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CHARACTERISTICS OF SOLAR CONCENTRATORS AS APPLIED TO SPACE POWER SYSTEMS

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ABSTRACT

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An analysis is presented of current solar concentrator types when integrated into complete space power systems with various electrical conversion methods. Concentrator designs such as inflatable-rigidized, petal, one-piece, and Fresnel are treated in the paper and their size, weight, and packaging characteristics, when combined with dynamic and static conversion schemes, are illustrated. Information presented in the paper provides insight into the selection of concentrator designs for space power applications.

AUTHOR

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CHARACTERISTICS OF SOLAR CONCENTRATORS AS APPLIED TO SPACE POWER SYSTEMS

By O. K. Houck* and A. R. Heath*, Jr.

NASA Langley Research Center

INTRODUCTION

Among the possible energy sources for the generation of electrical power in space is the radiant energy of the sun. In space, away from the attenuating effects of the atmosphere, the sun is a continuous energy source (about 130 watts/sq ft at the earth's mean distance from the sun). A number of conversion devices, requiring concentrated solar energy, are currently being considered for converting the sun's energy to electrical power. In addition, solar concentrator concepts have been advanced in an attempt to provide the required solar energy concentration. This paper will present some characteristics of current solar concentrator designs integrated with various energy conversion devices. Specifically, attention is focused on concentrator sizes, unit weights, and package volumes related to concentrators hypothetically used in space as heat sources for a number of energy conversion devices.

Thermal conversion devices such as dynamic, thermoelectric, and thermionic are considered in this paper. Electrical power produced from these devices will likely be from a few hundred watts upwards to 50 kilowatts for a duration of 1 to 2 years. To produce such quantities of power, solar concentrators as large as 100 feet in diameter may be needed in some instances. Additionally, concentrators must have sufficient focusing abilities such that heat source temperatures between 1,000° and 3,800° R can be realized. Past analyses(1) have

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*Aerospace Engineer.

indicated that a paraboloidal geometry is the only geometry having an adequate concentrating ability to meet this range of temperatures efficiently.

CONCENTRATOR TYPES

A number of paraboloidal and quasi-paraboloidal designs have been explored relative to meeting the basic requirements outlined above. Typical of such designs are those illustrated in figure 1.(2) The umbrella concentrator design,(3) which consists of an aluminized plastic film stretched over lightweight metallic ribs, is an acceptable lightweight, deployable space structure. However, experimental research has shown that, in its present state of development, it cannot efficiently achieve the temperature levels required for the solar energy conversion schemes considered in this paper. The inflatable concentrator,(4) basically a balloon with an interior reflecting surface and a transparent front cover, is highly susceptible to puncture by micrometeoroids and has absorptive and reflective energy losses as a result of the transparent end cap or front cover. These inherent disadvantages preclude further consideration of these two designs. The remaining four designs, petals, inflatable-rigidized, Fresnel, and one-piece, have achieved relatively high efficiencies. Furthermore, these designs are being developed to withstand the rigors of current launch environments. Construction concepts that have been most thoroughly developed and evaluated for these designs are briefly described in table I. The concepts listed in table I, by virtue of their relatively advanced status, have been chosen as the concentrator designs that will be analyzed in this paper.

The one-piece concentrator, consisting of a thin (nominally 0.012 in.) paraboloidal shell with attached torus, is made from the electrolytic deposition of nickel on a sensitized glass mandrel.[5] A number of 5-foot-diameter one-piece concentrators have been made by this process, using surplus 5-foot-diameter glass searchlight reflectors as mandrels. Electroformed one-piece concentrators have been tested for optical and structural performance and have been integrated with thermionic converters, so their operational characteristics are well understood.

Construction of the petal-type concentrator embodies the stretching of aluminum sheets over a suitably shaped mandrel, and bonding a backing or supporting structure to the obtained paraboloidal contour. The individual petals fabricated by this process are hinged at their roots to a common hub assembly allowing deployment into a complete paraboloidal concentrator. Petal concentrators of different sizes have been made in this manner, but the 32.2-foot-diameter aluminum petal concentrator[6] with an aluminum honeycomb supporting structure is used herein because of its relatively advanced stage of development.

The Fresnel concentrator, having undergone extensive testing required during the Air Force's EROS program (Experimental Reflector Orbital Shot) that resulted in successfully orbiting a 4.5-foot-diameter reflector,[7] also has well-defined performance characteristics. Like the one-piece concentrator, the Fresnel is made by electroforming nickel. Unlike the three other concentrator designs, however, the Fresnel is a quasi-paraboloid being essentially a foldable flat plate having a number of conical rings with a common focus.

The three concentrator designs just discussed are basically metallic structures. The fourth design listed in table I, the inflatable-rigidized concentrator,[8] is a plastic film bag that is packaged compactly during launch and inflated in space. A portion of the bag is designed to assume a paraboloidal contour upon inflation and is aluminized on the concave side to reflect solar energy. After the paraboloidal contour is obtained, it is made rigid by chemically reacting a suitable rigidizing medium. The rigidizing material may be predistributed over the surface before launch, or the material may be mixed once the reflector has been inflated in space and allowed to flow over the convex side of reflector prior to curing or hardening. After the rigidization sequence is completed, the unneeded front portion of the bag is removed from the concentrator. Performance characteristics of inflatable-rigidized reflectors capable of deployment and operation in space are not well defined at this time due to the lack of knowledge pertaining to rigidizing mediums that will perform reliably in the space environment. Research on this particular problem area is being actively pursued by the Air Force and the NASA. Insight into the performance expected from inflatable-rigidized concentrators has been gained from ground-type test models[9] built and tested under Air Force contracts. Test information used in this paper for the inflatable-rigidized design is based on a 10-foot-diameter ground-type test model.

Table I also contains values of concentrator reflectivity. These values are not the same for each design because of minute variations in the surface finishes of the four designs.

CONCENTRATOR-ABSORBER EFFICIENCY

Calorimetric test data are available for the four concentrator designs of table I. The concentrator efficiency obtained from calorimetric tests is the ratio of the thermal energy absorbed by a fluid circulated through the calorimeter or absorber to the sun's thermal energy incident upon the concentrator surface for various absorber openings. The temperature of the calorimeter is maintained close to ambient conditions for these tests to insure negligible heat losses from the absorber.

The top curve in figure 2 represents results from calorimetric tests on the inflatable-rigidized concentrator.[9] If it is assumed that the absorber is a black body with losses only from reradiation through the absorber entrance, concentrator-absorber efficiencies for various temperatures can be computed from the Stefan-Boltzmann law. Concentrator-absorber efficiencies, computed in this manner are also plotted in figure 2 for several assumed temperatures and for a solar flux of 130 watts/sq ft. As can be seen, concentrator-absorber efficiency curves have an optimum value for each assumed temperature at different size absorber openings. Optimized concentrator-absorber efficiency curves obtained from similar plots are shown in figure 3 for all four concentrator designs.

In addition to the operating temperature of the absorber, the concentrator-absorber efficiencies shown in figure 3 are dependent on the specular reflectivity, the geometric accuracy of the concentrator, and the ratio of the usable reflecting surface are to the area of the absorber aperture. For comparison, the efficiency curve of a theoretically perfect paraboloid having the same specular reflectivity (0.89) as the electroformed paraboloid is also plotted in figure 3. As shown in the figure, the electroformed one-piece reflector approximates the perfect geometry. This is attributed to two factors: (1) electroforming is an extremely accurate replication process, and (2) a high-precision mandrel was used. Larger electroforming mandrels (i.e., 9.5-foot diameter) have been accurately made and it is expected that concentrator replications from them will be as efficient as the indicated efficiency for the 5-foot-diameter one-piece reflector. Fabrication techniques used in the other designs are also sufficiently advanced so that it may be assumed, for purposes of this paper, that concentrator size will have little or no effect on efficiency. The performance of the petal, Fresnel, and inflatable-rigidized concentrators is seen to be considerably less than the one-piece concentrator. This performance reduction is caused by the inherent fabrication limitations of each concentrator design. A few major limitations are: (1) the nonusable area of the Fresnel design; (2) the comparatively low specular reflectance of aluminized plastic films used in the inflatable-rigidized concentrator; and (3) the surface slope errors introduced in the petal concentrator by its honeycomb backing structure. Improvement in these limitations is considered possible, but usually at the expense of increasing concentrator weight or degrading other performance parameters.

CONCENTRATOR CHARACTERISTICS

By combining the concentrator-absorber efficiencies of figure 3 with the conversion efficiencies of various dynamic and static energy conversion schemes, and by assuming perfect heat transfer in the absorber, required concentrator sizes, weights, and packaging factors may be determined. The conversion efficiency used is defined as the fraction of the energy available in the heat receiver that is converted to useful electrical power. It includes thermodynamic efficiencies in addition to individual component efficiencies.

Figure 4 illustrates typical conversion efficiency characteristics of a dynamic conversion system and two static conversion concepts. The Stirling cycle curve is based upon a combined component efficiency factor of 0.7 and a calculated thermal cycle efficiency curve[10] for 520° R minimum cycle temperature. While the indicated efficiency of this cycle is somewhat higher than other cycles (i.e., Brayton and Rankine), the trend of increasing efficiency with increasing temperature is typical for all cycles. The thermoelectric energy conversion curve[11] was obtained from calculations for lead telluride thermocouple junctions and an optimized hot to cold junction temperature ratio. The curve is seen to have an optimum value at about 1,600° R. The thermionic conversion efficiency curve was calculated from parametric analyses[12] for current densities and internal voltage losses considered to be within today's state of the art. The waviness of this curve, with optimum values at 3,000° and 3,600° R, is a result of different cathode materials being required for different temperatures. As was previously noted, these conversion efficiency curves were combined with concentrator efficiency curves to obtain concentrator characteristics as shown in the ensuing figures. These figures are based on calculations made for an all-sunlight earth orbit.

