REVIEW OF SOLAR CONCENTRATOR TECHNOLOGY

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Abstract

Continuing development of solar concentrator technology has been directed toward the improvement of methods and materials of construction to satisfy the particular design requirements of various space power conversion devices. Descriptions of fabrication techniques as well as a brief discussion of recent results from investigations made on concentrators are presented. In the area of one-piece concentrators, the stretch-formed aluminum process has been developed to the point where concentrator accuracy compares favorably with the high quality formerly obtained only by electroforming nickel. The aluminum electroforming process has been scaled up to the point where 0.76-meter-diameter concentrators have been fabricated. Two accurate 2.90-meter-diameter plastic spin castings have been fabricated, however, the concentrators subsequently electroformed of nickel were not of comparable quality. In the area of expandable concentrators, a modified model of the whirling membrane concept has given improved concentration of energy, however, the design parabolic cross section has not been attained. A 1.52-meter-diameter inflatable concentrator has been rigidized with a polyurethane foam in a simulated space environment. The concentrator gave an efficiency within 0.20 of a Rankine cycle design efficiency of 0.85.

Introduction

In the past solar energy concentrators or models of concentrators have been fabricated that are capable of generating the temperatures required for the operation of space power systems. Continuing development of solar concentrator technology has been aimed at improving the methods and materials of construction to satisfy the particular design requirements of various conversion devices. Thermionic devices with their high operating temperatures require concentrator surface accuracies that at present can only be met by the one-piece designs. Development of one-piece concentrators is continuing in order to (1) improve construction methods by the use of lightweight nonmagnetic materials, and (2) adapt present construction methods to larger diameter concentrators. Dynamic conversion devices with their lower operating temperatures and higher power levels can utilize less accurate, large diameter, expandable concentrators. Development in this area is continuing in order to improve surface accuracy (increased efficiency) as well as construction methods so that size, mass, and packaging volume may be reduced.

The status of solar energy concentrator technology was reported in 1964 at the AIAA Space Power Systems Conference.[1] Since then a continuing program has been supported by NASA to develop the technology of solar concentrators by both in-house and contractual research and development. Some recent results from investigations made on concentrators by the Lewis Research Center, the Jet Propulsion Laboratory, and the Langley Research Center are presented in this paper.

One-Piece Concentrators

Development of one-piece concentrator technology has been directed in general towards the fabrication of small (1.5 meters or less in diameter) highly accurate paraboloids suitable for thermionic conversion systems. An effort has also been directed towards the development of paraboloidal masters to be used in the fabrication of larger one-piece concentrators with surface geometries of comparable quality. In addition, work has continued on large (6.10 to 9.14 m) diameter concentrators with lower accuracies for dynamic systems. A discussion of the various fabrication techniques with the results of investigations made on several concentrators fabricated by these techniques follows.

Stretch-Formed Aluminum Concentrators

The stretch-formed aluminum approach to solar concentrator fabrication has been investigated and three 1.52-meter-diameter concentrators representing various stages in the development have been made[2,3,4] under contract. Figure 1 shows a sketch of the third model which consists of a shell made up of eight stretch-formed aluminum sectors bonded together and attached to a rear-mounted torus by a cylindrical transition strip. The design of the first two models differed from the third only in the shape and attaching scheme of the torus. The 0.4-mm-thick aluminum sectors were stretch-formed over a 1.52-meter-diameter glass searchlight mirror, given an epoxy plastic surface coating to cover the grainy surface resulting from the forming and then aluminized before assembly.

All three models have been solar tested at the Langley Research Center and the results of the calorimeter measurements are shown in figure 2. The calorimetric efficiency is defined as the ratio of the energy reflected from a concentrator and collected by a cavity-type cold calorimeter to the energy incident on the concentrator as measured by a pyrheliometer. Concentration ratio also known as area ratio is the ratio of the net projected reflective area of the concentrator to the area of the aperture of the cavity calorimeter. The data are identified by the numerals I, II, and III to indicate in which phase of the program each concentrator was built. Also shown is a theoretical maximum efficiency curve for a perfect concentrator with a solar specular reflectance of 0.91.

At concentration ratios above 5,000, a definite improvement in efficiency has been obtained with each suceeding phase of the program. For example, at a concentration ratio of about 14,000, which corresponds to that needed for thermionic operation, the efficiency has been increased from 0.42 to 0.80. The value of 0.80 is only about 0.07 below the curve

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for a theoretically perfect concentrator with a reflectance of 0.91. At the lower concentration ratios (below 1,000) the curves tend to reach a limiting value of efficiency. This value of efficiency is usually assumed to be the value of solar specular reflectance for the concentrator surface.

For concentrator III, a high value of reflectance of 0.91 is obtained which is 0.02 higher than the value of 0.89 measured with a spectrophotometer[4] on flat samples cut from trimmed portions of the stretched and coated panels. Spectrophotometer measurements on the flat samples at LRC verified the value of 0.89 so that it may be assumed that the calorimetric measurements are about 0.02 high possibly due to experimental error. It is also noted that a different reflectance was obtained for each model. Part of these differences may be attributed to the different coatings on each model (concentrators I and II had silicon oxide coatings over the vacuum deposited aluminum while concentrator III had aluminum only) and part may be due to the ability of the epoxy surface improvement coating to provide a specular surface.

To provide an indication of the improvements that have been made in the geometric accuracy, the efficiency data curves of figure 2 have been divided by their respective values of specular reflectance to give geometric efficiency which is shown in figure 3 as a function of concentration ratio. A definite gain has been made in geometric efficiency with each succeeding concentrator. These gains have been substantiated by optical measurements[4] which show that the standard deviation of error in the radial direction of the mirror surface has been reduced from 0.137° for I to 0.048° for II and to 0.017° for III. The value of geometric efficiency of 0.88 at a concentration ratio of 14,000 approaches closely the geometric efficiencies obtained on high quality solar concentrators fabricated by the nickel electroforming proce

Electroformed Aluminum Concentrators

The fabrication of solar concentrators by the method of electroforming has been shown to give highly accurate, specular surfaces especially when nickel is used as the electroforming material. As a consequence, the electroforming of aluminum has been investigated as a possible method for forming lightweight nonmagnetic concentrators.[5] Several 0.76-meter-diameter concentrators have been electroformed from a solution of aluminum chloride, lithium aluminum hydride, and ether using the cell arrangement shown in figure 4.

The cell consists of two tanks; a bath mixing tank and a plating tank. Glove boxes are included on top of the tanks to allow access to the tanks which must be operated under a nitrogen atmosphere to prevent explosions. The operation of the electroforming cell generally followed this procedure. The mixing tank was purged with argon and ether was then transferred to the tank. Aluminum chloride was then added in small increments with the mixer running constantly. Continuous cooling of the solution was necessary to control the exothermic reaction. The lithium aluminum hydride was added next and the solution was filtered. In the meantime the conforming aluminum anode was installed in the plating tank and the tank purged with argon. The ether solution was then transferred to the plating tank, the convex nickel master was lowered into the tank and the plating was started. A paraboloidal shell was then electroformed to a thickness of 0.6 mm. The resulting deposits were a soft aluminum with a modulus of about 55 GN/m^2 (8 × 10^6 psi) and a tensile strength of about 76 MN/m^2 (11,000 psi). Three concentrators were fabricated and all have been solar tested.

The results of the tests are shown by a typical efficiency curve in figure 5. The efficiency and concentration ratio are the same as defined previously for figure 2 and an efficiency curve for a perfect concentrator with a reflectance of 0.91 is included for comparison. At the concentration ratios of interest for thermionic conversion (above 10,000), the concentrator has an efficiency of only about 0.50 instead of a value near 0.85 to 0.90 which might be obtained on a more accurate paraboloid. The decrease in efficiency with increasing concentration ratio is the result of inaccuracies in the concentrator which are attributable to two facts. First, the master used for this concentrator was of rather poor geometry. Second, minute pinholes in the master, which normally are bridged over during electroforming with aqueous solutions, were penetrated by the ether solution so that aluminum was deposited in the microscopically small holes. When the concentrator was separated from the master, small holes were torn out of the mirror (where the aluminum was keyed into the master) and the surface was deformed around each hole.

These small holes and their associated deformed areas as well as a slightly nonspecular appearance of the reflecting surface due to poor coatings are considered to be responsible for the low value of specular reflectance (0.77 at a concentration ratio of about 300). Because of the high throwing power or ability to penetrate small holes, the electrodeposition of aluminum from ether solutions should give more exact replications than electrodeposition from aqueous solutions when suitable masters are used.

