NASA Technical Memorandum 102139

A Program for Advancing the Technology of Space Concentrators

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Prepared for the
24th Intersociety Energy Conversion Engineering Conference
sponsored by the IEEE, AIAA, ANS, ASME, SAE, ACS, and AIChE
Washington, D.C., August 6-11, 1989

NASA

(NASA-TM-102139) A PROGRAM FOR ADVANCING THE TECHNOLOGY OF SPACE CONCENTRATORS (NASA. Lewis Research Center) 8 p CSCL 10A

N89-29484

Unclas
G3/20 0232686

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E-4900

ABSTRACT

In 1985, the NASA Lewis Research Center formed the Advanced Solar Dynamics Power Systems Project Group for the purpose of advancing the technology of Solar Dynamic Power Systems for space applications beyond 2000. Since then, technology development activities have been initiated for the major components and subsystems such as the concentrator, heat receiver and engine, and radiator.

In this paper is described a program for developing long lived (10 years or more), lighter weight, and more reflective space solar concentrators than is presently possible. The program is progressing along two parallel paths: one is concentrator concept development and the other is the resolution of those critical technology issues that will lead to durable, highly specular, and lightweight reflector elements. Outlined in this paper are the specific objectives, long term goals, approach, planned accomplishments for the future, and the present status of the various program elements.

BACKGROUND

Interest in solar dynamic power systems (SDPS) for use in space has existed for over 25 years. NASA sponsored several programs in the 1960's and the early 1970's to develop the enabling technology for the solar concentrator, heat receiver and power conditioning unit (PCU). Much progress was made with the concentrators, Ref. 1: Several experimental concentrators of various sizes - 1.5, 3.0, 9.7, and 12.2 meters diameter were fabricated and thoroughly ground tested, but were not flight-qualified. The 1.5 meter concentrator was a one piece unit, whereas the others were an assembly of segmented hinged reflector panels. Autodeployability was demonstrated with the segmented concentrators. Each also withstood the shake tests that simulated launch loads. The surface contour of the smallest concentrator was accurate to less than a 1-sigma value of 1.0 milliradian slope error, and weighed 2.7 kg/m^2. The surface contours of the larger segmented concentrators were not as accurate: the slope errors ranged up to a 3-sigma value of 12 milliradians; and the weights were 1.27 kg/m^2. Although much progress was being made, the development was halted because of a shift in the NASA Space Program priorities. It should be noted here that these concentrators concepts did fly as antennas, one on the Pioneer spacecraft.

Interest in Solar Dynamics Power Systems (SDPS) technology was renewed when SDPS's were assigned a significant role as major power scource on the Space Station. The Space Station's SDPS's are being designed using today's proven technology to the extent that such relevant technology exists. In the meantime, NASA recognized that significant improvements in SDPS technology would be needed for future space applications. To meet these technology needs for the future, a new project office, the Advanced Solar Dynamics Project (ASD), was established. Its mission is to make significant advances in the technology of the major components, advances that will result in major reductions in weight and increased component and system efficiencies. The purpose of this paper is to review the Advanced Space Solar Concentrator Program.

PROGRAM DESCRIPTION AND STATUS

The Advanced Solar Concentrator Program began in 1986. It quickly became clear that the development of light weight, long-lived, efficient, and auto-deployable concentrators depends on the development of:

(1) lightweight concentrator concepts which are packageable into small volumes and are automatically deployable on orbit.
(2) durable, dimensionally stable reflectors (and refractive panels). (Herein, a reflector includes the substrate, the reflective layer, all the other thin protective layers, thermal coatings, and

adhesives that make up the reflector element.)

(3) a very smooth, highly reflective surface.

Concentrator configurations are in part dictated by their spatial and functional relationship to the spacecraft to which they are attached. It is not clear at this time whether they will be on-axis or offset or both; it will depend on the application. On-axis concentrators have a simpler configuration than the offset type because they are axisymmetric. The technical problems are numerous, difficult, and common to both types of concentrators. For these reasons, and because this Program is not driven by any specific mission requirements, the technology development efforts are primarily devoted on the on-axis type concentrators and only on those that will operate in the LEO environment. But weight is less important in LEO.

