress calculation was based on equations derived in reference 2. Having determined the stresses in the spinning membrane, it was possible to calculate the spatial displacement which the membrane would experience as a result of the stress distribution. The membrane was then constructed according to ordinates which differed from a perfect paraboloid by this displacement. In this way, the loading experienced during rotation would stretch the approximate paraboloid into the desired paraboloid.

According to reference 2, the meridional stress decreases with radial distance from the optical axis while the circumferential stress increases. For a hub of small diameter relative to the overall membrane diameter, reference 2 indicates that the meridional stress, at least over the outer portion of the membrane, becomes insignificant compared with the circumferential stress. If a thin sheet of material is tested in tension in one direction, large-scale wrinkles tend to form parallel to the applied force. These wrinkles may be eliminated by applying slight tension in the plane of the sheet at right angles to the wrinkles. Therefore, in order to prevent the formation of circumferential wrinkles in the spinning membrane due to the relatively large circumferential and small meridional stress values, a certain minimum ratio of meridional to circumferential stress appears to be necessary. One method of varying the meridional to circumferential stress ratio that was suggested in reference 2 is to vary the diameter of the fixed hub to which the membrane is attached. For this purpose, three models of the same overall diameter, but with different hub diameters were tested.

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[*]$1 \ N/m^2 = 1.45 \times 10^{-4}$ psi.

A further requirement for the formation of a paraboloid by spinning a preformed approximate paraboloidal membrane is the presence of an axial load at the membrane rim. This axial load was achieved by means of the cables extending from above the rim plane at the optical axis to the membrane rim. It was necessary to estimate the cable length and distance above the theoretical rim plane where they intersect the optical axis which would result in a cable configuration capable of properly supporting the spinning paraboloid. It was assumed that at the tab-membrane juncture, the tabs would make an angle with the rim plane equivalent to that of the cone-paraboloid configuration of reference 2. This assumption was used with a numerical process to determine the cable parameters.

TEST SETUP

The apparatus for testing the whirling membrane concentrator models is shown schematically in figure 2, and a photograph of one of the models under test conditions is shown in figure 3. A steel framework provided a support for the concentrator and associated optical ray trace measuring equipment. A variable-speed motor coupled to the shaft was used to rotate the models. A fixed polyethylene sheet was stretched horizontally just below the metal hub to support the membrane when at rest and during spin-up. As the rotational speed was gradually increased, the membrane lifted off the supporting sheet and assumed the shape of a concentrator by the time the desired speed was obtained.

The optical ray trace equipment used to determine the concentrating ability of the models consisted of a light source to provide a well collimated beam of light and 10 silicon solar cells to measure the reflected light distribution in the focal region. The zirconium arc lamp with its collimating lens gave a 7.6-cm-diameter light beam with a 0.025° collimation angle and was driven along an overhead track by means of a remotely controlled motor. A silicon solar cell located just below the lens of the light collimator continuously monitored the irradiance from the light source. The 10 other solar cells were spaced 2.5 centimeters apart in a line on the solar cell bar. The solar cell bar had three degrees of freedom as follows: (1) rotation about the concentrator optical axis, (2) translation perpendicular to the optical axis, and (3) translation along the optical axis. All three modes were remotely controlled, and the positions of the solar cell bar were determined by remote indicators. The solar cell in the light beam and the cells on the bar had heaters and thermocouples for maintaining a constant temperature and thus constant cell sensitivity.

Procedure for acquiring typical data consisted of placing the solar cell bar at a vertical location in or near the design focal plane, positioning the light source, and then surveying the plane by rotating and moving the solar cell bar. The light source was then moved to another radial location, and the survey was repeated. In all, the light source was positioned at five radial locations for each survey plane in order to obtain data representative of different areas of the membrane.

RESULTS AND DISCUSSION

Data from the investigation yield such factors as the shape and size of
the distribution of the reflected energy in and near the design focal plane.
Using this information, it is possible to estimate the shape, focal length,
and geometric efficiency of the concentrator.