Large Masters

Much of the development done on relatively accurate one-piece concentrators suitable for thermionic conversion systems utilized 1.52-meter-diameter glass searchlight mirrors as masters. Larger concentrators are now desired and several proposals for fabricating the masters have been advanced. One method being investigated uses the spin casting process to produce a concave paraboloidal surface. Three separate operations required in the process are as follows: (1) spin casting with a concave surface, (2) master with a convex surface, and (3) solar concentrator with a concave surface. Under NASA contracts, two spin castings have been fabricated and used to produce two solar concentrators 2.90 meters in diameter.[6] For the spin castings, epoxy resins were filled with an inert material to reduce shrinkage and then rotated at constant speed until the resins hardened. The two convex masters were formed by electroforming nickel on the spin castings and the concentrators were then formed by electroforming nickel on the masters.

Both concentrators have been solar tested and the results are shown in figure 6 which has calorimetric efficiency plotted as a function of concentration ratio. The theoretical maximum efficiency curve for a perfect concentrator with a specular reflectance of 0.91 is also shown for comparison. Concentrator I was the first one built and the results have been shown previously.[7] Both concentrators gave efficiencies that are well below theoretical values. One reason for the low efficiencies is attributed to the low specular reflectance of each. Concentrator I had a measured value of reflectance of 0.816[8] while it can be seen from the figure that concentrator II had a value near 0.70. The low reflectance of concentrator I has been attributed to a slightly etched surface of its master,[6] while concentrator II had a very hazy appearance of undetermined origin.

Although concentrator II had a lower reflectance, the slope of its efficiency curve in the region of a concentration ratio of 10,000 is about the same as the slope of the curve for concentrator I thus indicating similar geometries. This can be seen more clearly in figure 7 where geometric efficiency, based on the efficiency data of figure 6 and the specular reflectances, is shown as a function of concentration ratio. In the region of interest for thermionic systems near a concentration ratio of 14,000, the geometric efficiency of concentrator II is higher than concentrator I, which is the reverse of the calorimetric efficiencies, thus indicating that the surface accuracy of concentrator II is slightly better.

In view of the poor efficiencies measured on the two 2.90-meter-diameter concentrators, comparisons of concentrator geometry with the respective spin casting geometry are made. As solar tests were not made on the spin castings, comparisons must be based on optical inspections and the results are shown in figure 8 where mean slope errors are presented for spin castings and concentrators.[6] Although improvements are indicated in the second attempt for both spin castings and concentrators, the main point to be made is that the spin castings have small slope errors while the concentrators have errors exceeding those on their respective spin castings by a factor of 5. Unpublished preliminary optical inspection of the second convex master has been made under contract. This inspection indicates that the majority of the surface error is introduced in the replication between the spin casting and the convex master rather than between the convex master and the concentrator. Therefore, the replication process for producing the convex master appears to be in need of further development in order to realize the potential of spin castings for fabricating large one-piece concentrators.

Large Concentrators

The Lewis Research Center is continuing its efforts towards making 6.10-meter- to 9.14-meter-diameter rigid solar concentrators for use with solar dynamic conversion systems. A 6.10-meter concentrator is being built using formed magnesium sectors. It is too early to evaluate the technique, but preliminary results are encouraging.

Expandable Concentrators

Expandable solar concentrators have continued to receive attention because of their compact packaging potential. Development has been directed primarily at improving the concentrating ability of two types. These two are the whirling membrane concentrator and the inflatable-rigidized concentrator.

Whirling Membrane Concentrators

The whirling membrane concentrator is a preformed plastic-film paraboloid that is rotated about the optical axis at a speed sufficient to maintain the correct shape by centrifugal force.[1] A sketch of one model and associated test apparatus is shown in figure 9. The concentrator is 3.05 meters in diameter, has a 60° rim angle, and is made of 0.013-mm-thick aluminized plastic film. Seventy-two steel cables extend from a hub on the shaft to the concentrator rim and help to maintain the paraboloidal shape. Three different models were built with metal hub diameters of 20, 35, and 50 percent of the concentrator diameter. Information on one of these models was reported previously[1] which indicated that modifications to the concentrators were required. Three new models were built with the same hub diameters as noted previously, but modified by locating the cable hub higher on the shaft, and lengthening the cables. These modifications were made in an attempt to provide the proper axial force at the paraboloid rim which is needed to give the correct parabolic cross section and to prevent the formation of circumferential wrinkles in the membrane.

All tests were made in a vacuum sphere at a pressure of less than 133 N/m^2 (1 mm Hg) to avoid flutter of the membrane which was rotated at 71 rad/s (680 rpm). Accuracy of the concentrator was determined at five radial locations by the apparatus shown in figure 9. A 7.6-cm-diameter collimated light beam was reflected from the rotating concentrator, and the distributions of intensity in and near the theoretical focal plane were measured with a bar containing 10 solar cells 2.54 cm between centers. Cross sections of these intensity distributions were obtained at different angular locations by rotating the solar cell bar about the optical axis during tests.

Figure 10 shows cross sections of the intensity distributions obtained at the best focal lengths for the original and modified models with the 50-percent concentrator diameter metal hub. The cross sections are 90° apart with the radial distribution in the plane containing the collimated light rays and the concentrator axis. The ordinate of the figure is the ratio of the intensity of the light in the focal plane to the intensity of the collimated light. The intensity ratios in the figure are averages of the distributions obtained with the collimated light at five different radial locations. It can be seen that the peak intensity ratio has been increased by a factor of about three as a result of the modifications. The dispersion of intensity along the radial direction for the original model, figure 10(a), occurred because of circumferential wrinkles and a nonparabolic shape along a radial cross section. Examination of the individual intensity distributions obtained with the light at various radial locations for the modified model showed that the membrane still had a nonparabolic radial cross section. This deviation from a parabola is about the same as was noted on the original model. However, the individual intensity distributions of the modified model were much narrower in width than those of the original model thus indicating that a reduction in the size of the circumferential wrinkles has been accomplished. For the original model, the dispersion of energy in the circumferential direction, figure 10(b), was apparently caused by deviations in the circular shape of the membrane similar to those in a parachute.[1] A slight increase in the image width is noted for the modified model which is not considered to be significant in terms of concentrating ability of the concentrator. A definite improvement in the concentrating ability of the whirling membrane has been achieved by the cable modifications, although, the desired parabolic cross section has not been attained.

Inflatable-Rigidized Concentrators

A review of inflatable-rigidized technology has recently been made[9] which included information on concentrators rigidized in a simulated space environment as well as concentrators rigidized in an earth atmosphere environment. In the present paper, the discussion will be restricted to concentrators that have been rigidized in a vacuum chamber to simulate space environment and for which quantitative data on their concentrating ability exist. A sketch of one type is shown in figure 11. A plastic paraboloidal membrane, aluminized on the concave side, forms one section of a lenticular body. A disposable plastic membrane forms the front of the body, and an inflatable torus, used to maintain the correct diameter, is attached at the disposable membrane-paraboloid juncture. Once in space, the body would be inflated, the paraboloidal portion would be rigidized by such methods as indicated in figure 11, and the plastic membrane discarded. Three rigidizing methods have been proposed and development of these methods into reliable rigidizing processes suitable for space application has been studied. All three processes have one thing in common; i.e., the rigidizing material while still in a plastic state is applied to the membrane before packaging. Two methods utilize the foam approach shown in figure 11. One is an epoxy syntactic foam which is formed by adding small hollow phenolic spheres to an epoxy resin.[10] Rigidization occurs upon heating the foam to about 365° K for 24 hours. The second is an azide base polyurethane foam formulation,[11] and foaming occurs upon heating the formulation to a temperature between 350° to 365° K. This process takes only about 30 minutes. The third process also shown in figure 11 utilizes a reinforced laminate of fiber-glass and polyester resin[10] attached to the reflective membrane with a flexible layer of polysulphide to prevent show-through of the fiber-glass fabric weave. Ultraviolet radiation acts as a catalyst to the resin and complete rigidization occurs after an exposure of approximately 16 hours.