To be durable, the materials that comprise the reflector elements must be, first and foremost, immune to the LEO environment (i.e. atomic oxygen, ultraviolet radiation, space debris, micrometeorites, protons and electrons) in which they operate. Equally important, reflectors must withstand the effects of thermal cycling caused by the day/night cycles. These can cause a variety of structural and optical distortions and fatigue failures because the various materials that comprise a reflector element have different thermal expansion coefficients.

PROGRAM OBJECTIVES

The general objective of this program is to develop the enabling technology for parabolic concentrators that will power advanced solar dynamic power systems in low earth orbit (LEO).

The specific objectives are to:

- o Identify at least one on-axis lightweight concentrator concept that will be packageable into a small volume for launch and automatically deployable on orbit.

- o Identify the materials and construction techniques that will enable the concentrators to operate in LEO environment for more than 10 years.

- o Identify techniques and materials for producing reflecting surfaces with high reflectance and specularity.

- o Build and ground test a reduced scale (2-meter diameter) concentrator of the most promising concept, to demonstrate some of the technology.

APPROACH

The Program objectives will be met with a combination of in-house and contractual efforts as shown below.

(1) Concentrator Concepts Identification and Selection; four contractual efforts, and cooperative effort between Cleveland State University and NASA Lewis Research Center.

(2) Supporting Research and Technology; reflector concepts development; materials identification and selection for:
- reflective surfaces
- leveling layers
- thermal, reflective, and protective coatings

CONCENTRATOR CONCEPTS IDENTIFICATION AND SELECTION

The objectives of this Program element have been to:
- o Develop a conceptual design of in innovative concentrator concept.
- o Identify the critical technical barriers to successful development.
- o Remove the barriers.

To meet these objectives this Program element was divided into two parallel efforts:
- o Industry contracted design studies.
- o A cooperative agreement with the Cleveland State University.

Each contractor was given the following set of requirements and goals that his proposed concept was to meet:
- o Concentration ratio -
  - Minimum - 2000
  - Goal - 5000
- o Concentrator Efficiency:
  - Minimum - 90%
  - Goal - 95%
- o Maximum EOL degradation: 10%
- o Specific Weight:
  - Maximum: 1.5 kg/m^2
  - Goal: 1.0 kg/m^2
- o Operational Life: 10 yr in LEO
- o Deployment: Automatic without EVA
- o Size Range: 1 to 100 kWe @ a system efficiency of 30%
- o Survivability: terrestrial, launch, and LEO environments

One contract was awarded in 1985, and three contracts were awarded in 1988 to the following companies to develop a conceptual design of innovative concepts as listed below.

- o Entech Inc., Dallas, Texas - Awarded in 1985; completed in 1988. An assembly of thin refractive panels on a dished-shaped support frame.
- o Acurex Inc., Mountain View, CA. - 24 months effort. An assembly of rigid pie shaped, parabolically contoured, reflector panels.
- o Harris Corp., Melbourne, FLA. - 12 month effort. Splined radial composite panel concept (an assembly of many thin, slender, flexible reflector strips on an umbrella shaped support system of ribs and cords.
- o Science Applications International Corp., San Diego, CA. -12 month effort. A continuous thin stainless steel membrane type concentrator concept which is rolled up into a tube for the launch phase and unrolled by inflating a toroidal tube.

The conceptual designs of all four contractors are complete. The Entech Corporation study, which ended in July 1988, was aimed at developing a conceptual design of refractive type concentrator. This type of concentrator has two important advantages over the reflective type:

(1) The surface contour does not have to be nearly as accurately maintained.
(2) The pointing accuracy error margin is much broader.

These two advantages may greatly simplify the fabrication of a concentrator if a suitable material can be developed for fabricating the refractive panels. Entech found in the course of the study that the main obstacle to the development of the refractive type concentrator has been, and still is, the lack of a Fresnel lens material that will resist degradation by atomic oxygen (AO) and ultraviolet radiation (UV) in low earth orbit (LEO). Acrylic lens, which have been used for many years as terrestrial trough type concentrators, were found to be very susceptible to damage by AO and UV, and no coatings were found that could protect them. In addition, there did not appear to be any more durable material substitute available that was highly transparent and light weight. Glass in the form of sol-gel was considered to be a possible alternative to acrylic. Small samples of lens were successfully made, but the development was not pursued because of the lack of funding.