Concentrator Size

Figure 5 shows concentrator size variation for a dynamic energy conversion system using the Stirling engine with a useful output of 10 kw. The trend of decreasing concentrator size with increasing absorber temperature is seen to be more pronounced at temperatures below approximately 1,300° R because of the relatively lower thermodynamic efficiencies obtainable at these temperatures. The minimum concentrator size is obtained at the highest temperature consistent with state-of-the-art thermal properties of materials and working fluids. The one-piece concentrator is seen to be the smallest of the four designs at any temperature. The closeness of the size characteristics of the expandable concentrator designs is attributed to the closeness of their concentrator-absorber efficiencies within the temperature range shown.

Thermoelectric-concentrator sizes are depicted in figure 6 for an output of 1 kw from lead telluride thermocouple junctions. As previously noted, thermoelectric conversion efficiency is highest at approximately 1,600° R for the material considered in this figure; hence, all types of concentrators have a minimum size near this temperature. The one-piece design is the smallest of the four designs at any temperature and is approximately 20 percent smaller at the optimum temperature.

Concentrator size variation for another static conversion system, thermionic conversion, is shown in figure 7 for an output of 1 kw. Here, as with thermoelectric conversion, there is a minimum concentrator diameter with respect to temperature for the expandable designs. The optimum temperature in this instance is about 2,700° R. The size of the one-piece concentrator is seen to remain virtually constant with temperature. This characteristic is a result of the unique variation of concentrator-absorber and conversion efficiencies with absorber temperature, that is, the product of concentrator-absorber and conversion efficiencies remains constant with respect to temperature. Once more, the one-piece concentrator is the smallest design for any temperature. Thermionic converters that operate relatively efficiently at upwards to 3,600° R are being developed.[13] If these higher temperature converters are to use solar energy as a heat source, the one-piece concentrator design will be even more attractive than the expandable designs for such an application.

Figures 5 to 7 have shown concentrator size variations as a function of absorber temperature at constant electrical output. The next three figures illustrate the effect electrical output has on concentrator size while absorber temperature is held constant.

In figure 8, concentrator size as a function of converter output is depicted for a typical dynamic conversion system, the Stirling cycle. An absorber temperature of 1,700° R is used as being a practical operating temperature for the Stirling cycle. As one would expect, concentrator size must increase as power level increases so that an adequate amount of the sun's energy is intercepted to deliver a given power level. Conversion efficiency has been assumed to be constant with power level in this figure. Therefore, concentrator size varies according to the square root of power level. The size characteristic curves of the expandable designs almost coincide due to the closeness of their efficiency characteristics (see fig. 3). The one-piece concentrator is the smallest of the four designs at any power level because of its superior performance as compared to the expandable designs. The figure also shows that, about 2 kw can be generated by using the 10-foot-diameter inflatable-rigidized concentrator while upwards to 20 kw can be obtained with the 32.2-foot-diameter petal-type concentrator.

Concentrator size variation with power level for static conversion is shown in figures 9 and 10. Optimum absorber temperatures obtained in previous figures are used as operating temperatures in these figures. As has been the case in the preceding figure, conversion efficiency is held constant allowing concentrator size to vary with the square root of electrical output. It is seen in figures 9 and 10 that the one-piece concentrator is the smallest concentrator design for both static conversion systems regardless of power level. Because of the relatively small differences in concentrator efficiency at thermoelectric temperatures, 1,600° R, the size characteristics of the expandable concentrator-thermoelectric systems are seen to be almost coincident as shown in figure 9. On the other hand, larger differences in concentrator efficiency at thermionic temperatures, 2,700° R, causes a wider spread variation in size of the expandable designs as evidenced in figure 10. At the present time, thermionic conversion concepts are being developed in conjunction with 9.5-foot-diameter one-piece concentrators. According to figure 10, approximately 1.2-kw converter output is possible with this size and type concentrator.

Concentrator Weight

In figures 5 through 10, the one-piece concentrator, as a result of its superior efficiency, is always smaller than the other concentrators regardless of absorber temperatures and power levels. On a weight basis, however, the expandable designs could be equal to the smaller one-piece concentrator if they can be made at a lower weight per unit area (unit weight) than the one-piece design. To demonstrate this fact, figure 11 shows what the unit weight variation of each expandable design must be relative to the one-piece design. Concentrator unit weight could be a flyable unit weight based on all the hardware required to integrate the concentrator into a launch vehicle and to make the concentrator operate in space. However, data on flyable concentrator unit weights are limited. Furthermore, flyable unit weights are dependent upon end applications that are restricted by packaging limitations, ascent and orbital thermal balance, vehicle vibratory characteristics during launch, etc. Therefore, in order to make a reasonable comparison, all of the unit weight values in the figure are based upon weights of the reflecting skin and integral structural backing only. Also shown in the figure are the general operating temperatures for the three conversion schemes.

As indicated by the straight line in figure 11, a nominal unit weight of 1.0 lb/sq ft[2] has been achieved for the electroformed nickel one-piece concentrator. The required unit weights of the expandable concentrator designs are seen to decrease with increasing temperature in order for their total weight to be equal to the total weight of the 1.0 lb/sq ft one-piece concentrator design. Petal concentrators have been built at 0.18 lb/sq ft[2]. Since this value is below the required unit weight curve for the petal concentrator at temperatures up to 3,700° R, the 0.18 lb/sq ft petal concentrator design will weigh less than the one-piece design up to this temperature. Similarly, the Fresnel design used in project EROS, which had a unit weight of 0.45 lb/sq ft,[7] is lighter than the one-piece design for the temperature range between 1,000° and 2,200° R which includes thermoelectric and dynamic conversion applications. The unit weight of the inflatable-rigidized concentrator is an estimated value of 0.38 lb/sq ft supplied to the Air Force by the manufacturer specifically for a 10-foot-diameter design with a 2 lb/cu ft rigidizing material. At this value, the inflatable-rigidized design is seen to be lighter than the one-piece design until a temperature of 2,700° R is reached.

While discussing unit weights, it is interesting to note the growth in unit weight resulting from hardware additions required to fly one of the concentrator designs. The flyable Fresnel design for project EROS had a unit weight of about 1.66 lb/sq ft[7] when all the associated deployment apparatus, attachment pads, etc. were added to the basic reflector design that weighed 0.45 lb/sq ft.

Concentrator Packaging

Another important characteristic to be considered, is the packaging volume required by the four concentrator designs. Packaging characteristics of the designs as a function of electrical output are shown in figures 12 through 14 for the three conversion schemes. The ordinate in the figures, packaging factor, is defined as the ratio of the volume of the nose fairing required to enclose a specific concentrator to the total volume of the nose fairing of an

Agena launch vehicle. (Representative dimensions of the cylindrical nose fairing are 10-foot diameter by 25-foot height.) Packaging configurations of some of the concentrators are such that they do not exactly fit the circular cross-sectional area of the nose fairing. However, since the nose fairing will be jettisoned on orbit, and the concentrators will need to move during erection and deployment, it is assumed that the unused space around the packaged concentrator cannot be utilized for packaging other equipment. Consequently, all of the cylindrical nose fairing volume required to enclose the packaged concentrator is included in the packaging factor.

The packaging envelope for the four concentrators is based upon feasible folding methods and characteristic concentrator dimensions. The Fresnel design, for instance, is assumed to have square sections that are folded to be perfectly inscribed within the circular cross section of the vehicle. The thickness of each section is assumed to be 1 inch which is the dimension of the EROS design.(7) The packaged height of the petal-type concentrator is assumed to be one-half the difference between the concentrator diameter and the diameter of the central hub from which the petals are hinged. A hub diameter of 9 feet has been assumed which is characteristic of the sunflower concentrator design.(6) For the inflatable-rigidized concentrator, a 3/16-inch-thick predistributed foam is assumed to be used and its packaging factor is based on solid to packaged volume for similar inflatable plastic-film space structures.(14) One-piece concentrator modules no larger than 10 feet in diameter are assumed to facilitate packaging the one-piece concentrator. The modules are assumed to be stacked one on the other within the vehicle, but are not "nested" within each other.

Concentrator packaging characteristics for a typical dynamic energy conversion system, the Stirling cycle, are shown in figure 12. As output power is increased, concentrator packaging factor is seen to increase since the concentrators necessarily become larger with increasing power level. The figure shows that the petal-type concentrator requires larger packaging volumes than the other designs up to about 20 kw where its packaging characteristics become less than those of the one-piece design. The figure also shows that the Fresnel and inflatable-rigidized designs have considerably better packaging characteristics than the other two designs with the inflatable-rigidized concentrator having the smallest packaging factor of all designs regardless of power level.

Figure 13 shows concentrator packaging characteristics related to thermoelectric conversion. Based on this figure, there is no concentrator packaging problems for thermoelectric systems at least for power levels and efficiencies currently associated with these systems, that is, none of the concentrators take up all of the assumed nose fairing. The figure also shows that the inflatable-rigidized concentrator requires less packaging volume than the other concentrator designs for any power level, but there is little difference between its packaging characteristics and those of the Fresnel design.