Demonstration models, each 1.52 meters in diameter, have been fabricated in vacuum chambers utilizing the three rigidizing processes[10,12] and the results of solar tests of the models are shown in figure 12. The calorimetric efficiency and concentration ratio have been defined previously for figure 2. A solar concentrator design point for a Rankine cycle power system is indicated on the figure to show a typical requirement for this type of concentrator. The polyurethane foam model has the highest efficiency which is about 0.20 below the Rankine cycle design point but is about 50 percent higher than the efficiency measured on the epoxy syntactic foam and polyester fiber-glass models. The difference in concentrating ability that exists between the polyurethane foam model and the other two models cannot be wholly attributed to the rigidizing process as varying degrees of surface irregularities or "orange peel" were noted on all models. Another possible source contributing to the difference in concentrating ability may be the construction methods used in forming the paraboloids. The polyurethane foam model had a reflective paraboloid constructed of gores built up on a convex master, while the two other models consisted of flat reflective membranes shaped into paraboloids by the stretch-relaxation process.[10] Briefly this process consists of inflating the flat membranes to the shape of an oblate ellipsoid followed by the relaxation of the inflation pressure until the desired paraboloid is obtained. A direct comparison of the effect of the two construction methods on the membrane contour has not as yet been evaluated. However, both the epoxy syntactic foam and polyester fiber-glass models used the same construction methods and the performance of these two models is essentially equal; it is probable therefore that the construction methods rather than the rigidizing processes are the major source contributing to the difference in efficiencies. The encouraging fact should be noted that an inflatable concentrator has been rigidized in a simulated space environment and is within 0.20 of the Rankine cycle design point. Prior to obtaining these data, only concentrators that had been rigidized at atmospheric pressure had efficiencies approaching the design requirements of the Rankine conversion devices.

Concluding Remarks

In summary, a description of the various solar energy concentrator technology projects under NASA sponsorship has been given. Investigations have been made on several of the concentrators and some results are indicated.

In the area of one-piece concentrators, the stretch-formed aluminum process has been developed to the point where concentrator accuracy approaches closely the high quality formerly obtained only by electroforming nickel. The aluminum electroforming process has been scaled up to the point where 0.76-meter-diameter concentrators have been fabricated. The process appears promising for very exact replication when suitable masters are used. Two accurate 2.90-meter-diameter spin castings have been fabricated, however, the solar concentrators subsequently electroformed of nickel were not of comparable quality. The loss in accuracy has been attributed to problems associated with replication of the convex master that forms the intermediate step between the spin casting and the concentrator.

In the area of expandable concentrators, a modified model of the whirling membrane concept has improved concentrating ability because of a reduction in circumferential wrinkles. However, the desired parabolic cross section has not been attained. A 1.52-meter-diameter inflatable concentrator has been rigidized with a polyurethane foam in a simulated space environment. The concentrator gave an efficiency within 0.20 of a Rankine cycle design efficiency of 0.85.

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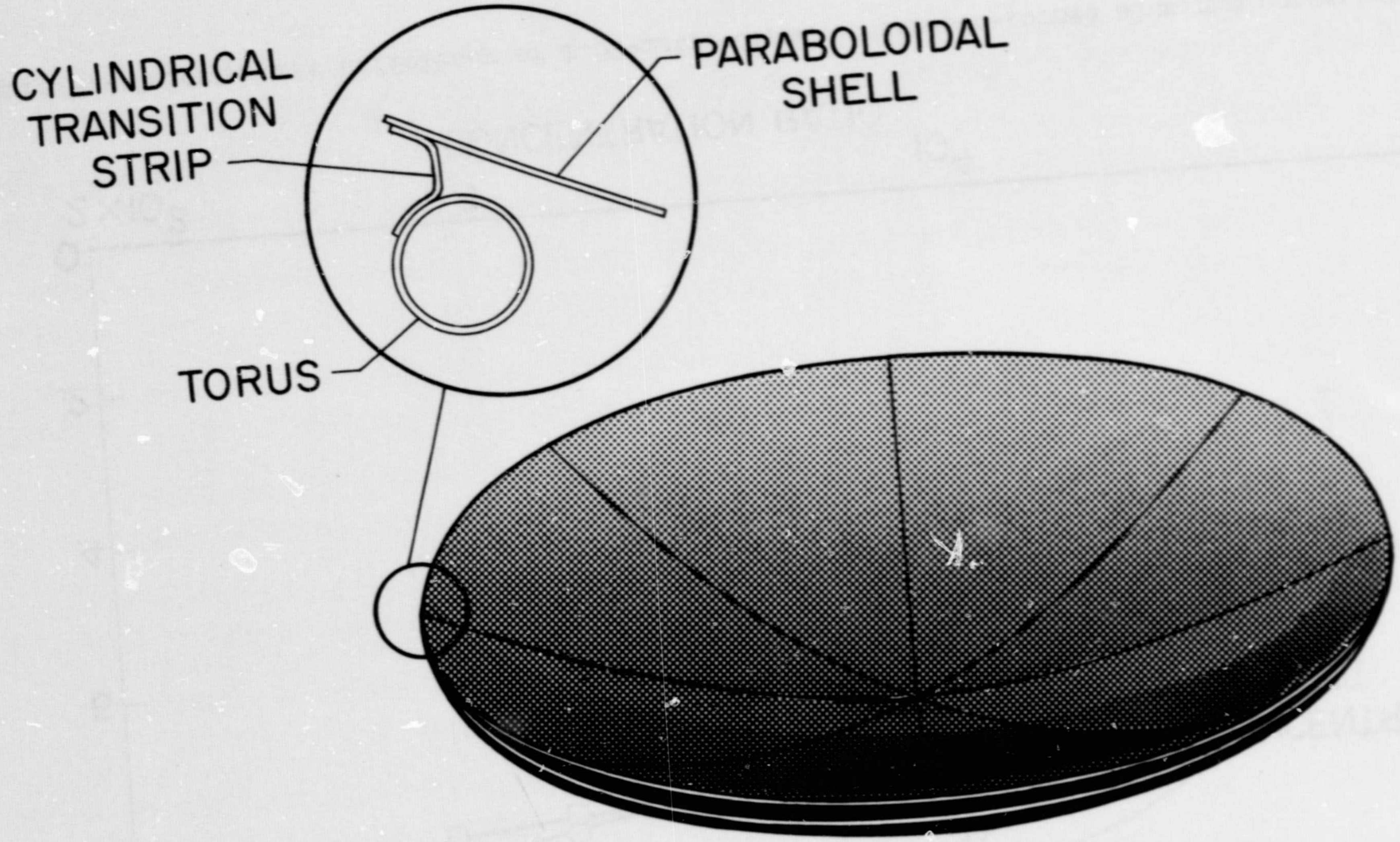


Figure 1.- Stretch-formed aluminum solar concentrator 1.52-meter diameter.

