N72-19057

NASA TECHNICAL MEMORANDUM

NASA TM X-2520

NASA TM X-2520

LARGE-SCALE TERRESTRIAL SOLAR CELL POWER GENERATION COST - A PRELIMINARY ASSESSMENT

by Adolph E. Spakowski and Lloyd I. Shure

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1972

1. Report No. NASA TM X-2520	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle LARGE-SCALE TERRESTRIAL SOLAR CELL POWER GENERATION COST - A PRELIMINARY ASSESSMENT		5. Report Date March 1972
		6. Performing Organization Code
7. Author(s) Adolph E. Spakowski and Lloyd I. Shure		8. Performing Organization Report No. E-6675
		10. Work Unit No. 113-33
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A cost study was made to assess the potential of the large-scale use of solar cell power for terrestrial applications. The incentive is the attraction of a zero-pollution source of power for wide-scale use. Unlike many other concepts for low-pollution power generation, even thermal pollution is avoided since only the incident solar flux is utilized. To provide a basis for comparison and a perspective for evaluation, the pertinent technology was treated in two categories: current and optimistic. Factors considered were solar cells, array assembly, power conditioning, site preparation, buildings, maintenance, and operation. The capital investment was assumed to be amortized over 30 years. The useful life of the solar cell array was assumed to be 10 years, and the cases of zero and 50-percent performance degradation were considered. Land costs, taxes, and profits were not included in this study because it was found too difficult to provide good generalized estimates of these items. On the basis of the factors considered it is shown that even for optimistic projections of technology, electric power from large-scale terrestrial use of solar cells is approximately two to three orders of magnitude more costly than current electric power generation from either fossil or nuclear fuel powerplants. For solar cell power generation to be a viable competitor on a cost basis, technological breakthroughs would be required in both solar cell and array fabrication and in site preparation.

17. Key Words (Suggested by Author(s)) Silicon, Solar cells, Terrestrial applications, Array assembly, Electric power generation, Zero pollution, Cost basis, Solar energy, Electricity		18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 12	22. Price* $3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

LARGE-SCALE TERRESTRIAL SOLAR CELL POWER GENERATION COST - A PRELIMINARY ASSESSMENT

by Adolph E. Spakowski and Lloyd I. Shure

Lewis Research Center

SUMMARY

A cost study was made to assess the potential of the large-scale use of solar cell power for terrestrial applications. The incentive is the attraction of a zero-pollution source of power for wide-scale use. Unlike many other concepts for low-pollution power generation, even thermal pollution is avoided since only the incident solar flux is utilized. To provide a basis for comparison and a perspective for evaluation, the pertinent technology was treated in two categories: current and optimistic. Factors considered were solar cells, array assembly, power conditioning, site preparation, buildings, maintenance, and operation. The capital investment was assumed to be amortized over 30 years. The useful life of the solar cell array was assumed to be 10 years, and the cases of zero and 50-percent performance degradation were considered. Land costs, taxes, and profits were not included in this study because it was found too difficult to provide good generalized estimates of these items.

On the basis of the factors considered it is shown that even for optimistic projections of technology, electric power from large-scale terrestrial use of solar cells is approximately two to three orders of magnitude more costly than current electric power generation from either fossil or nuclear fuel powerplants. For solar cell power generation to be a viable competitor on a cost basis, technological breakthroughs would be required in both solar cell and array fabrication and in site preparation.

INTRODUCTION

Our electric energy requirements are growing rapidly (refs. 1 and 2), while our fuel resources are fixed. Superimposed on this is the rising awareness of the general public to the problems of our environment, which has led to vigorous federal efforts to control thermal and atmospheric pollution. Thus, as the demand for power increases, the growth of fossil and nuclear fuel powerplants will be constrained by fuel availability and pollution control requirements. Advances in nuclear breeder technology and fusion power may ameliorate the fuel availability part of this problem, leaving the pollution aspects to be resolved. Solar energy conversion potentially offers a more complete solution. Although diurnally variable and relatively low in intensity, solar energy is practically universally available. Also since only normal solar insolation is utilized in solar energy conversion systems, there is no thermal or atmospheric pollution.

To date, there have been few direct applications of solar energy for generation of electricity. The primary effort being in the space program, where solar cells are the main source of electric power for space vehicles. From all evidence there is no technological reason why solar cells could not be used to provide large quantities of terrestrial power. It remains, however, to be shown that a solar cell power system is economically feasible.

It is the purpose of this report to provide a cost estimate of large-scale terrestrial solar cell power generation.

CONVENTIONAL ELECTRICAL POWERPLANTS

Conventional electrical powerplants use heat produced from fossil or nuclear fuels or hydropower to drive electric generators. The plants are built on a large scale and usually are depreciated over a long period (~36 yr) to obtain the maximum advantage of their capital investment. For purposes of comparison the plant costs for two powerplant types, coal and nuclear, are given in table I.