Required packaging factors for concentrator-thermionic converter combinations are presented in figure 14. Trends shown in this figure are much like those seen in the preceding two figures - packaging factors increase with increasing power levels; the inflatable-rigidized concentrator occupies the smallest volume of the four designs regardless of power level; and packaging factors of the Fresnel and inflatable-rigidized designs are approximately the same. Like thermoelectric converter-concentrator systems, it is seen that none of the concentrator designs, when combined with thermionic converters, require the whole nose fairing for packaging.

SUMMARY

The selection of a solar concentrator for specific space power applications must be based upon a judicious analysis of the numerous design limitations related to the application in combination with the available solar concentrator state-of-the-art performance characteristics. This paper aids in such a selection by pointing out some of the more salient characteristics of solar concentrators combined with several space power systems. Concentrators which are considered to be in advanced stages of development; and which were, consequently examined, in this paper are: (1) the electroformed nickel one-piece paraboloid; (2) the stretch-formed, aluminum, expandable paraboloidal petal type; (3) the electroformed nickel, expandable Fresnel; and (4) the inflatable-rigidized, paraboloid.

Examination of the size characteristics of the four concentrator concepts revealed that the one-piece concentrator, because of its superior performance, is the smallest concentrator concept for all of the space power systems considered. At the higher temperatures associated with thermionic converters, the one-piece concentrator is very attractive from the size standpoint. From a weight standpoint, however, the one-piece design might not be the lightest concentrator. On the basis of achieved concentrator unit weights for reflective skins and supporting structure, the petal-type concentrator has been seen to be lighter than the smaller one-piece concentrator for all of the conversion applications considered. Examination of the vehicular packaging requirements of the four concentrators, based on an Agena type nose fairing, shows that the

inflatable-rigidized concentrator will have the smallest packaging volume of the four designs.

While the investigation of concentrator characteristics as applied to space power systems has not pointed to any previously unknown conclusions regarding solar concentrator technology, resultant findings have served to reemphasize a known fact - there are so many design facets involved in integrating concentrators with space power systems, it is unlikely that one concentrator design will be optimum for all space power applications.

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TABLE I

DESCRIPTION OF CONCENTRATOR CONCEPTS

Concentrator concept	Structural components	Diameter, ft	Measured reflectivity	Reference number
One-piece-electroformed	Aluminized nickel paraboloidal shell with supporting torus	5.5	0.89-0.90	5
Petals - stretch formed	Aluminum paraboloidal segments with honeycomb supporting structure	32.2	0.86	6
Fresnel - electroformed	Aluminized nickel Fresnel foil with nickel box type supporting structure	4.5	[a]0.87	7
Inflatable rigidized	Aluminized plastic film with plastic foam supporting structure	10	[a]0.76	8,9

[a]Estimated from calorimetric testing.

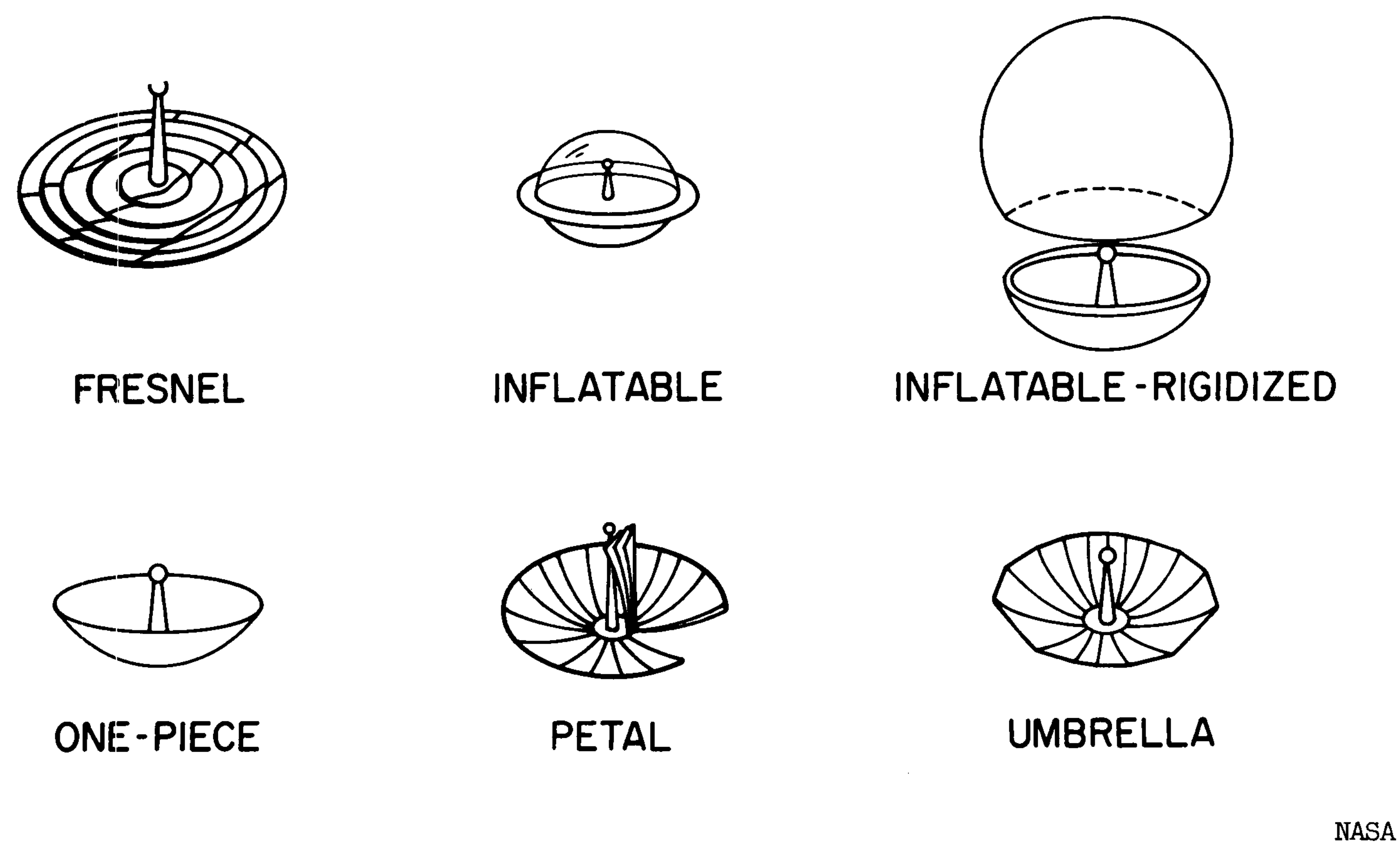

Figure 1.- Solar concentrator types.

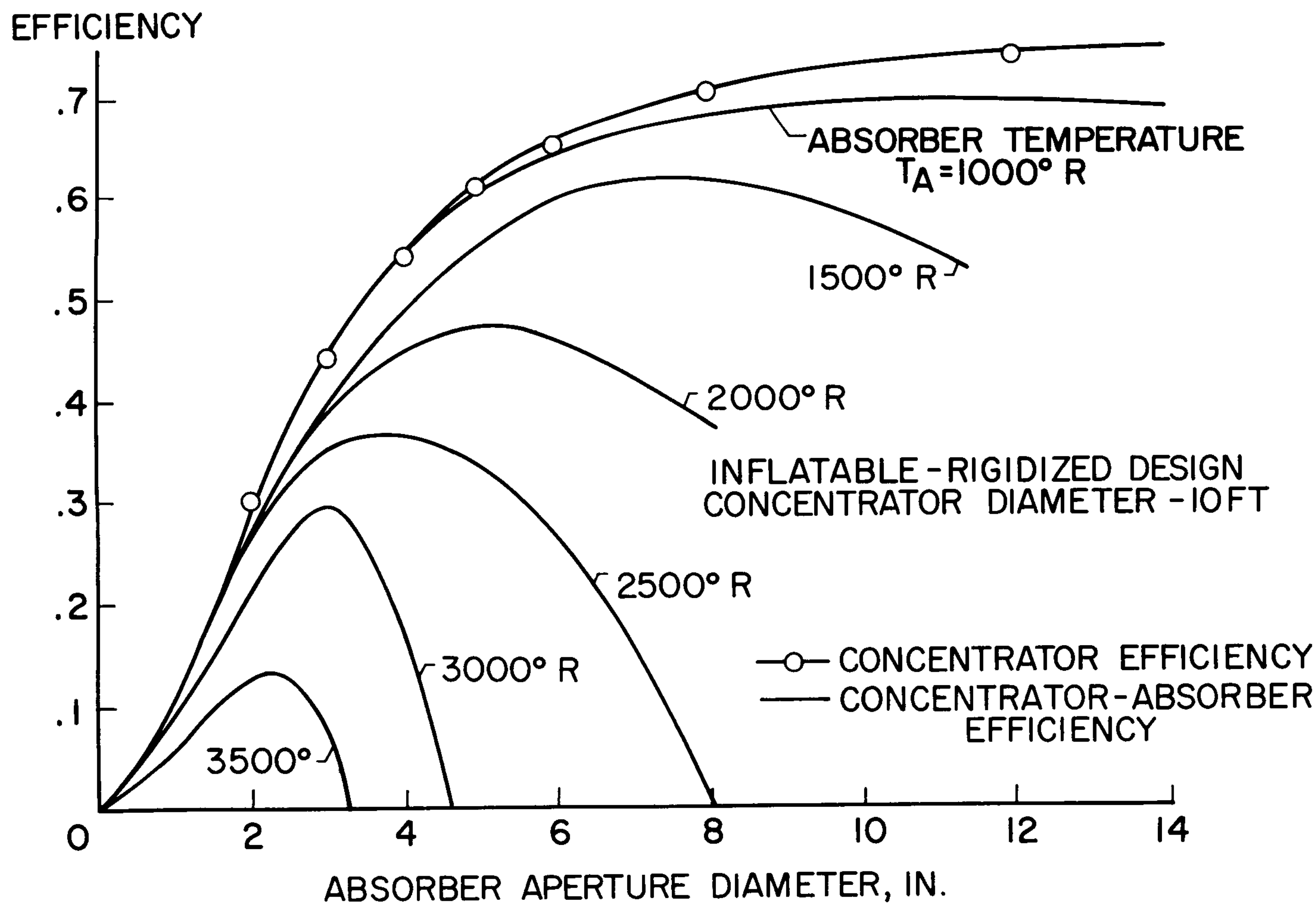

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Figure 2.- Concentrator performance.