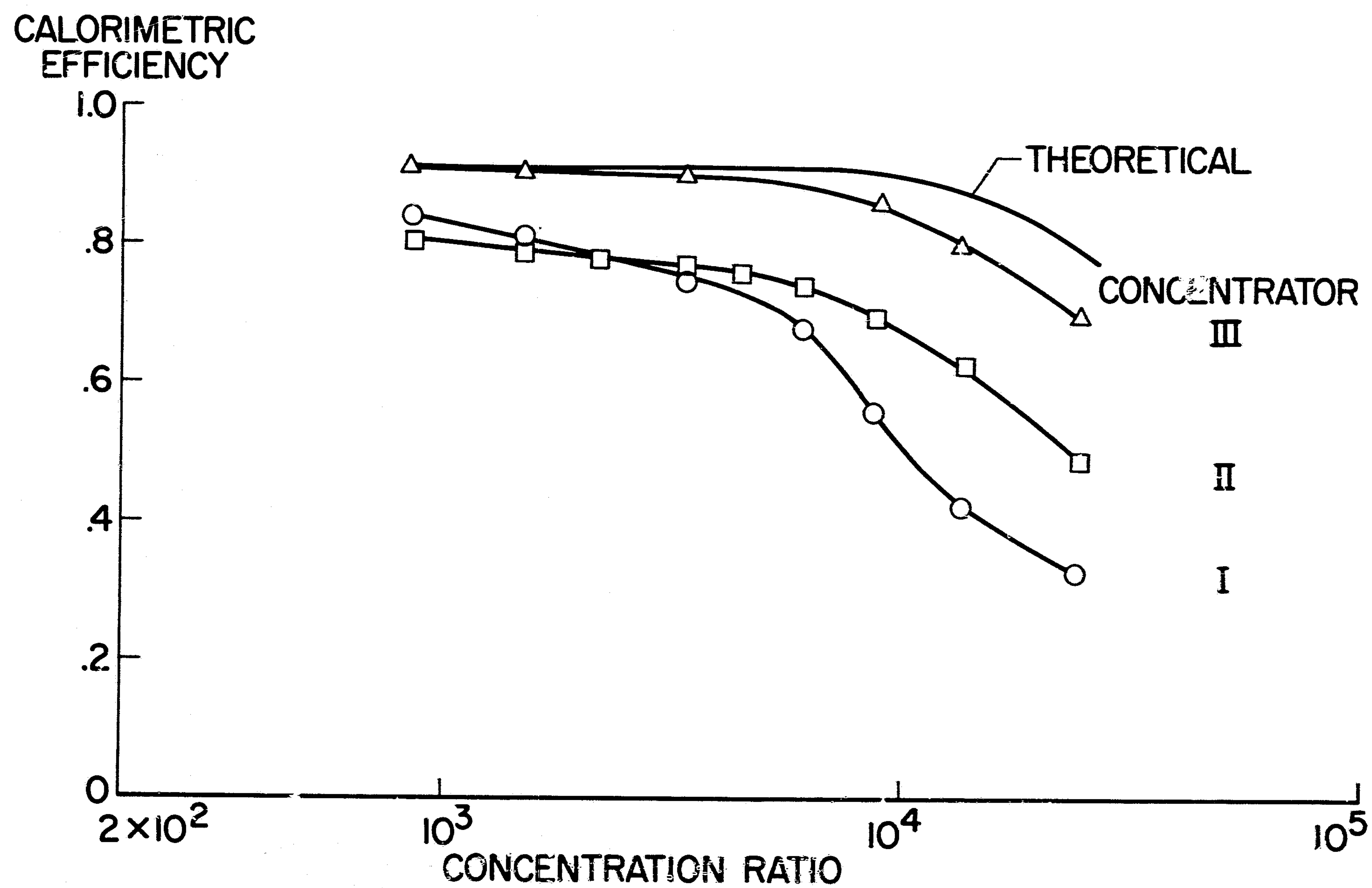


Figure 2.- Calorimetric efficiency of 1.52-meter-diameter stretch-formed aluminum concentrators.

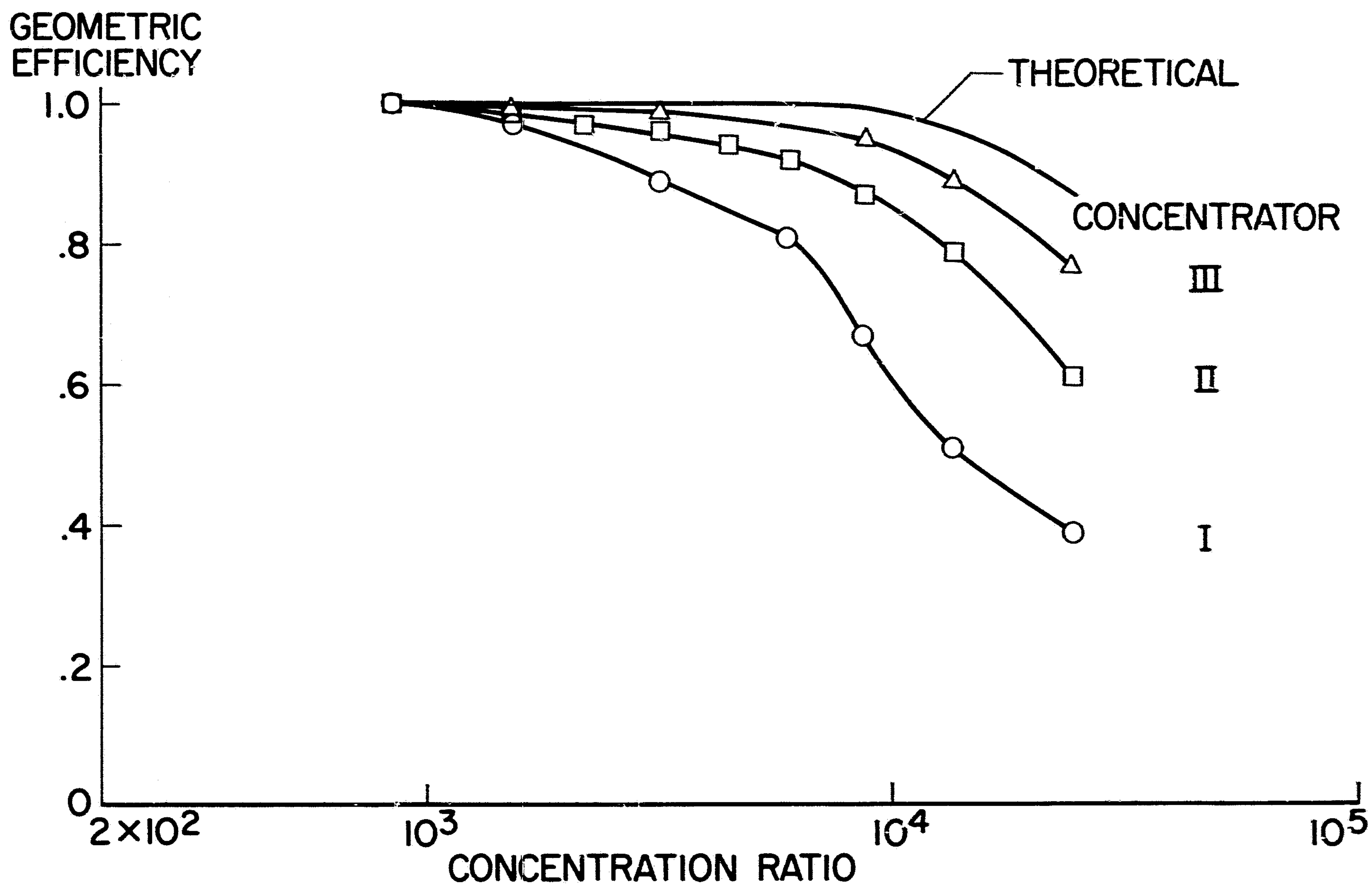


Figure 3.- Geometric efficiency of 1.52-meter-diameter stretch-formed aluminum concentrators.