An illustration of the type of data obtained during the investigation is
presented in figure 4. In this figure, irradiance ratio is shown as a func-
tion of radial distance from the optical axis in a survey plane 3.8 centi-
meters below the design focal plane and with the light source located at a
radial distance of 1.20 meters from the optical axis. Irradiance ratio is the
ratio of the reflected light irradiance occurring in the survey plane to the
light irradiance approaching the concentrator. This ratio represents the fac-
tor by which the irradiance of the incident light beam has been modified by
concentrator geometry and specular reflectance of the aluminized plastic. The
magnitude of the irradiance ratio will also vary directly with the diameter of
the collimated light beam used. However, this ratio provides a convenient
means of analyzing the data as the magnitude does not affect determination of
the membrane properties such as shape, geometric efficiency, and focal length.
In figure 4 the two irradiance ratio distributions represent cross sections
of the reflected energy distribution in the survey plane, taken 90° apart.
The 0°-180° distribution is in the plane containing the light source and
the optical axis. The incident light beam, with its circular cross section,
would produce an elliptic image in the focal plane if reflected from a perfect
paraboloid. The major axis of the elliptic image for the whirling membrane
test setup should lie along the 0°-180° axis of figure 4(a) while the minor
axis should lie along the 90°-270° axis of figure 4(b). With the test light
source at the radial location indicated for figure 4, a perfect whirling
membrane concentrator would produce an elliptic image having a major axis
length of 0.16 centimeter and a minor axis length of 0.11 centimeter. Fig-
ure 4(a) shows an image spread of about 15 centimeters along the 0°-180°
axis. This dispersion of energy was probably caused by circumferential wrin-
kles in the membrane, which were visually observed, indicating that apparently
the meridional stress was not sufficient to remove the wrinkles resulting from
the relatively large circumferential stress. Figure 4(b) shows an image
spread of about 7 centimeters along the 90°-270° axis. The energy spread
in this direction was probably caused by deviations in the circular shape of
the membrane similar to cusping or scalloping. Although there is considerable
dispersion of energy along the two axes shown in figure 4, the distribution
peak occurs on the optical axis. The location of the peak value relative to
the optical axis is used to determine concentrator focal length which is dis-
cussed with figure 5.

Data such as those in figure 4 were obtained for each concentrator model
with the light source at five different radial locations. Data from the five
light source locations were used to prepare figure 5 which shows the displace-
ment of the irradiance ratio distribution peak from the optical axis and the
peak magnitude as a function of distance along the concentrator radius. When-
ever the survey plane is below or above the focal plane, the peak of the irra-
diance ratio distribution along the 0°-180° axis will lie to one side of
the optical axis. Therefore, the concentrator focal length is determined by

locating the survey plane position in which the distribution peaks fall closest to the optical axis. Figure 5(a) shows that only one of the irradiance ratio distribution peaks occurs slightly off the optical axis which indicated that this survey plane is the focal plane for most of the membrane. Therefore, most of the membrane has assumed a parabolic radial cross section, but with the focal plane 3.8 centimeters below the design focal plane or about 3 percent less than the design value. The variation of peak magnitude with radial distance in figure 5(b) shows that the center region of the membrane is producing the least dispersion of the incident light.

The data from the five light source locations were averaged to obtain the irradiance ratio distribution in the focal plane that would result from illuminating a complete radial band of the concentrator with a well collimated beam of light of cross-sectional area equal to that of the test light source. The average irradiance ratio distributions were obtained for the focal plane of each test model, and figure 6 shows these distributions along the $0°$-$180°$ axis. The focal lengths are 130.7 centimeters, 129.1 centimeters, and 128.2 centimeters for the 0.20, 0.35, and 0.50 hub diameter ratio models, respectively, as compared to the design value of 132.1 centimeters for all models. These focal plane distributions also represent the best concentration of energy, or the most energy in the smallest area, occurring in the various planes surveyed for each model. To obtain these optimum energy distributions, it was necessary to locate the cable hub above the design position on the shaft as much as 14 centimeters. As compared with the other models, the distribution for the 0.20 hub model shows an image of greater width and smaller peak magnitude. Since data for the three models indicate that each membrane was a body of revolution with essentially a parabolic radial cross section, it appears that the greater dispersion of reflected light for the 0.20 hub model was due to the presence of additional circumferential wrinkles. The difference in energy concentration between the 0.35 and 0.50 hub models is not very significant, indicating that the amount of circumferential wrinkling was relatively comparable for the two models. This circumferential wrinkling was visually observed for all three models.