The results of the remaining three contracts have not yet been formally been submitted to NASA and evaluated. The plan at present is to evaluate the three concepts and select one of the three for fabrication and ground test of a reduced scale unit, if funding permits.
The objective of the NASA/CSU cooperative agreement is to carry forward the development of the Sunflower concept because it is the most promising concept with high near term potential for success. The plan is to demonstrate, as early as possible, the technology of a packageable and auto-deployable concentrator with a high concentration ratio. The approach is to design, build, and ground test a 2-meter diameter unit patterned after the Sunflower concept reported in Reference 1 and illustrated in Figure 1. The intent is to utilize as much of the technology of that concept as is possible. For example, as was done on the Sunflower concentrator, each radial panel will be an aluminized all-aluminum honeycomb sandwich. The preliminary design is completed. The final design and fabrication are scheduled to begin, respectively, in spring of 1989 and early 1990. The radial panels are doubly curved to a parabolic shape.

SUPPORTING RESEARCH AND TECHNOLOGY

This Program element addresses the critical technology issues that must be resolved if concentrators are to achieve the stated goals. The foremost issues are concerned with the development reflectors that are lightweight, highly reflective, very specular, and immune to the effects of the harsh LEO environment.

Weight is a prime design driver for all spacecraft components and subsystems.

Our approach to weight reduction is to reduce the weight of the reflecting elements and to eliminate, or minimize, the structure used to support the reflecting elements. Among the candidates concepts for lightweight reflector substrates are:
- o honeycomb sandwich panels made of lightweight materials.
- o thin metal membranes.
- o thin rigid and flexible composite solid panels.
- o very thin glass mirrors bonded onto a rigid substrate.
- o rigid foam substrate

High specular reflection is achieved by depositing a highly reflective material on a very smooth substrate surface. Silver and aluminum are the prime candidate reflecting materials because they are the only materials that have a high reflectivity over the entire solar spectrum. While the total reflectance of silver is slightly higher than aluminum, silver, on the other hand, is much more susceptible to damage by AO. In this program, aluminum is the favored reflective coating for the near term because aluminum is total immune to AO and is easier to work with than silver.

The ability to produce a very smooth surface is a critical problem whose solution is not straightforward. Glass has long been used for making terrestrial mirrors. It is produced with a very smooth flat surface and is a strong enough to support itself. But, glass as a substrate for space reflectors is too heavy except as very thin sheets of the order of 0.003 to 0.010 inches thick (called microsheet glass in this report). Hence, the reason why microsheet glass is a candidate smooth surface. Many metals, including aluminum, can be made with very smooth surface by various techniques, but when smooth flat thin sheets, 0.003 to 0.010 inches thick, are stretched into a parabolic or spherical shape, the smoothness is usually degraded to an unacceptable roughness. The problem then becomes one of how to improve the smoothness of the dished surface. One method under investigation is that of finding and applying a thin coating of a suitable material that will levelize the roughened surface. A search for just such a levelizing material is a major program activity.

Earlier in this report the major LEO environmental hazards were listed, the primary one being atomic oxygen. With a few exceptions, metals are immune to AO and most organic substances, such as adhesives and composite structural materials, are heavily attacked. To achieve low weights with metallic substrates, they must be thin. Composites, which are lighter, must be protected with impervious coatings. The challenge, therefore, is to develop lightweight metallic substrates and to find materials to protect those made of composites. The goals for reflectors are:

- o Specific weight: 1.0 kg/m^2
- o Total solar relectance: 90% or greater
- o Surface specularity: less than 1 milliradian
- o Service life: >10 years

To achieve these goals, the major thrust of the work is to:

- o Identify promising lightweight reflector concepts.
- o Identify, select, and evaluate candidate materials for:
  - substrates
  - adhesives for bonding together various materials
    - surface smoothing layers
    - protective and thermal control overcoats
- o Conduct materials and reflector survivability tests:
  - atomic oxygen
  - ultraviolet light
  - thermal cycling
  - effects on optical quality
  - surface waviness and roughness

These technology issues are being attacked along two parallel paths: contracted and in-house efforts.