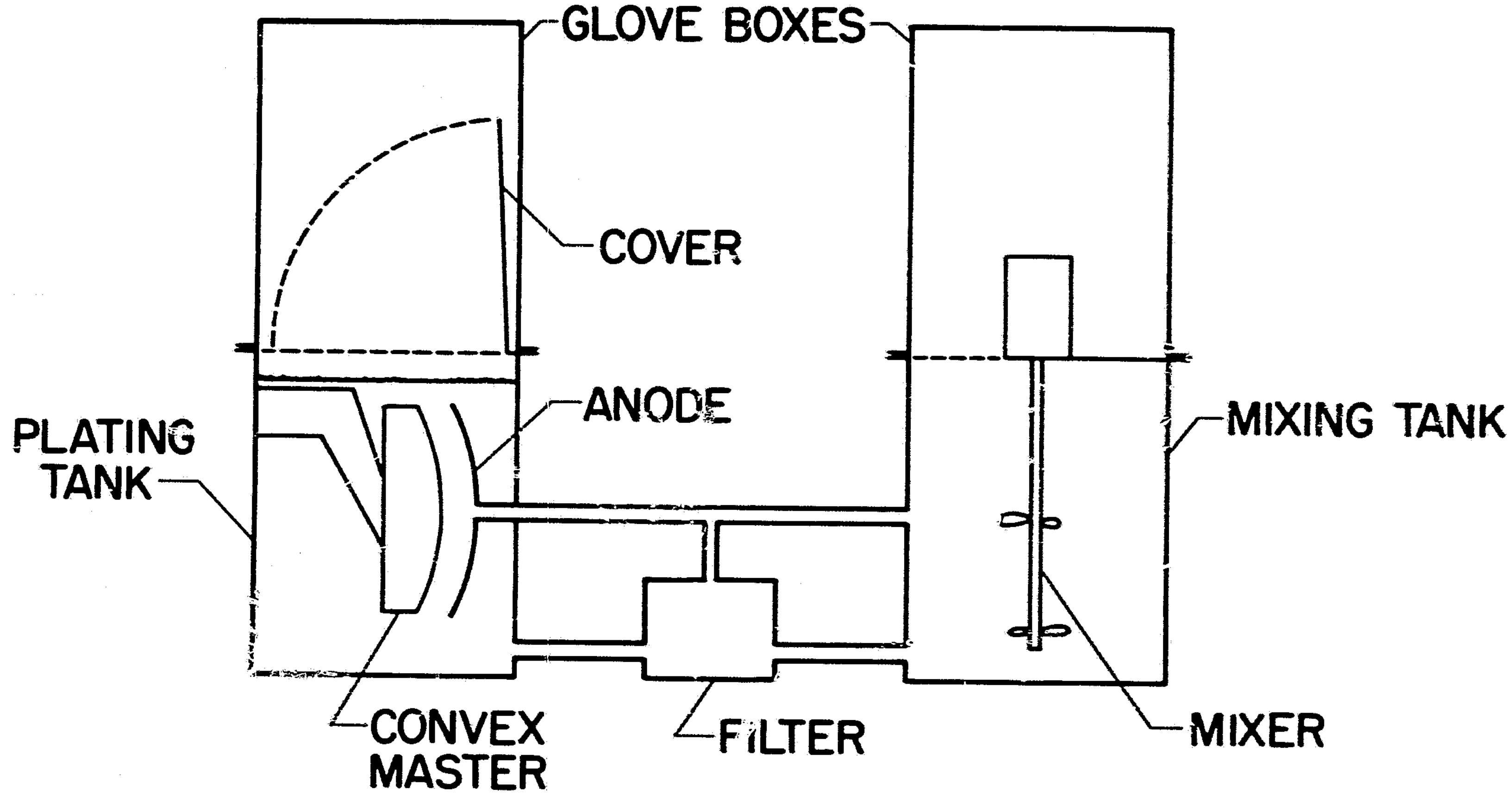


Figure 4.- Aluminum electroforming cell.

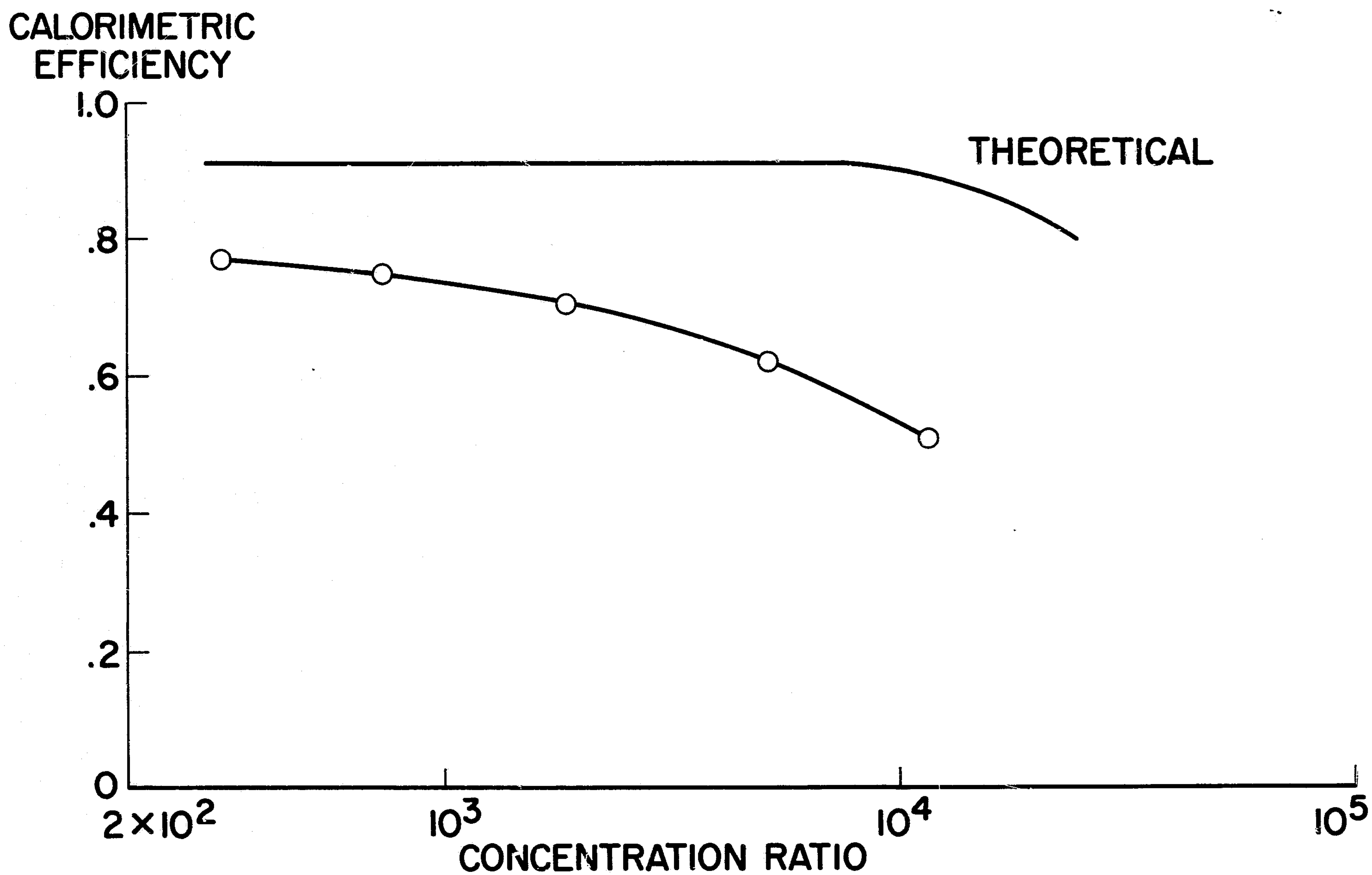


Figure 5.- Calorimetric efficiency of 0.76-meter-diameter electroformed aluminum concentrator.