The best concentration of energy in a focal plane appears to have been produced by the 0.50 hub model. Therefore, data were used from this model to calculate the geometric efficiency of a whirling membrane concentrator. The variation of the geometric efficiency with aperture diameter ratio of a completely illuminated 0.50 hub whirling membrane is presented in figure 7. The geometric efficiency is defined as the ratio of energy passing through an aperture in the focal plane to the total energy reflected from the concentrator. The aperture diameter ratio is the ratio of aperture diameter to concentrator diameter. Curves for two other expandable solar concentrators,[1,4] which also use aluminum-coated plastic are presented in the same figure for comparison purposes. It should be noted that the data for the inflatable-rigidized and split-rib umbrella concentrators are for solar illumination with an $0.533°$ angle of collimation, while the whirling membrane data are for the test light source illumination with an $0.025°$ angle of collimation. Calculations indicate that for solar concentrators of the quality of the whirling membrane, the angle of collimation over the range, $0.025°$ to $0.533°$, has little effect on the geometric efficiency curve. On this basis, the efficiency of the whirling membrane under solar radiation would still be comparable to that of the two other expandable-type concentrators.

It might be expected that the whirling membrane could be packaged into a very small volume because the thin plastic film requires no backup structure. However, the relatively large fixed hub which is necessary to suppress circumferential wrinkles limits the packaging capabilities of the whirling membrane. Estimation of the packaged volume for the 0.50 hub whirling membrane model gave a value of 0.14 m^3. This value includes a one-piece paraboloidal mirror to replace the flat hub. Such a paraboloid would serve the same structural purpose as the flat hub but by having an identical focal length to the membrane, it could provide the concentration of additional energy. A packaged volume of 0.15 m^3 for a 3.05-m-diameter umbrella concentrator is reported in reference 5, and an estimated packaged volume of 0.12 m^3 for a 3.05-m-diameter inflatable-rigidized concentrator with predistributed foam is given in reference 6. Therefore, the whirling membrane concentrator appears to be comparable with the two other types of expandable concentrators shown in figure 7 as regards geometric efficiency and packaged volume. However, since the focal plane data for the 0.50 and 0.35 hub models are relatively similar (e.g., see fig. 6), the efficiency of the 0.35 hub model should nearly equal the efficiency of the 0.50 hub model, and the packaged volume could be reduced approximately 50 percent.

CONCLUDING REMARKS

In summary, the results of a program to investigate the whirling membrane solar concentrator concept have been presented. An optical ray trace method was employed in order to estimate such concentrator properties as shape, focal length, and geometric efficiency. Three 3.05-m-diameter models with ratios of hub diameter to concentrator diameter of 0.20, 0.35, and 0.50 were examined and results are given for each model.

All models generally achieved a parabolic radial cross section, but with focal lengths of 130.7 centimeters, 129.1 centimeters, and 128.2 centimeters for the 0.20, 0.35, and 0.50 hub models, respectively, as compared to the design value of 132.1 centimeters. Undesirable dispersion of the reflected image probably resulted from circumferential wrinkles and deviations in the circular shape of the membrane similar to cusping or scalloping. Comparison of the data for the three models shows that there was considerably less circumferential wrinkling in the 0.35 and 0.50 hub models, which were similar in behavior, than in the 0.20 hub model.

Estimation of the geometric efficiency at various aperture ratios for the 0.50 hub model indicates that the whirling membrane has a concentrating ability comparable to two other expandable-type solar concentrators, an inflatable-rigidized and split-rib umbrella, which also use an aluminized plastic membrane. The whirling membrane appears to be capable of efficient operation (greater than 0.90) in the aperture ratio range near 0.04 which would make it applicable for relatively low-temperature space power conversion systems.

REFERENCES

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   Meeting (Boston, Mass.), March 1966.