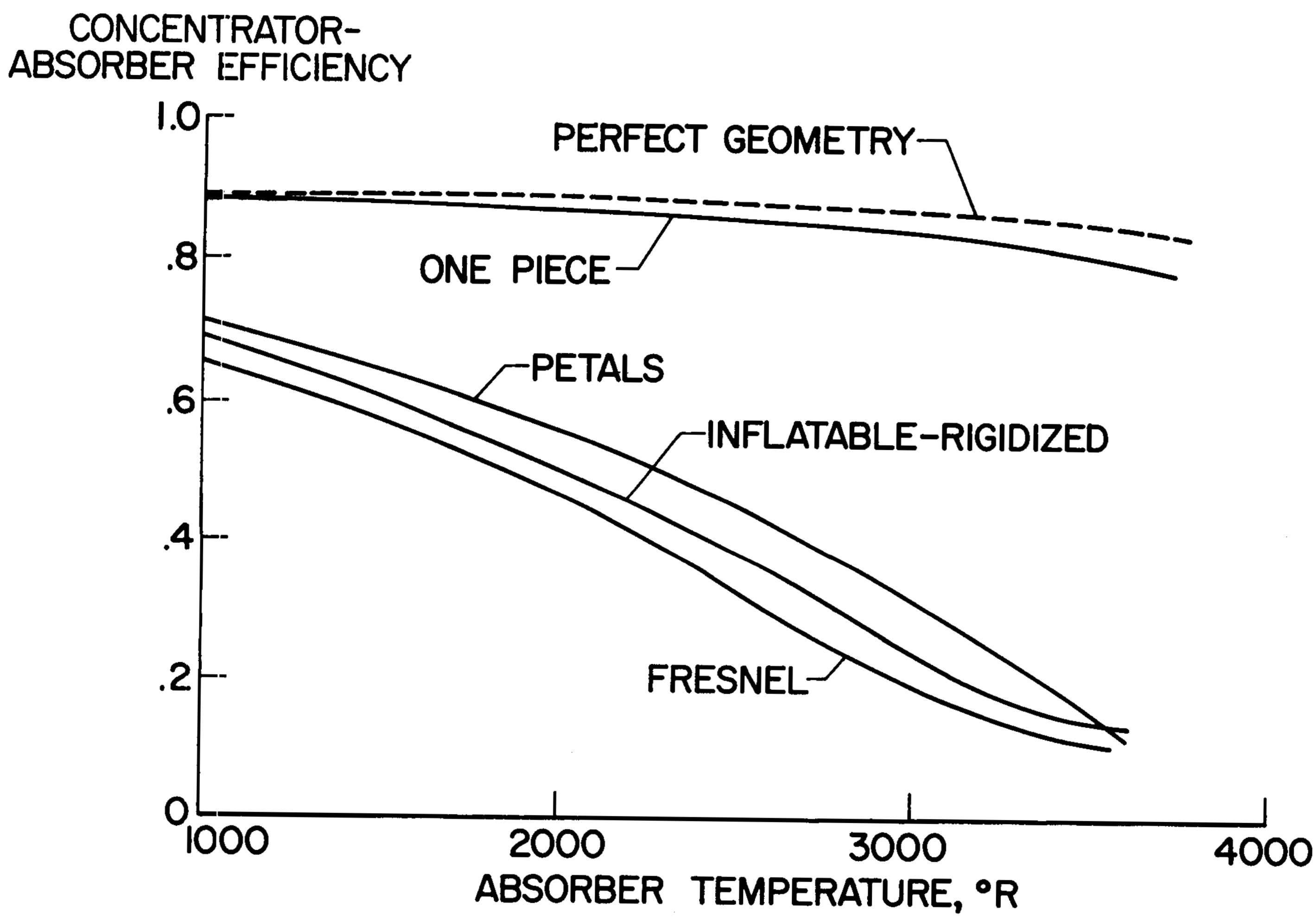

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Figure 3.- Concentrator-absorber efficiency.

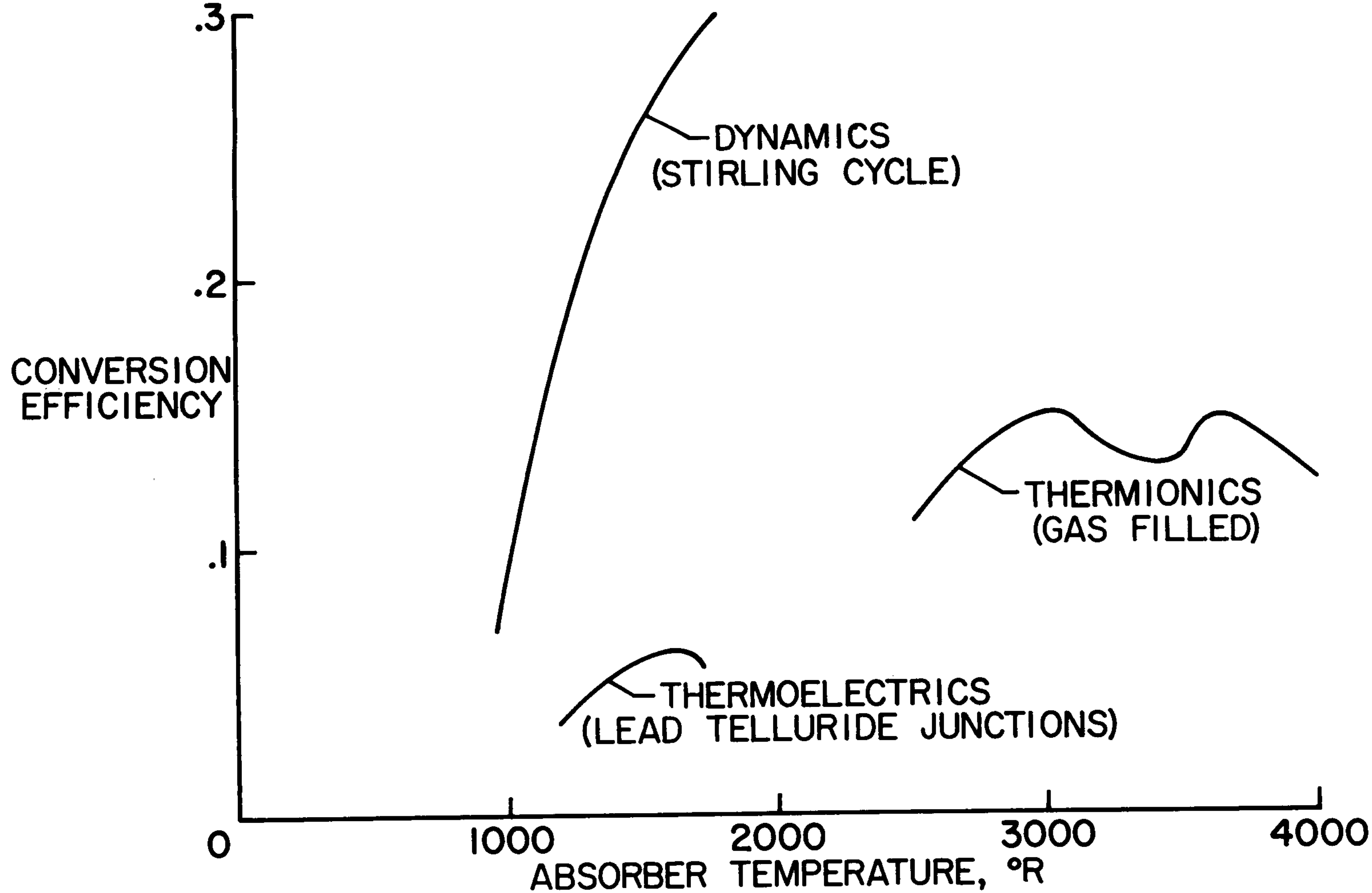

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Figure 4.- Convertor performance.