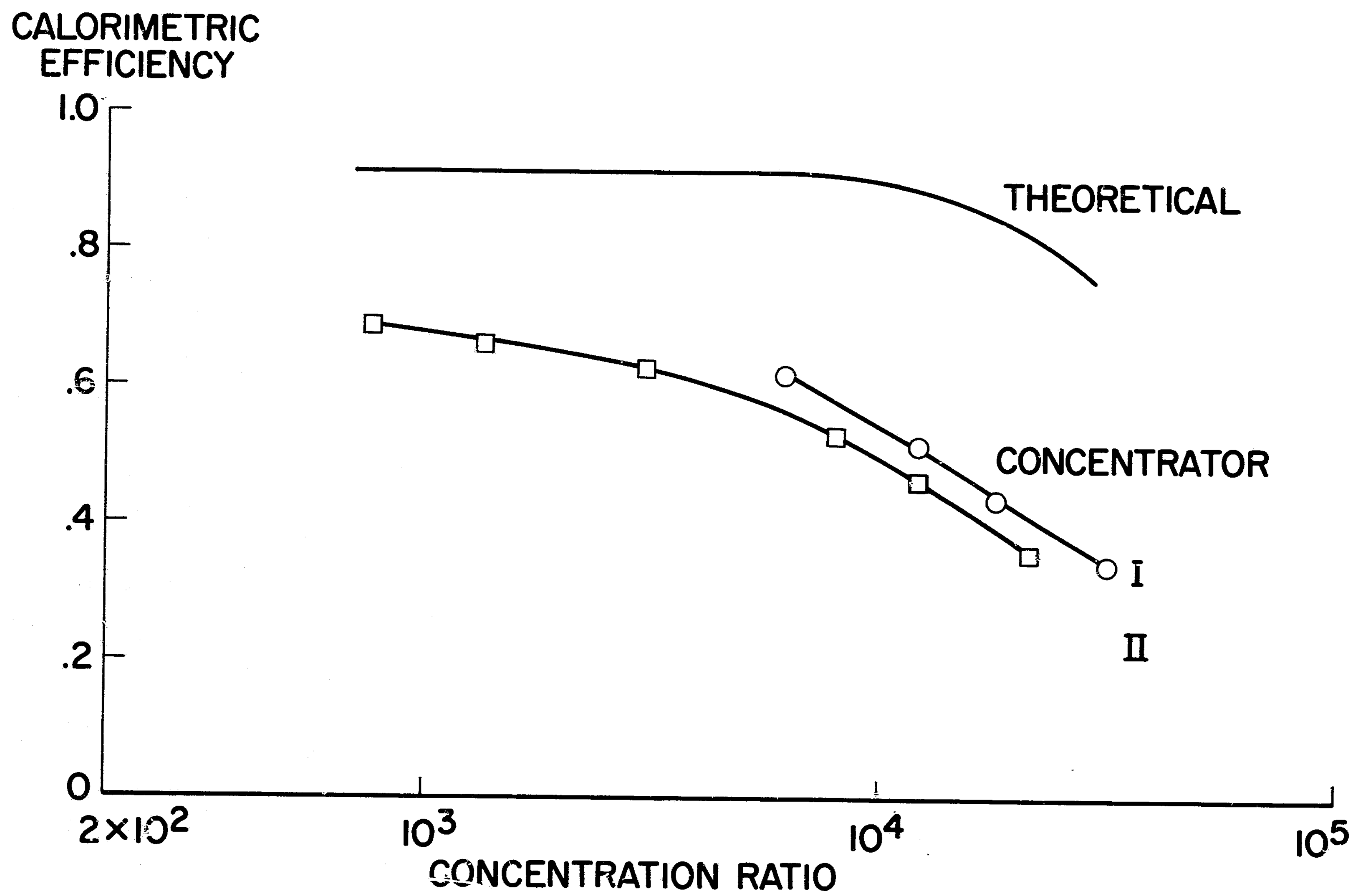


Figure 6.- Calorimetric efficiency of 2.90-meter-diameter electroformed nickel concentrators.

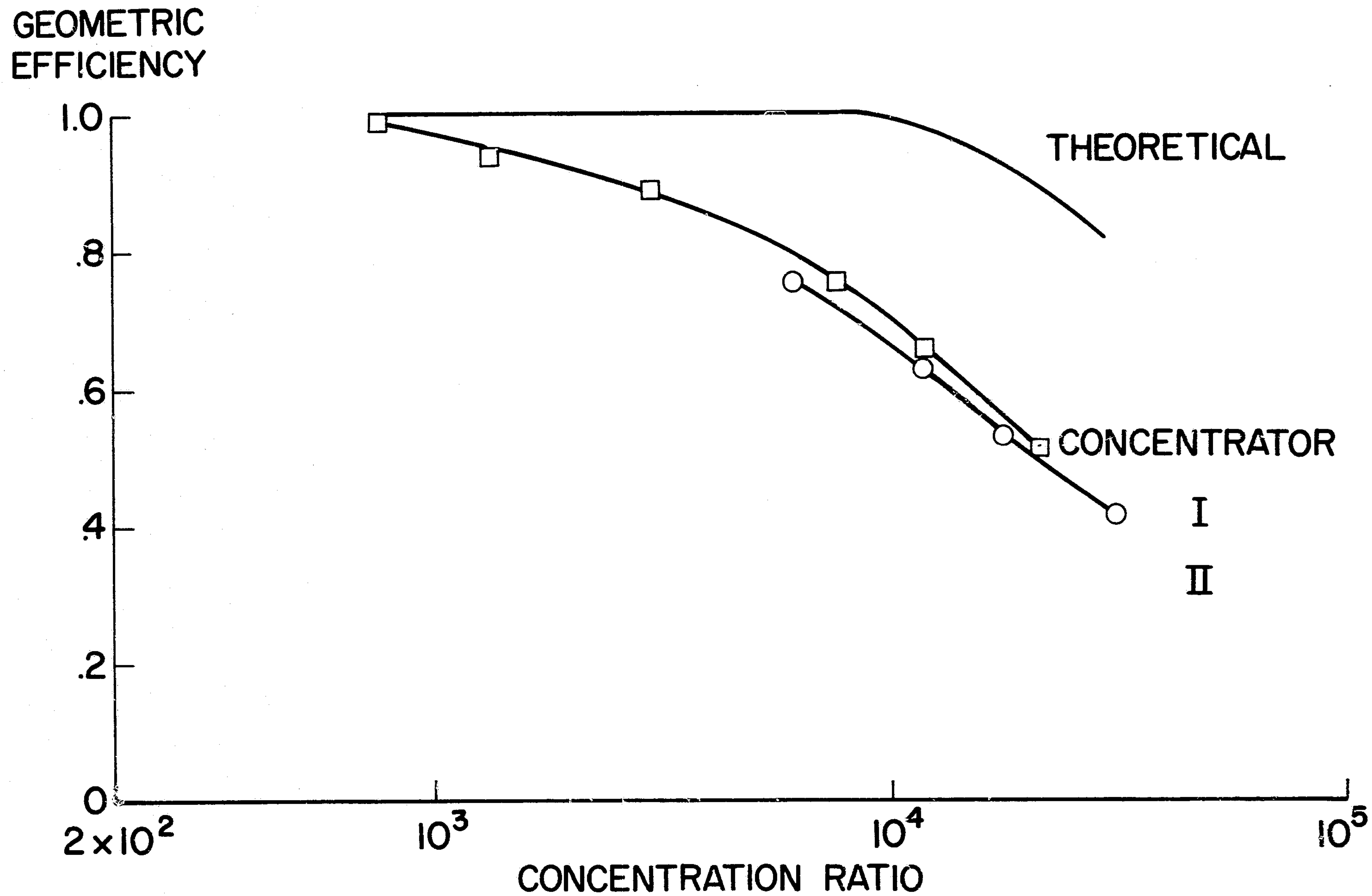


Figure 7.- Geometric efficiency of 2.90-meter-diameter electroformed nickel concentrators.

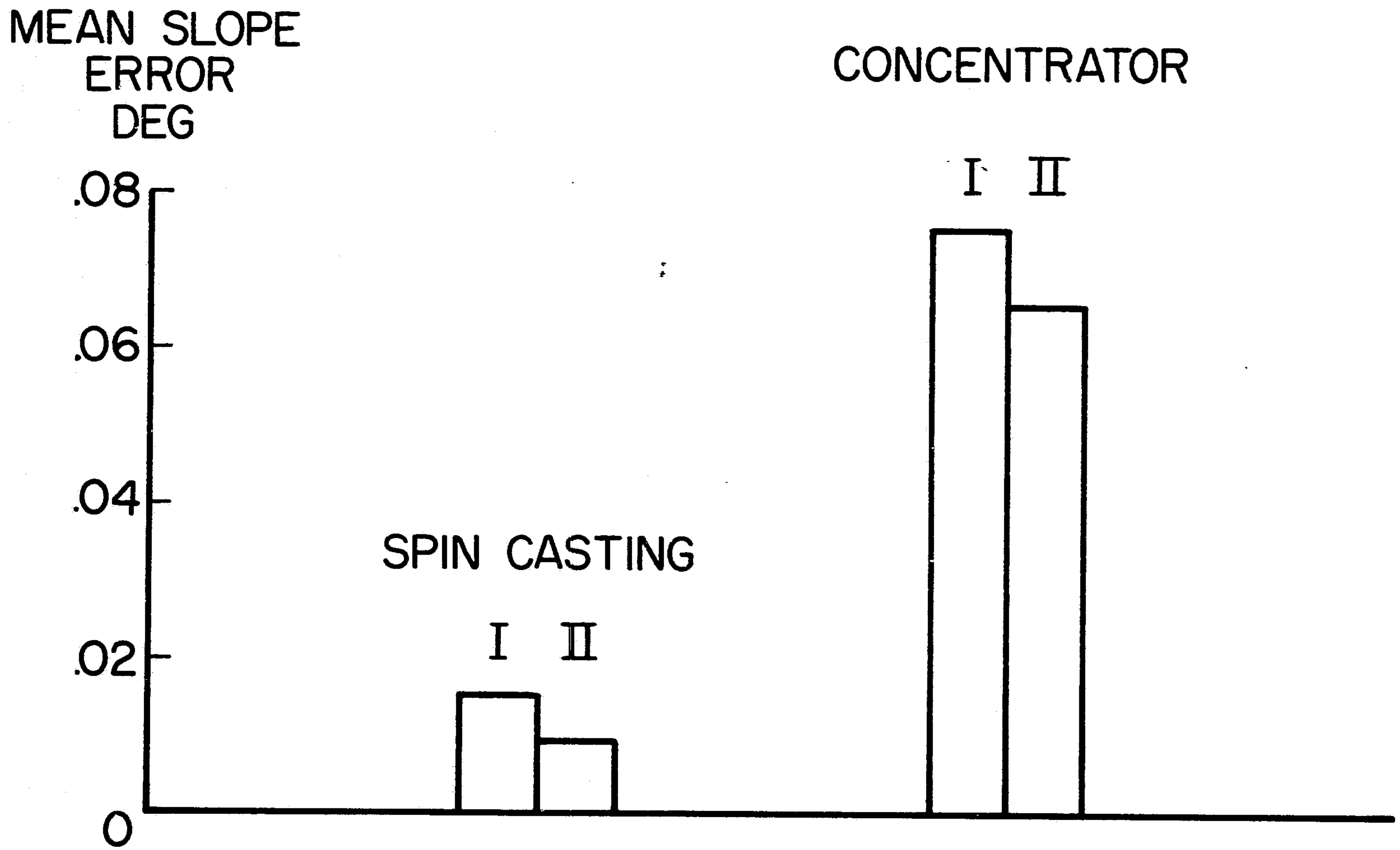


Figure 8.- Mean slope errors of 2.90-meter-diameter spin castings and nickel concentrators.