Reflector Developments - Contracted Efforts

Two contracts were awarded in 1988:

- o Perkin Elmer Optical Group to develop a micro-sheet glass mirror bonded to a honeycomb sandwich.
- o Sandia National Laboratory to develop sol-gel as a levelizing layer for thin stainless steel foil. Sol-gel is a liquid form of glass that must be cured at elevated temperatures.

Perkin Elmer was successful in developing a method for fabricating samples of micro-sheet mirror bonded on honeycomb sandwich (HCS) panels up to 12 inches diameter in a first phase study. A set of HCS panels were made of Kevlar. Subsequent thermal/stress analyses showed that Kevlar is not a suitable material and that the HCS materials have to be chosen such that interface stresses are low enough to avoid fatigue damage due to thermal cycling imposed by the day/night cycles. At present, Perkin Elmer is evaluating a HCS that is a combination of glass fiber/composite face sheets and aluminum HC core.

Sandia National Laboratories has been developing sol-gel glass as a coating for smoothing rough surfaces prior to depositing the reflecting layer of terrestrial concentrators. In support of both the DOE and NASA Lewis, Sandia has produced smoothed silvered surfaces on small samples of as-purchased thin stainless steel. The results thus far have shown that applying sol-gel as a leveling layer increased the solar averaged specularity from 83% to 93%. At present, the sol-gel smoothed and overcoated silvered samples are being subjected to AO tests to determine their susceptibility to AO attack.

A number of reflector substrate concepts were also being evaluated by the contractors mentioned above that are developing advanced concentrator concepts:

- o SAIC: a thin stainless steel membrane reflector with a fiber glass epoxy backing layer to give it protection against crinkling when it is rolled up into a tube like configuration for launching.

- o Harris Corp.: thin flexible reflector strips made of a multilayer carbon fiber composite.

- o Acurex Corp.: thin rigid reflector panels made of a multilayer composite material.

Refractive Material Development

As was stated earlier, the major barrier to development of refractive lens is the lack of lightweight materials that can withstand the LEC environment, are very transparent to the sunlight, and are strong enough to hold their shape. At present there are no candidate materials for the near term. No further research is planned for the foreseeable future.

Reflector Developments - In-House Program

The major thrust of the in-house efforts are devoted to reflectors and related materials research. This research will include:

- o identifying candidate materials for reflector substrates, leveling coatings, adhesives, and fabrication techniques.
- o testing of materials and small samples of candidate reflectors for the effects of AO, UV, and thermal cycling.
- o experimenting with leveling and protective coatings.

A laboratory dedicated to conducting some of this research is being set up and equipped with the appropriate equipment. Support with AO, UV, thermal cycling, surface roughness measurements, and reflectance measurements is being provided by the NASA Electrophysics Branch.

Some of the activities now in progress are:

- o searching for methods for bonding microsheet glass to nonporous surfaces.
- o testing commercially available materials as leveling coats.
- o testing materials for their ability to resist AO attack. The Sandia sol-gel levelized and sol-gel overcoated samples are presently being tested in a plasma Asher.

Thermal And Stress Analyses - Cooperative Agreement

Thermal and stress analyses are essential tools in the identification, evaluation, and selection of various candidate reflector concepts. The Cleveland State University, since December 1986 under a cooperative agreement with NASA, has been developing and using computer programs to determine the time dependent temperatures and stresses that would be imposed onto various reflector concepts while operating in LEO. With these programs it has been possible to:

- o evaluate the effects and importance of a number of important reflector concept configurations, material properties, surface emissivities, and others.
- o estimate the properties required to reduce the amplitude of the temperature fluctuation, achieve low stresses and long fatigue life.

To date CSU has analyzed reflectors made using:

- o honeycomb sandwich panels made of different materials and with various thermal control coatings
- o mutilayer composite substrates with a thin (0.005inches) second surface glass mirror bonded to one side.