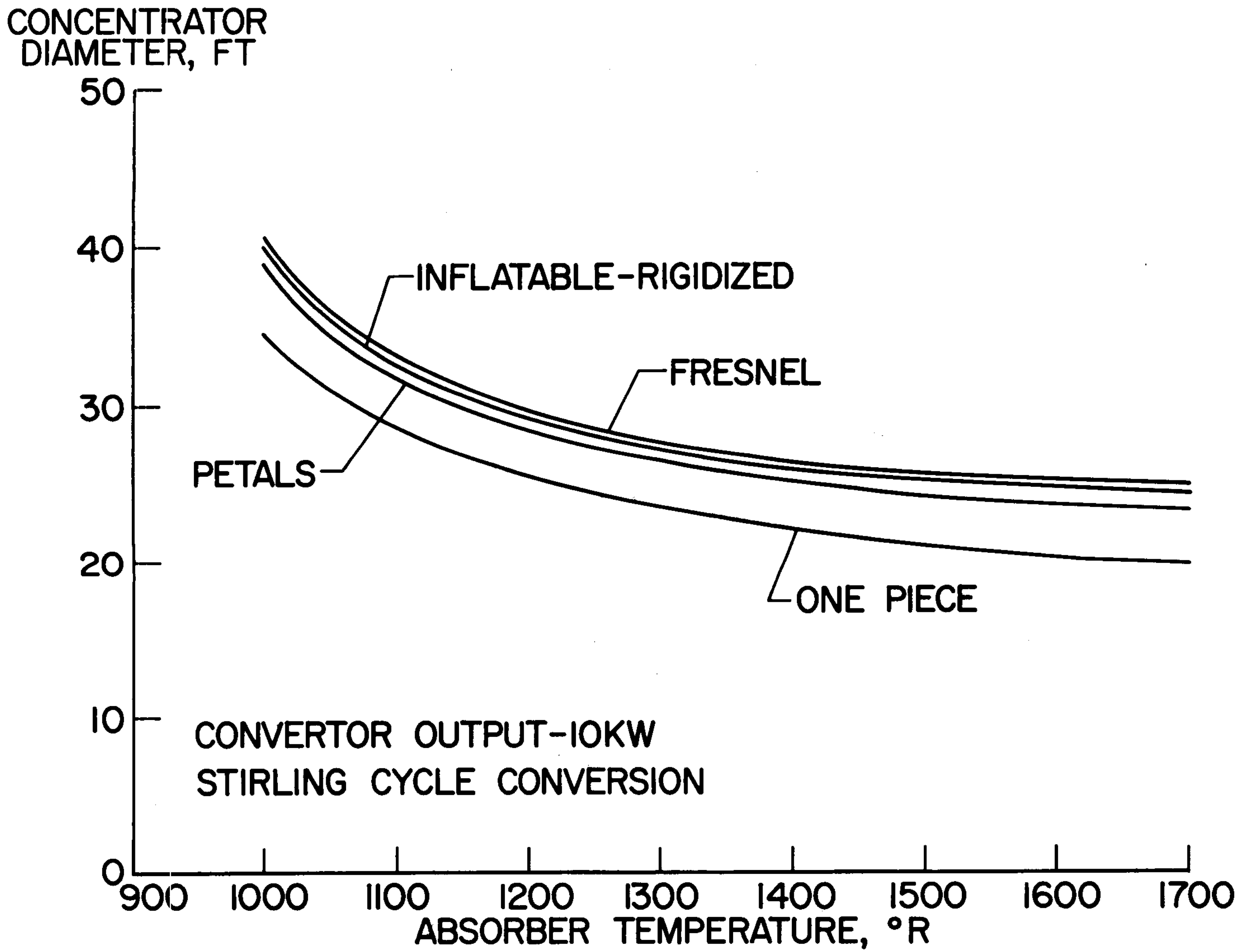

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Figure 5.- Concentrator size - dynamic conversion, constant output.

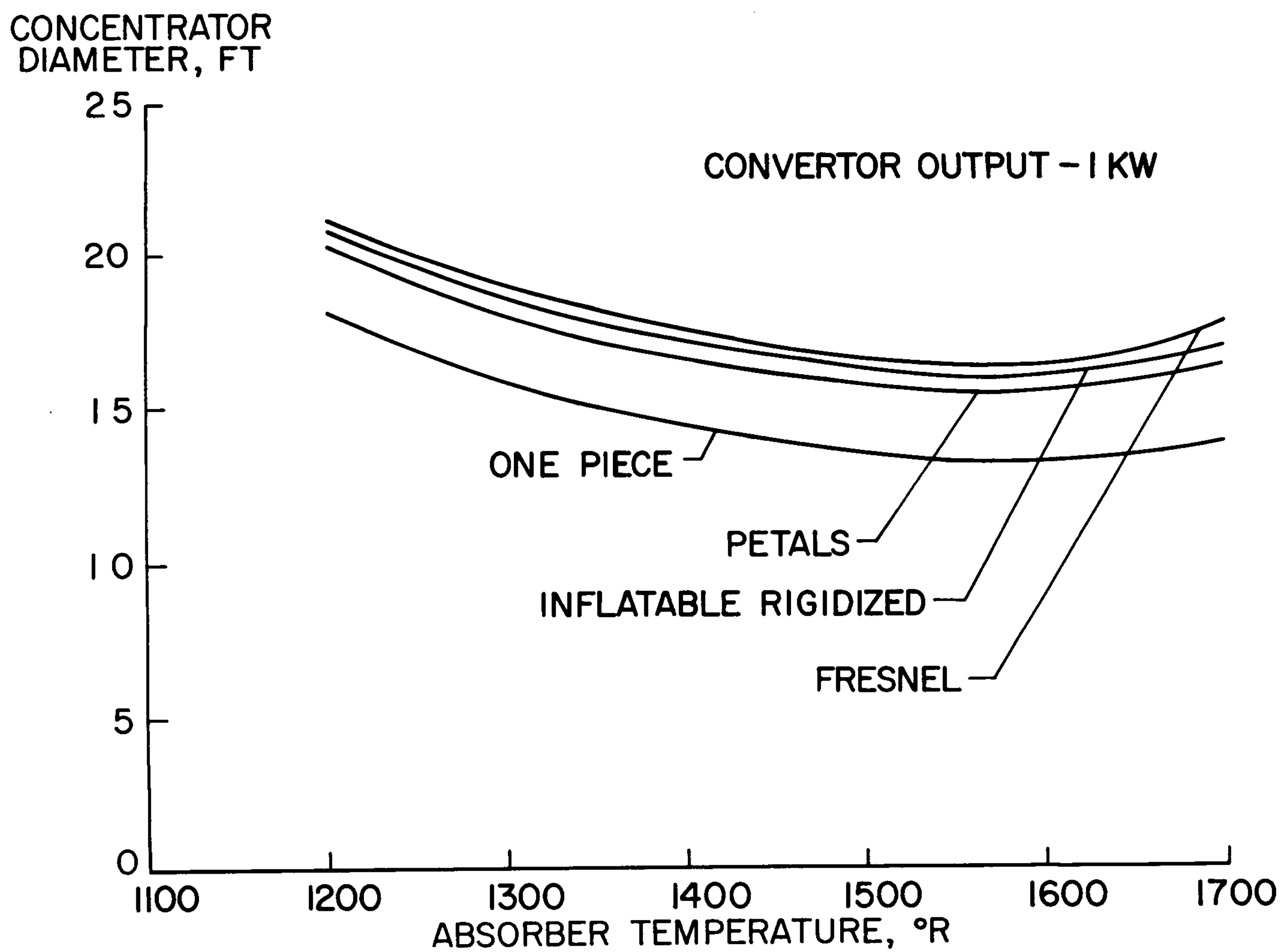

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Figure 6.- Concentrator size - thermoelectric conversion, constant output.

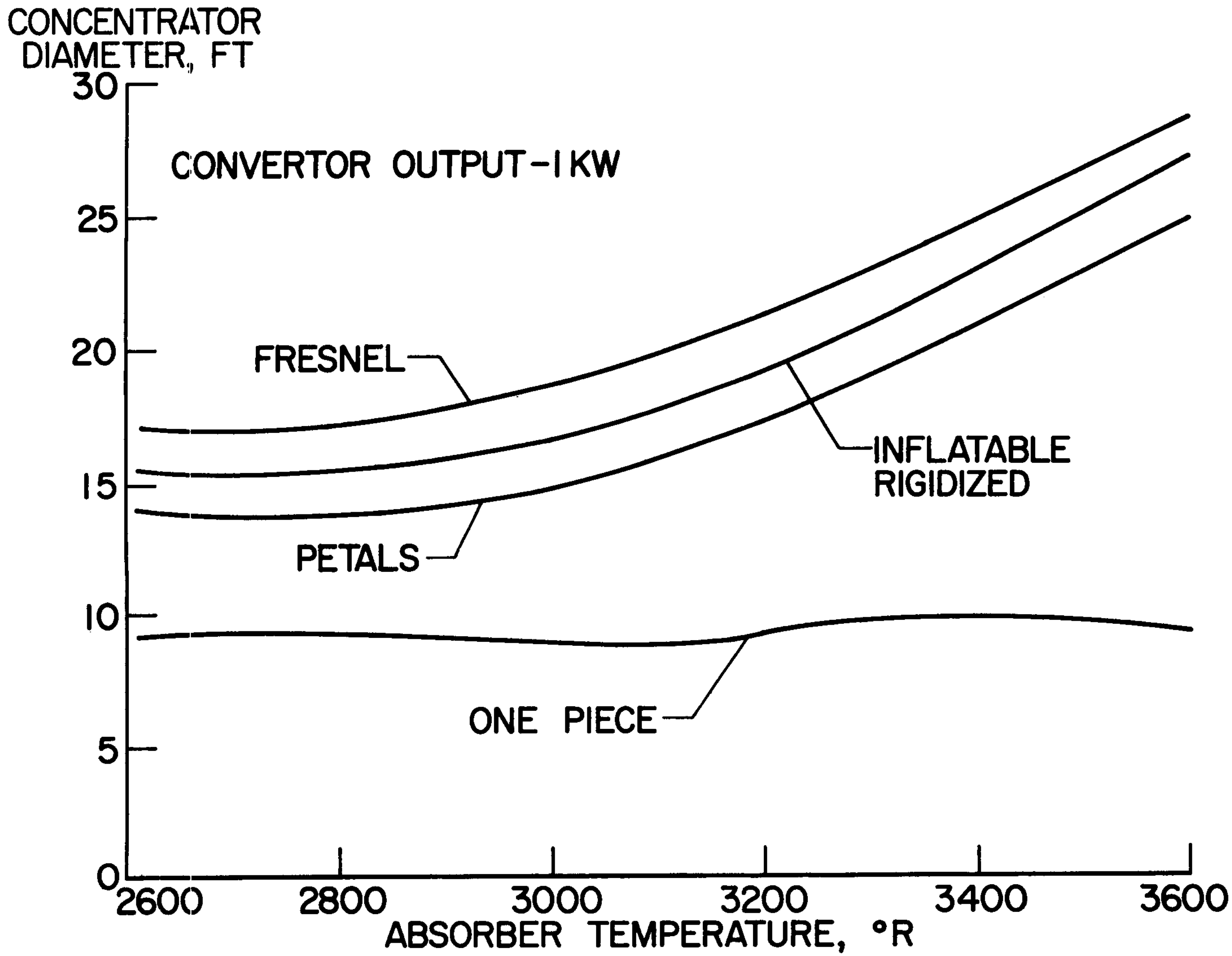

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Figure 7.- Concentrator size - thermionic conversion, constant output.