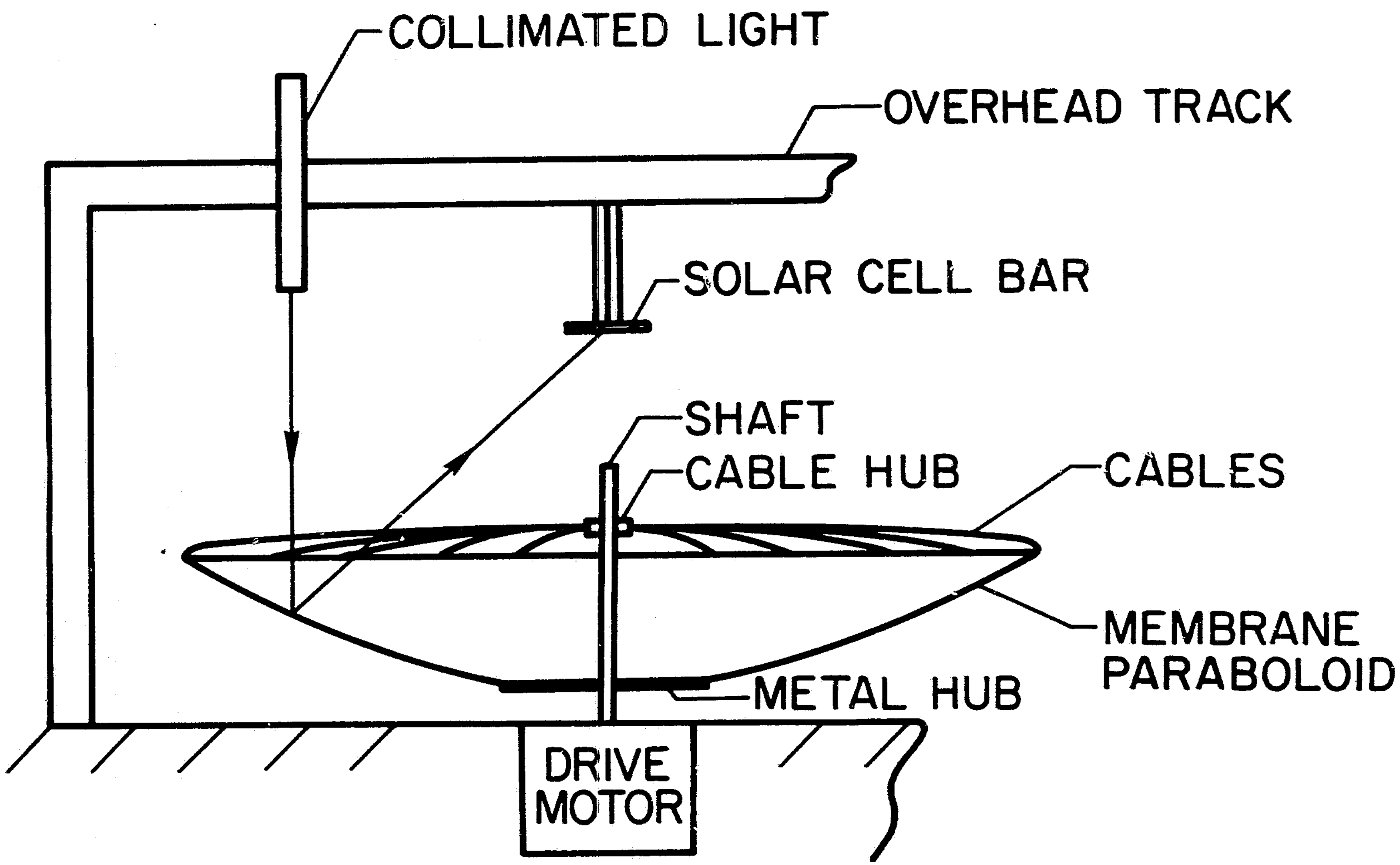
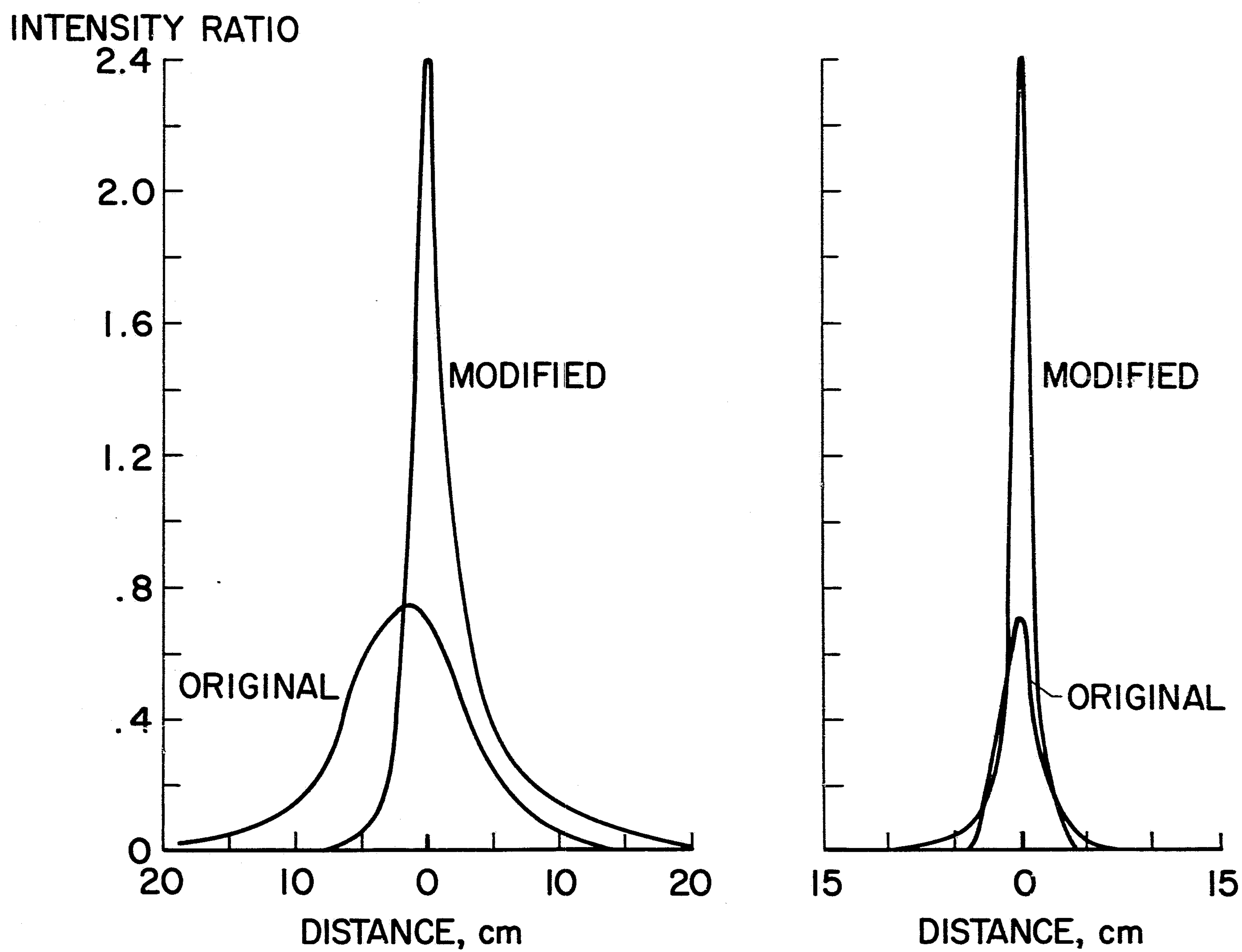


Figure 9.- Whirling membrane solar energy concentrator and test apparatus.