The following are some of the interesting and useful results generated by the analyses:

- o the average temperature of a reflector made with microsheet glass is strongly affected by whether the mirror is a first or a second surface mirror. A first surface mirror operates at a much higher temperature than does a second surface mirror.
- o the surfaces of honeycomb panels will develop dimples if the cure shrinkage of the adhesives that bond the face sheets to the core is high and if the filets at the face sheet/core interfaces are large. Clearly, to avoid dimpling of the reflective surface, the adhesive cure shrinkage and the adhesive filet must both be small as possible.
- o the reflector temperatures seldom reach steady values during the orbit cycle.

Future analyses will include calculations to determine the amount of thermal distortion the reflector panels will experience during a typical orbital cycle.

Small Business Innovative Research Contracts

SBIR contracts are making valuable contributions to the concentrator technology development program. For maximum effectiveness, the SBIR research activities are well integrated with those of the main program.

Two SBIR PHASE I contracts were awarded and completed:

- o Ultramet Inc., Pacoima, CA. (completed July 1987).
- o Solar Kinetics Inc., Dallas, Texas (completed July 1988).

Both companies have been awarded a Phase II contract, each for a 24 month period of performance.

Ultramet Inc. is developing a reflector concept with a substrate of lightweight, open cell foam that is made by vapor depositing boron carbide onto a carbon foam. Boron carbide was the material of choice because it can be deposited easily on the carbon foam using chemical vapor deposition, and it has demonstrated immunity to AO. In Phase I, Ultramet successfully produced small samples of a light weight reflector, thereby demonstrating that this concept has promise. A Phase II contract to continue the development was awarded in October, 1988.

Solar Kinetics Inc. (SKI) has completed a Phase I contractual effort to fabricate lightweight all-metal honeycomb sandwich reflector substrates. The advantage of an all-metal substrate is in its immunity to the orbital environment. All test panels were made of a single material: all aluminum and all titanium. The samples were not mirrorized. The surface slope error SKI achieved was 0.6 mrad, with aluminum, exceeding our program goal of 1.0 mrad at a weight of about 1.5 Kg/m^2. The SKI results are very promising, and in Phase II, SKI will design, build, and test one meter sized concentrator panels to demonstrate that the technology can be used to make large reflector panels.

CONCLUDING REMARKS

In this paper, the authors have briefly described a program to develop some of the critical technology needed for future advanced space solar concentrators. The major technical issues have been identified. The program elements and R&T activities required to resolve those issues have been formulated and initiated.

This program is a modest one; its scope is constrained by the available funding. It is, nonetheless, a significant one because it reflects a renewed long term interest in developing an alternate source of power for use in space.

The results to date have singled out some important issues that must be resolved if SDPS are, in the future, to become an important alternate to solar cells. These important issues are:

1. Future concentrators must be lightweight, packageable into a small volume for the launch phase, and automatically deployable on orbit without astronaut assistance. The development of concentrator concepts that will meet these requirements demands innovativeness of design.

2. Highly specular, efficient reflectors that can survive the LEO environment and the orbital day/night cycles for more than 10 years are second critical issue. The solution to the problem lies in the choice of the suitable LEO environmental resistant materials and the reflector substrate design.

References

1. "Sunflower Solar Collector," NASA Contractor Report CR-46, May 1964 by TRW Inc. under NASA Contract NAS 5-462