PLASTIC TAB

CABLE

FOCAL POINT

60°
RIM ANGLE

OPTICAL AXIS

CABLE HUB

CABLE

ALUMINIZED PLASTIC
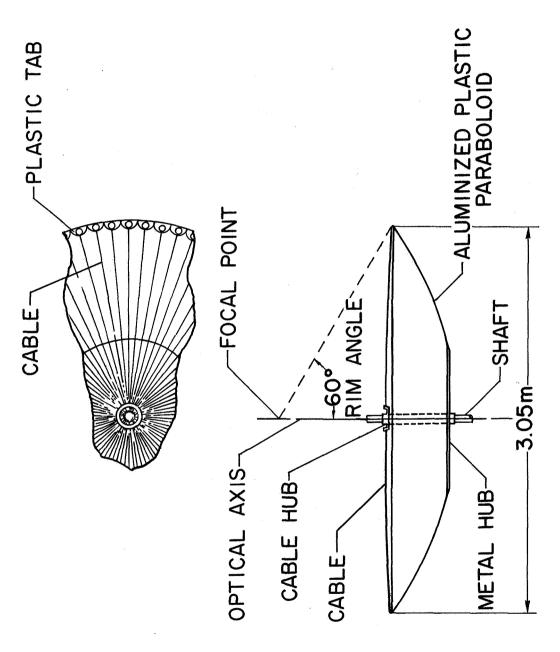PARABOLOID

SHAFT

METAL HUB

3.05m

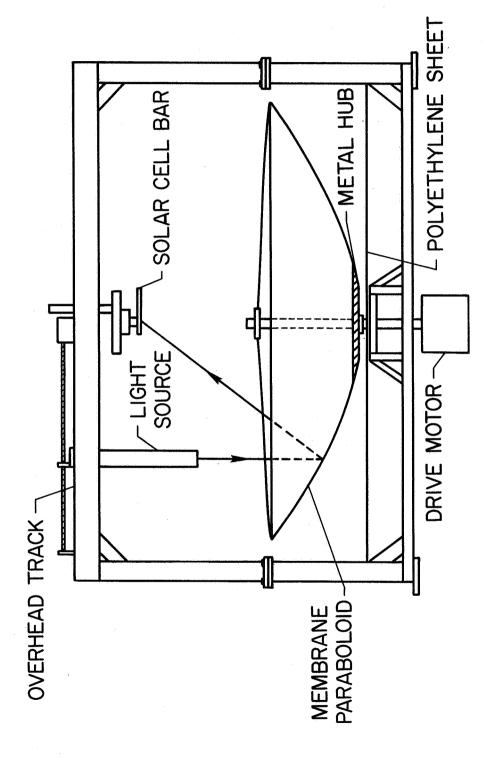Figure 1.- Sketch of whirling membrane solar concentrator.
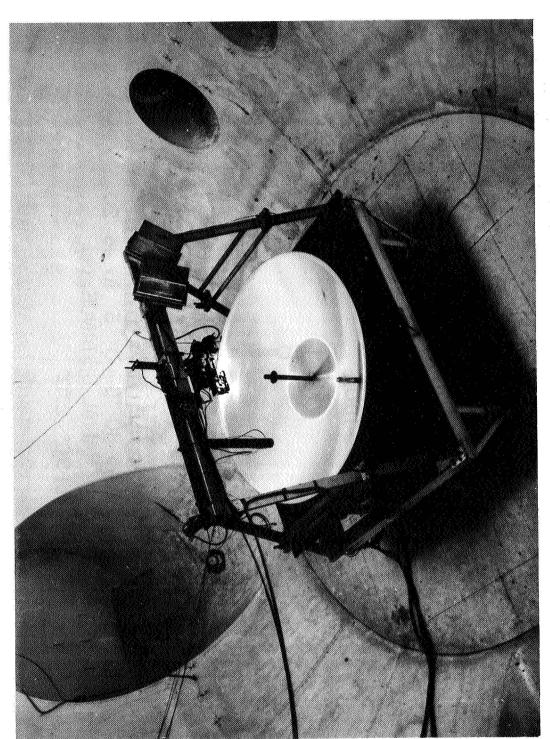
Figure 2.- Schematic of test apparatus.