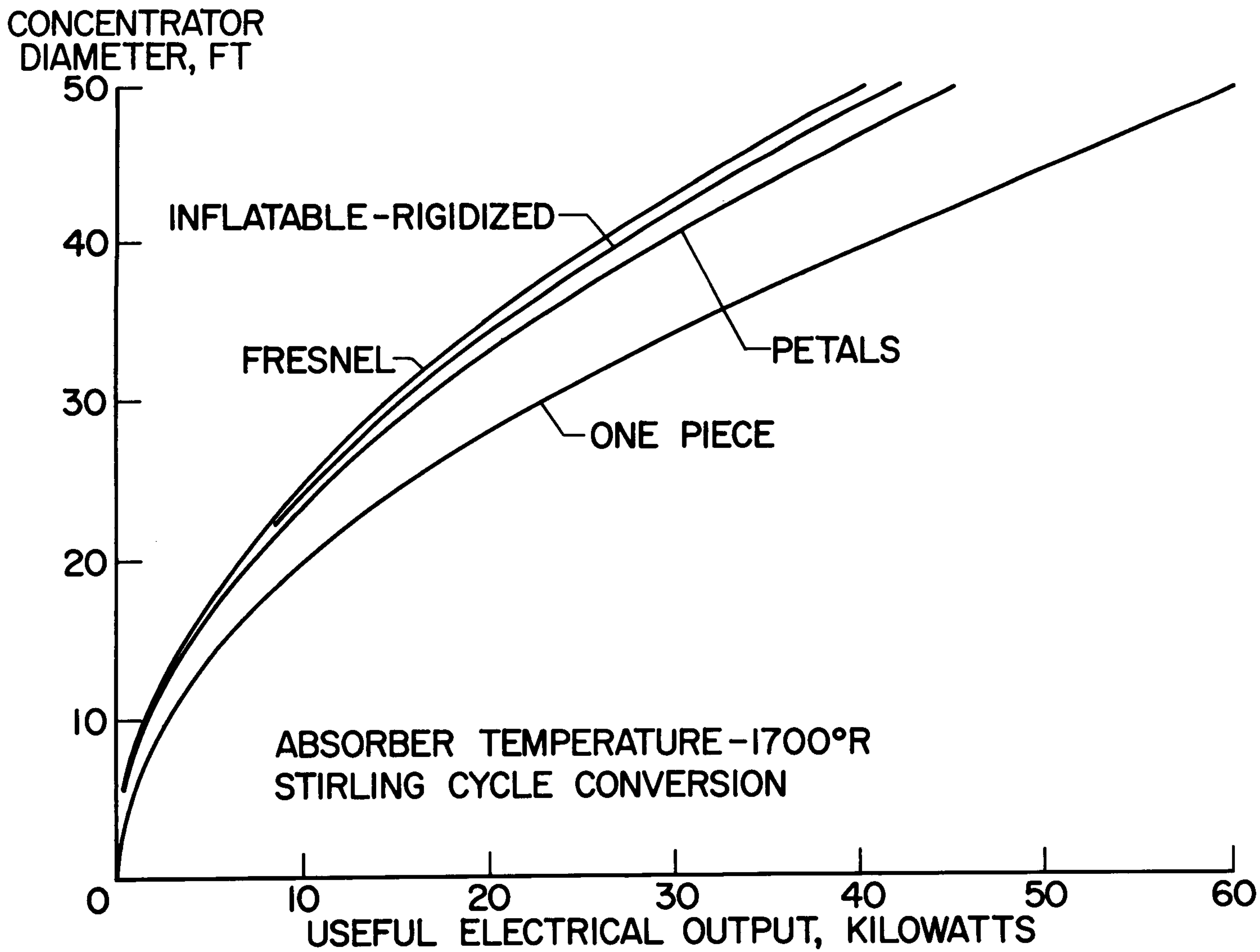

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Figure 8.- Concentrator size - dynamic conversion, constant absorber temperature.

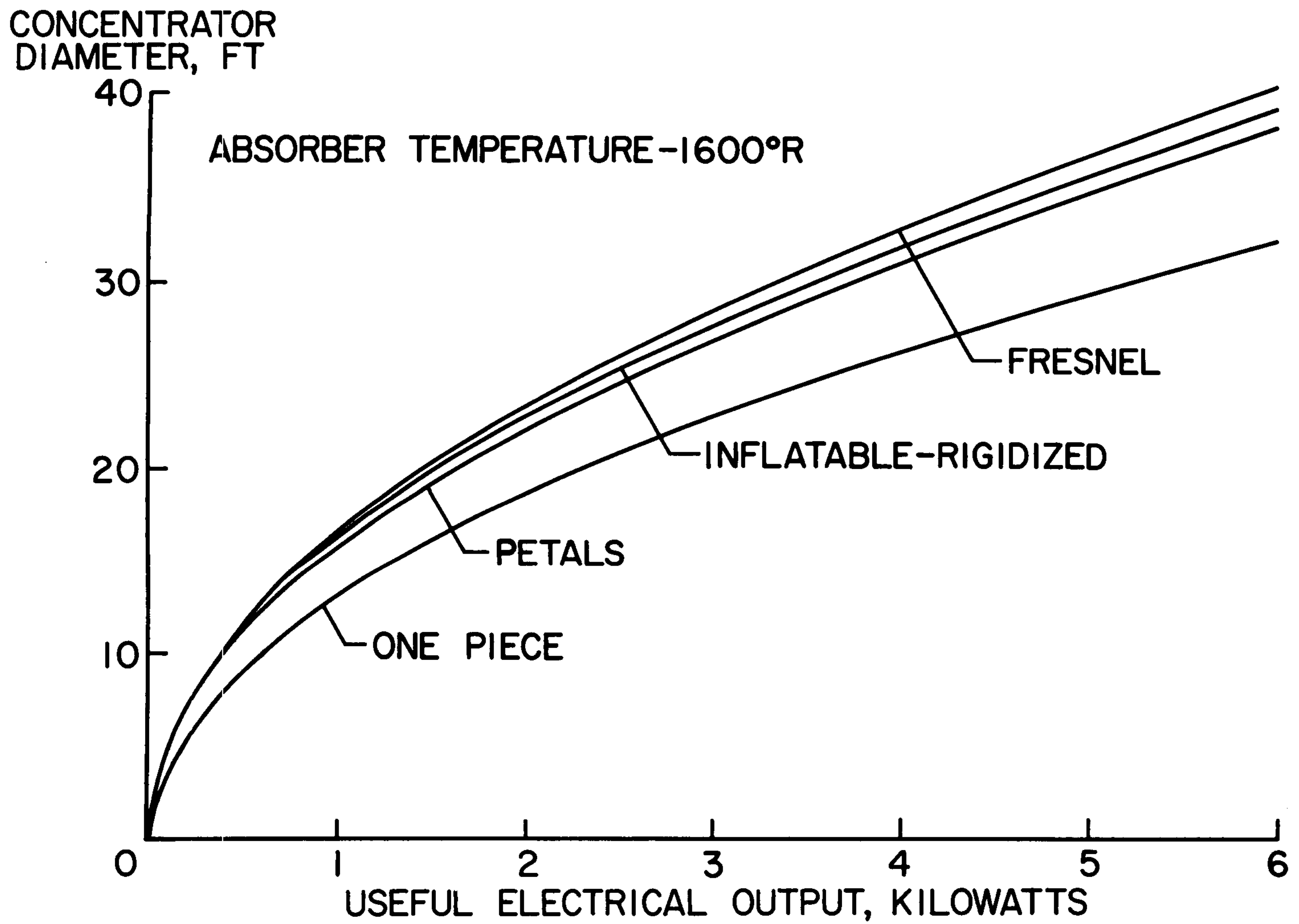

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Figure 9.- Concentrator size - thermoelectric conversion, constant absorber temperature.