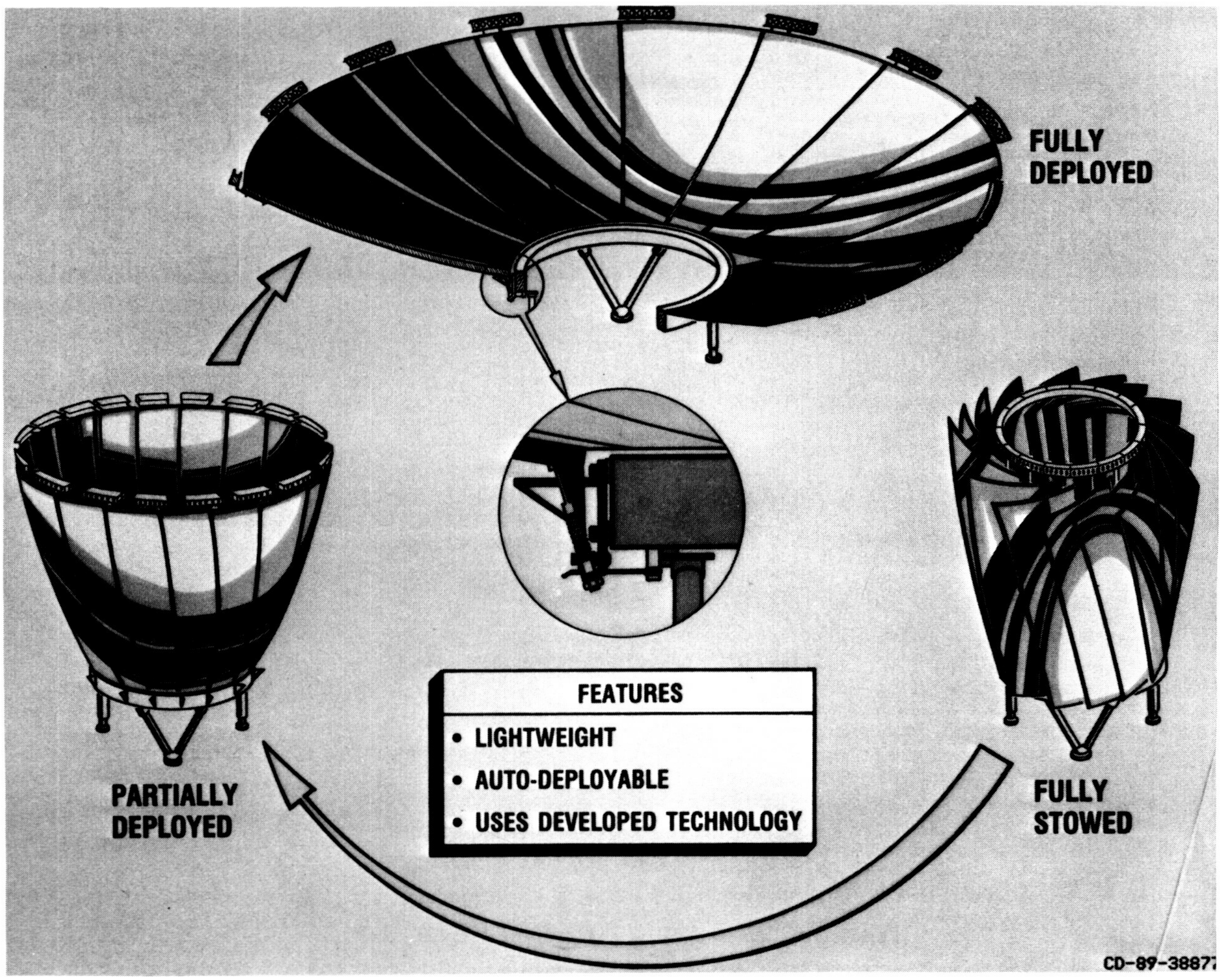

FIGURE 1. - THE NASA/CLEVELAND STATE UNIVERSITY 2 METER DIAMETER AUTO-DEPLOYABLE PROTOTYPE CONCENTRATOR.

Report Documentation Page

NASA
National Aeronautics and Space Administration

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102139		

4. Title and Subtitle	5. Report Date
A Program for Advancing the Technology of Space Concentrators	
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Gerald J. Naujokas and Joseph M. Savino	E-4900
	10. Work Unit No.
	506-41-31
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 24th Intersociety Energy Conversion Engineering Conference cosponsored by the IEEE, AIAA, ANS, ASME, SAE, ACS, and AIChE, Washington, D.C., August 6-11, 1989. Gerald J. Naujokas, Sverdrup Technology, Inc., NASA Lewis Research Center Group, Cleveland, Ohio 44135; Joseph M. Savino, NASA Lewis Research Center.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Space power Space solar concentrators Solar dynamic power	Unclassified – Unlimited Subject Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	8	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161