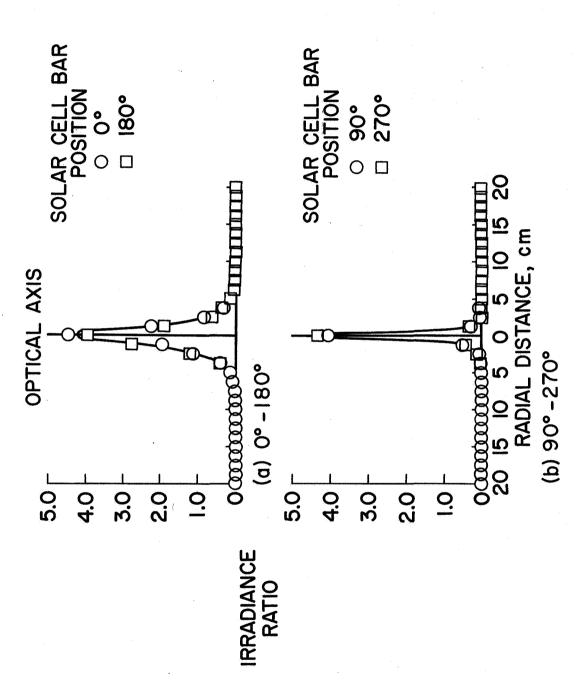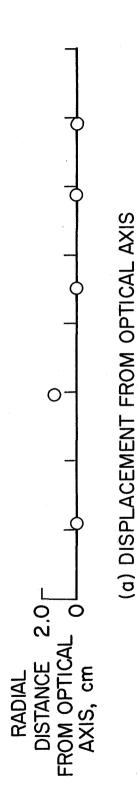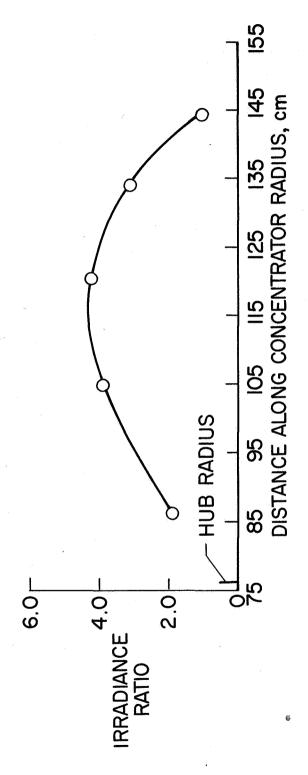Figure 3.- A whirling membrane model during tests.

Figure 4.- Irradiance ratio distributions along two orthogonal axes in the focal plane of a whirling membrane model. (0.50 hub diameter ratio.)

RADIAL
DISTANCE
FROM OPTICAL
AXIS, cm

(a) DISPLACEMENT FROM OPTICAL AXIS

IRRADIANCE
RATIO

HUB RADIUS

DISTANCE ALONG CONCENTRATOR RADIUS, cm

(b) MAGNITUDE

Figure 5.- Variation of displacement of the irradiance ratio distri-
bution peak from the optical axis and the peak magnitude with dis-
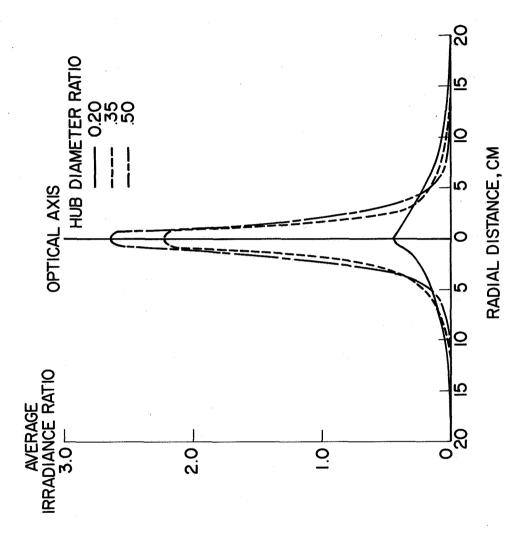tance along the concentrator radius. (0.50 hub diameter ratio.)

Figure 6.- Focal plane average irradiance ratio distribution along the 0°-180° axis of the three whirling membrane concentrator models.
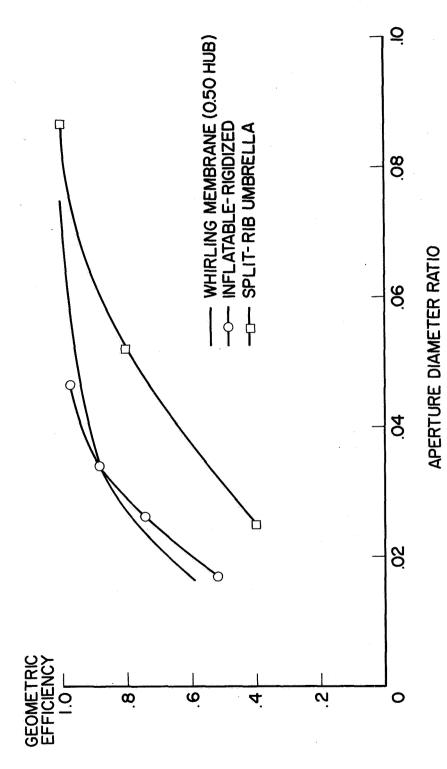
Figure 7.- Geometric efficiency of the whirling membrane and two other expandable concentrators.