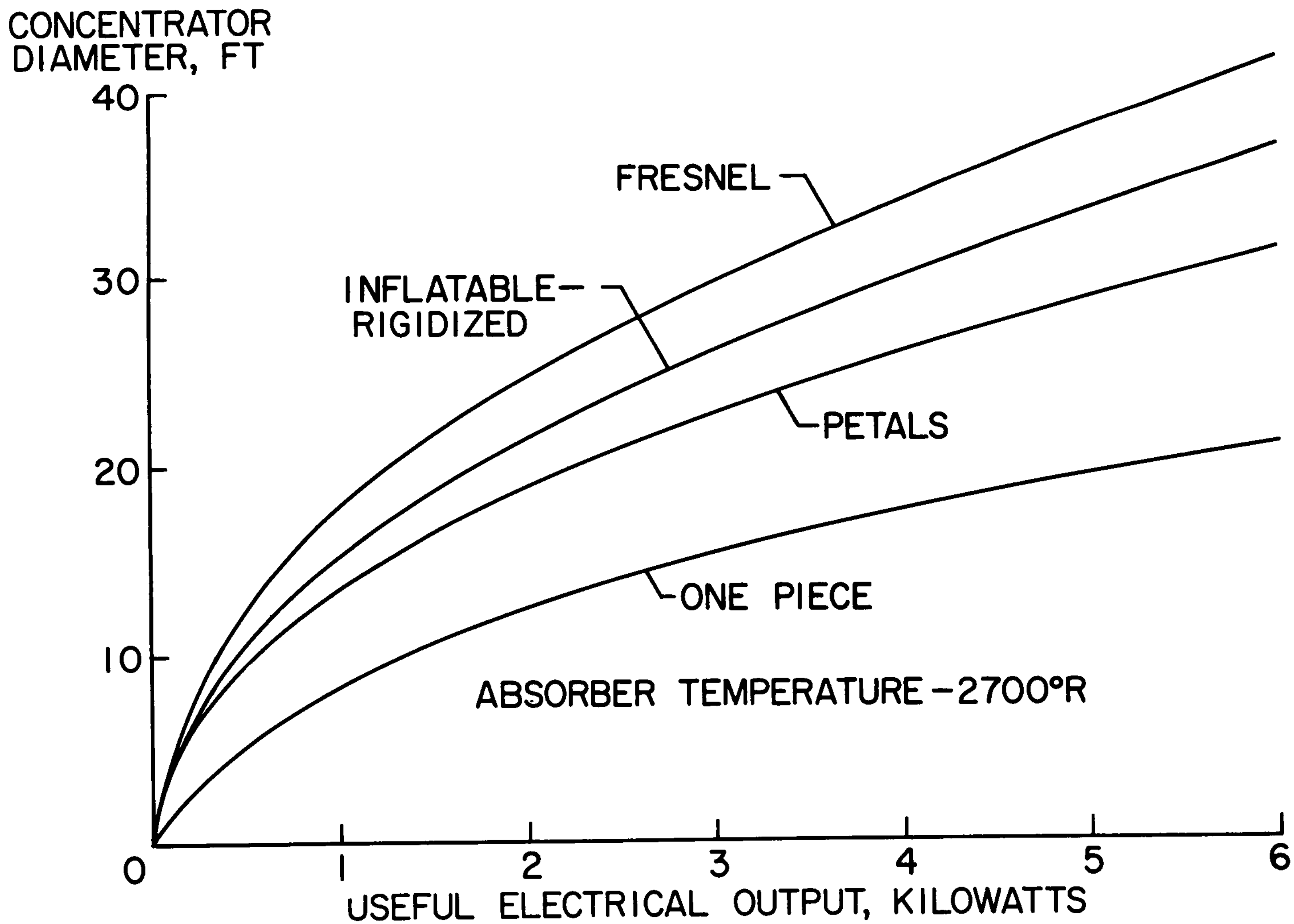

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Figure 10.- Concentrator size - thermionic conversion, constant absorber temperature.

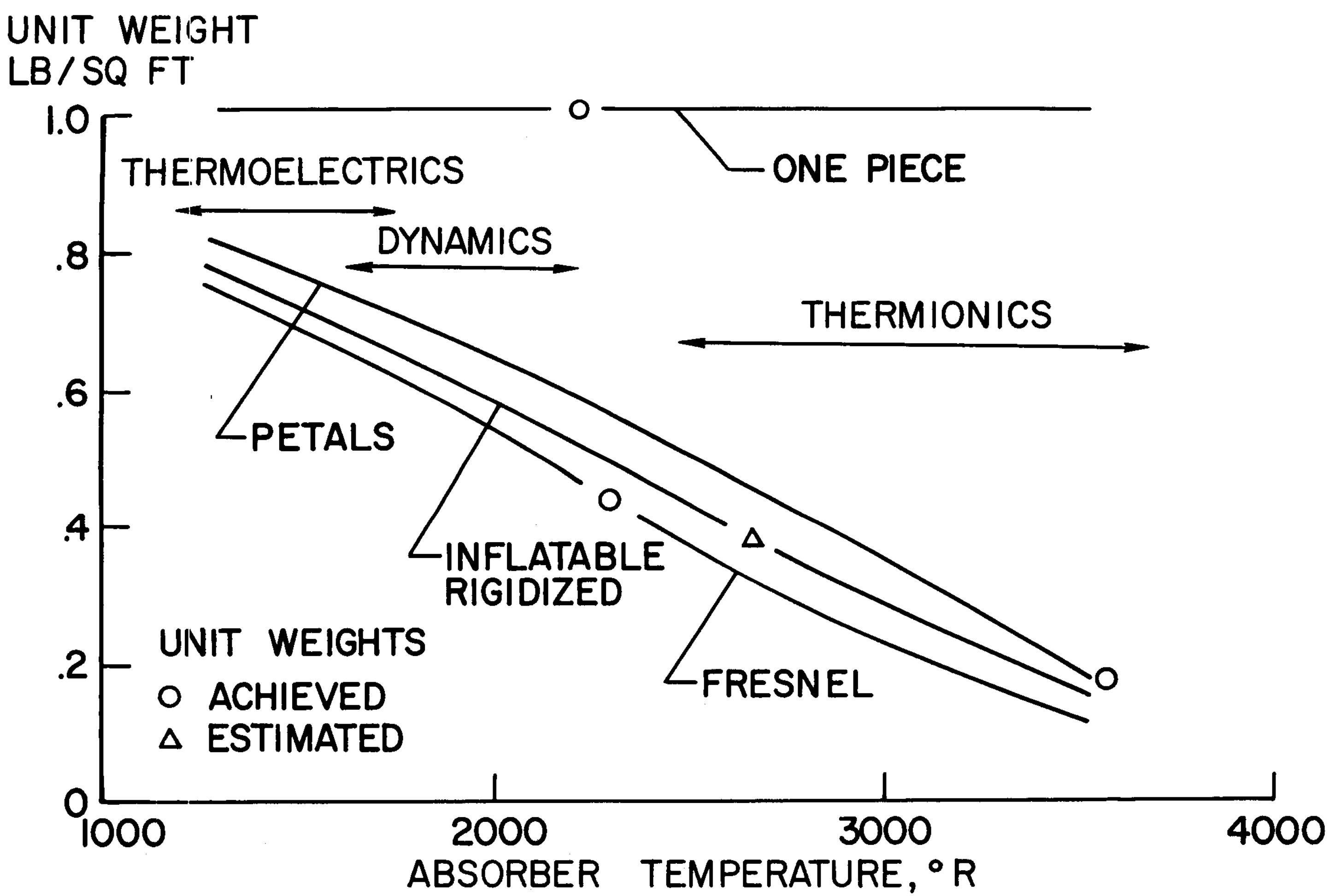

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Figure 11.- Required concentrator unit weight.