(a) Radial. (b) Circumferential.

Figure 10.- Focal plane intensity ratio distributions of a 3.05-meter-diameter whirling-membrane concentrator.

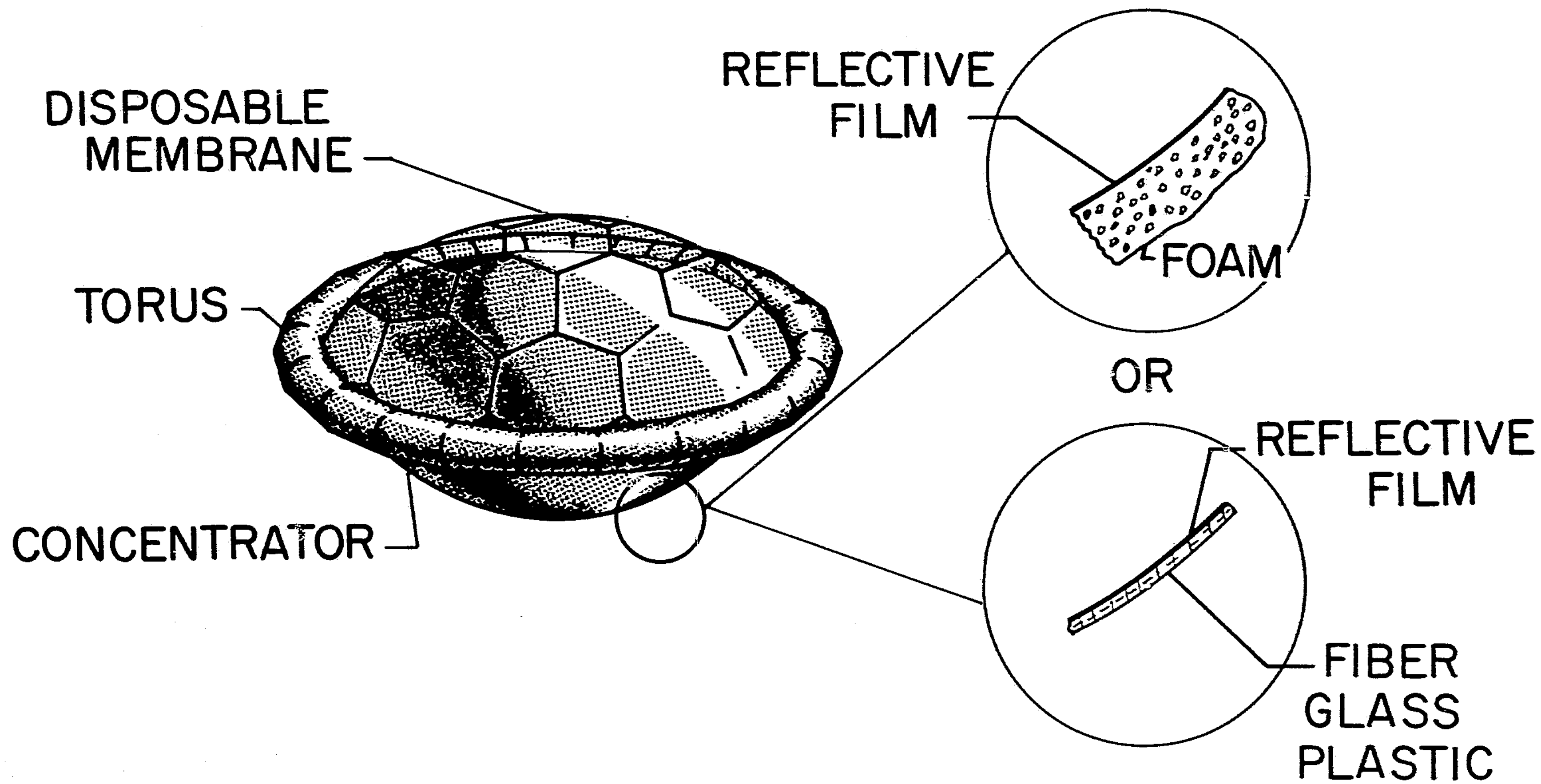


Figure 11.- Inflatable-rigidized solar concentrator.

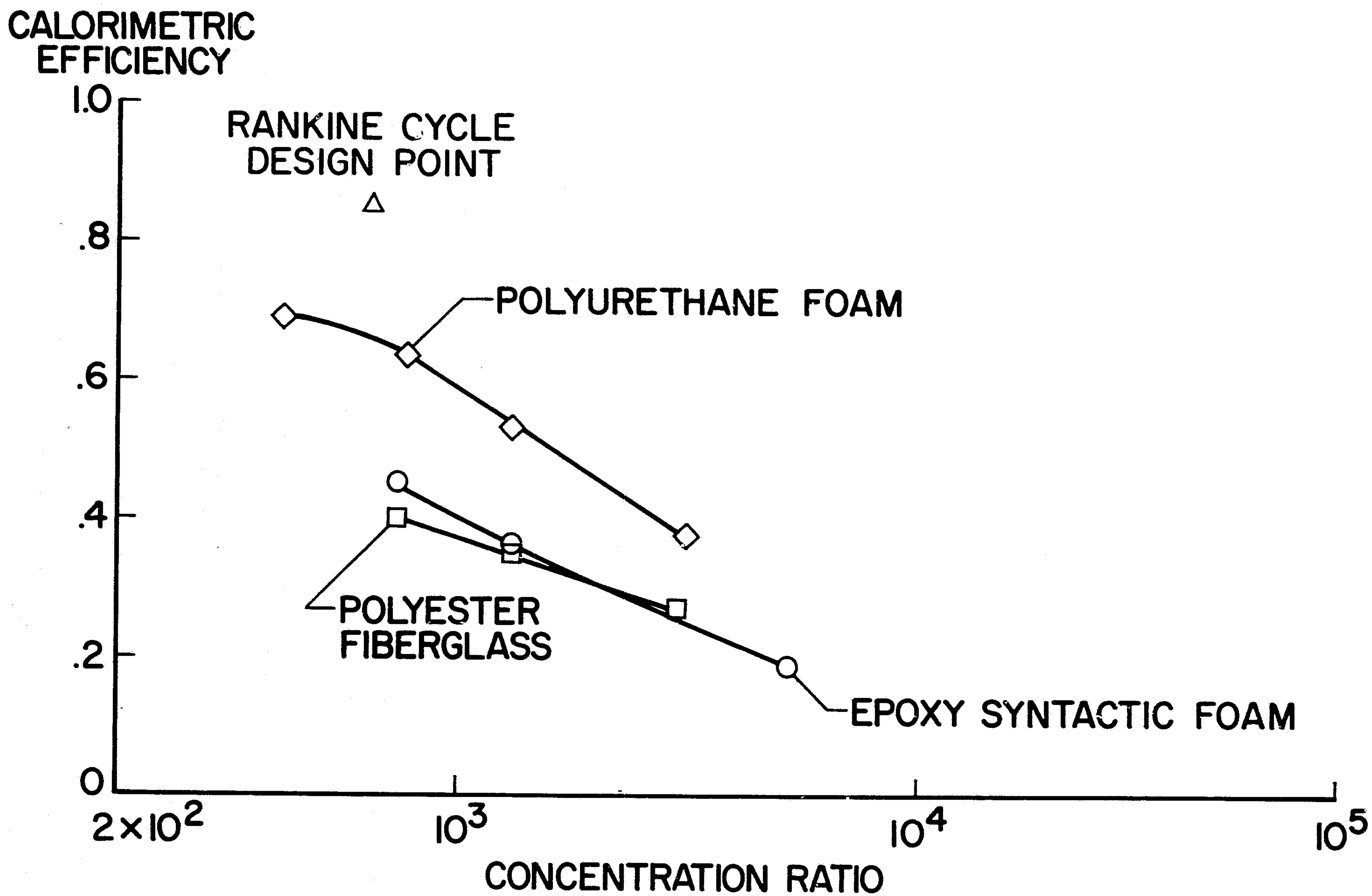


Figure 12.- Calorimetric efficiency of 1.52-meter-diameter inflatable-rigidized concentrators.

NASA-Langley, 1966