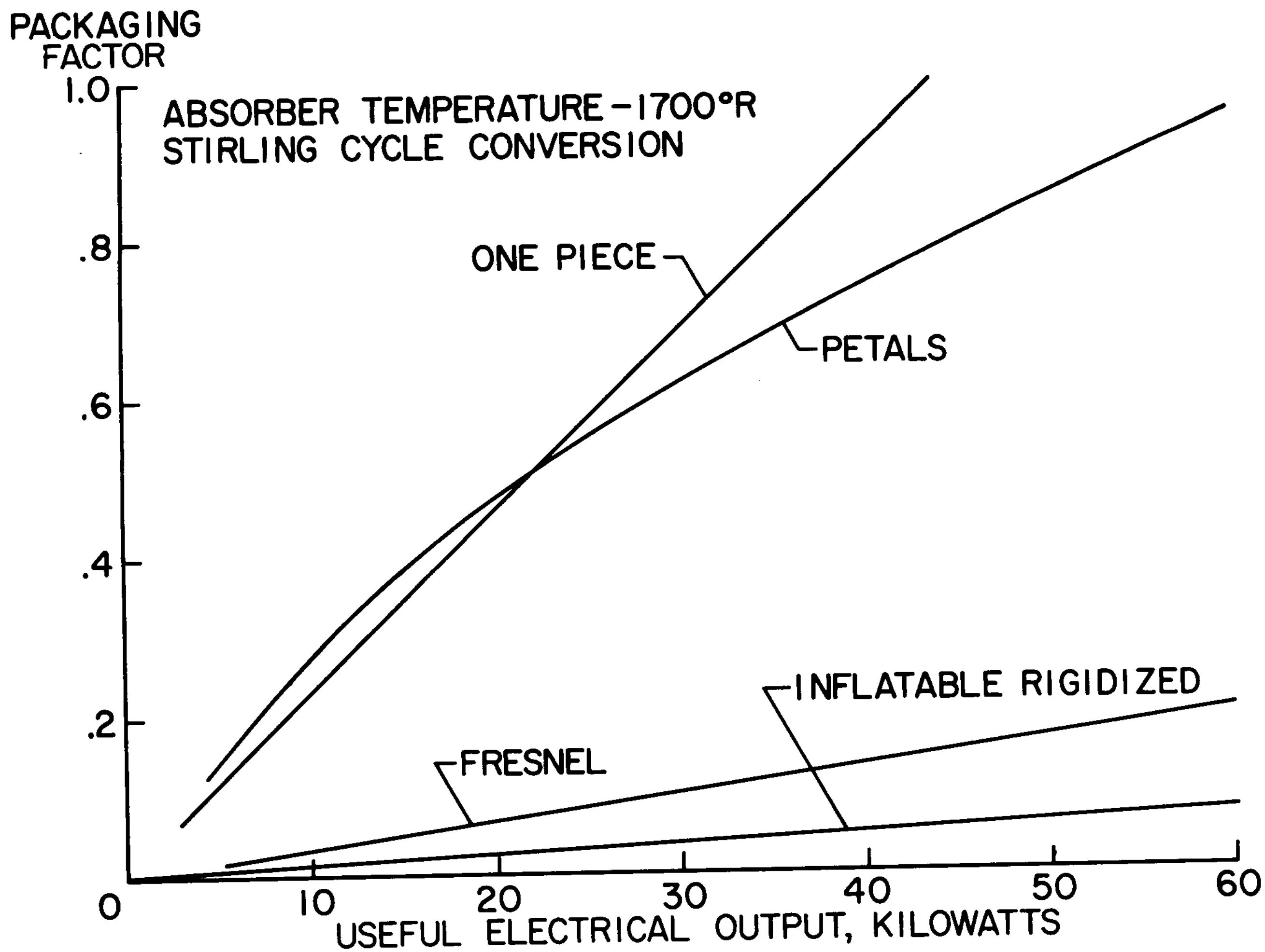

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Figure 12.- Concentrator packaging characteristics - dynamic conversion.

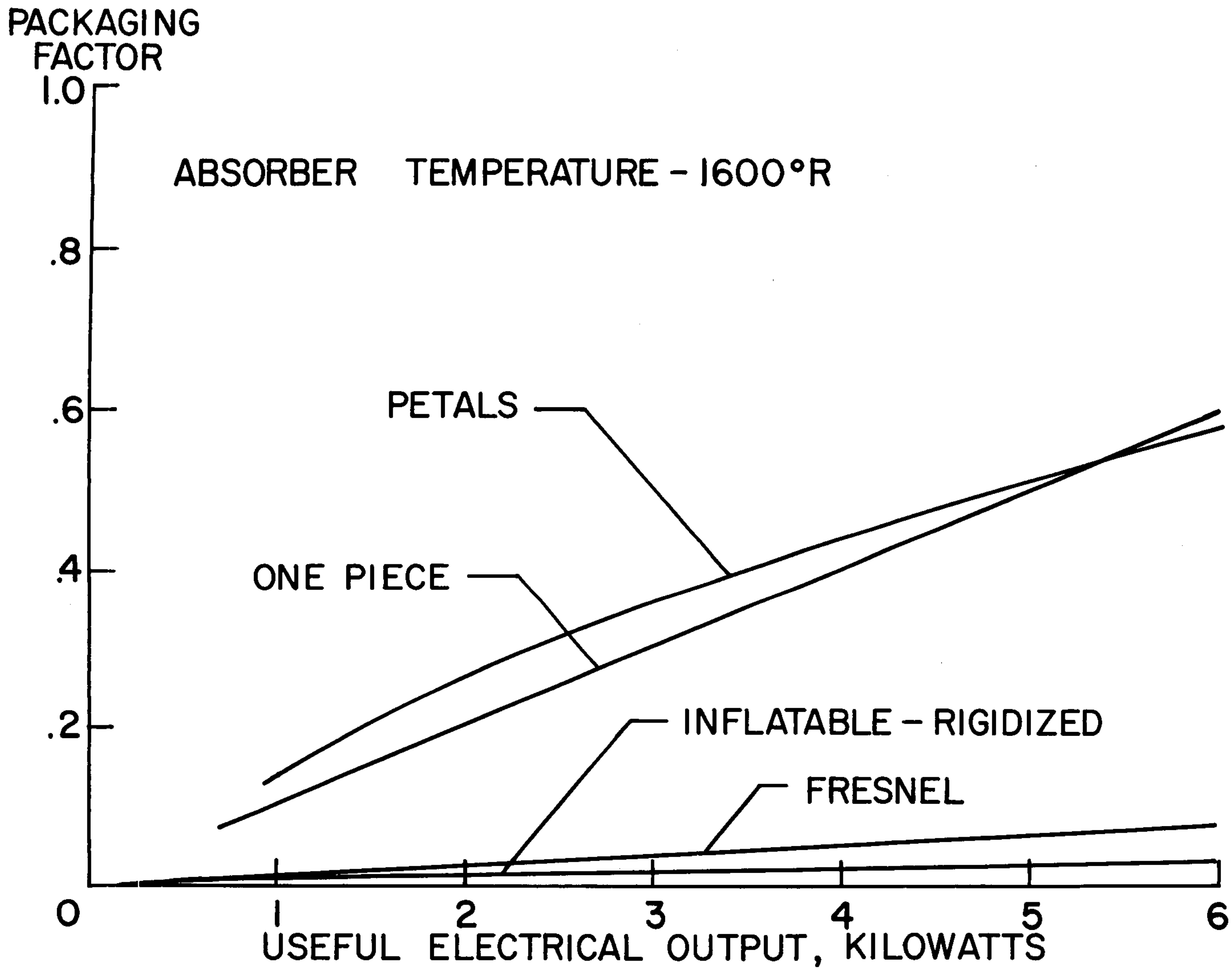

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Figure 13.- Concentrator packaging characteristics - thermoelectrics.

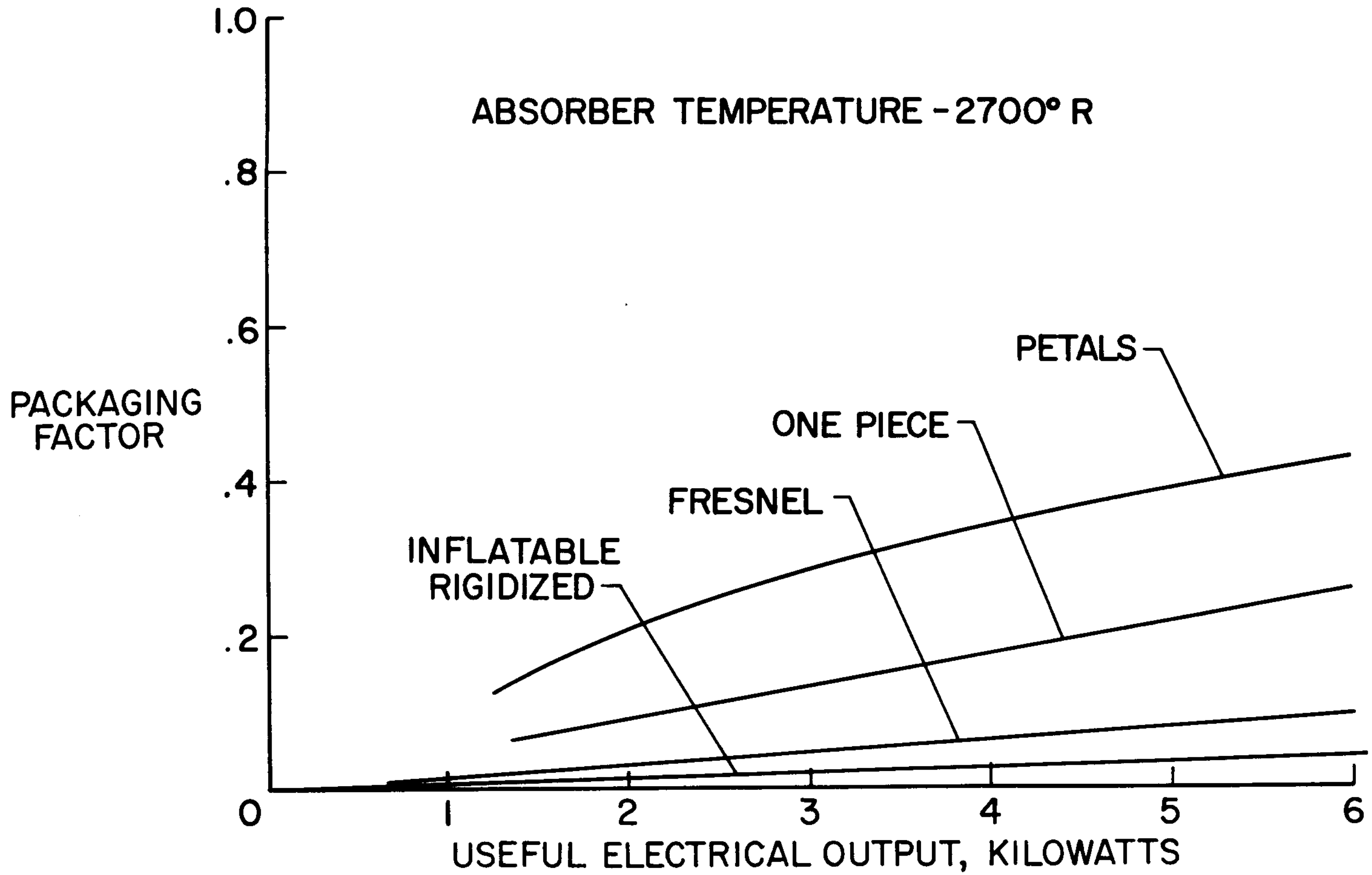

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Figure 14.- Concentrator packaging characteristics - thermionics.

NASA-Langley, 1964