In table II a power generation cost breakdown is presented (ref. 3). Both types of plants generate power at approximately the same cost (6 mills/kW-hr), including the cost of some modest pollution control. In the future, more stringent requirements will be placed on the effluents emanating from the facilities, which will increase the cost of power (ref. 4). Estimates made for a coal-burning plant that uses one of the processes developed to remove all the fly ash and most of the sulfur dioxide indicate that about 8 percent will be added to power costs (ref. 5). Increases in fuel costs may be expected due to decreased availability of high-grade coal and uranium (if breeder reactors are not successful). It is concluded, however, assuming increases due to pollution control devices and even assuming a twofold increase in fuel cost, that the cost of electric power generation will still be well under 10 mills per kilowatt-hour.

TABLE I. - CONVENTIONAL ELECTRIC

POWERPLANT: PLANT COSTS - 1971

	American Electric Power (coal)	Davis-Besse (nuclear)
Power capacity, MWe	2600	870
Cost, dollars	488×10^6	270×10^6
Specific cost, dollars/kW	188	310

TABLE II. - CONVENTIONAL ELECTRIC

POWERPLANT: POWER GENERATION

COSTS[a]

	Coal	Nuclear
	Power generation cost, mills/kW-hr	
Plant carrying charge	2.70	3.40
Fuel carrying charge	----	.46
Fuel cost	2.25	1.34
Operation and maintenance	.30	.42
Sulfur dioxide removal	.38	----
Thermal pollution control	.12	.17
Total cost	5.75	5.79

[a]Ref. 3.

SYSTEM CONFIGURATION

To estimate the cost of obtaining electrical power from large-scale, terrestrial, solar cell power systems, a module approach is taken. The basic module is a square mile of solar cells, but this area could be extended quite easily (fig. 1). Provision must be made for support, maintenance, and replacement of the solar arrays and protection from storm damage, water, dust, plant growth, and animals. The solar cell array is placed parallel to the ground, with fixed orientation. The array is composed of solar panels 100 feet by 10 feet separated by 2-foot walks. The electricity from all the series-parallel connected panels is brought together at the power station. Here the transformers, the power conditioning equipment, and the controls for accomplishing these functions are located.

The cost for the power system is given in terms of 1971 dollars and includes the array, the power conditioning equipment (to convert from dc to ac), the facility (site, buildings, maintenance, and operation), and the interest. Not included in the total costs are land, taxes, and profits, which are quite dependent on the location of the solar power generation farm.

Power from the solar cell farm will be available only when the sun is shining since no storage capability is envisioned. Any nearby electrical network can use this power as a supplement to their own power. In the case of an ac network, power conditioning equipment is used to convert from direct current to alternating current. In the case of a dc network, power conditioning may be needed to provide appropriate voltage matching.

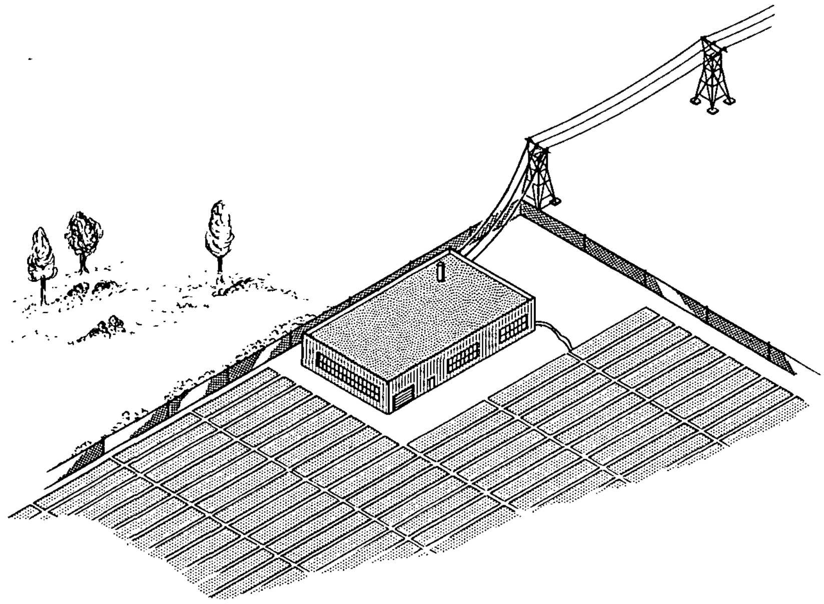

Figure 1. - Sketch of solar cell electrical generation farm.

GROUND RULES AND ASSUMPTIONS

General

Two areas - Phoenix, Arizona and Cleveland, Ohio - were chosen as illustrative of the range of solar cell powerplant sites in the United States. The total output of the solar cell system is calculated from the average daily radiation, both direct and diffuse, falling on a horizontal plane. The annual daily average insolation and solar cell array output for Phoenix and Cleveland are given in table III.

Component cost estimates are given for two levels of technology: current and optimistic. Power generation costs are given in detail for optimistic technology only. Current technology is as of 1971. Optimistic technology is that reasonable extension of current technology employing all sound scientific and engineering principles to achieve the maximum in cost reductions. Optimistic technology is not predicated on "breakthroughs" or new discoveries.

TABLE III. - INCIDENT ENERGY AND ARRAY OUTPUT

	Phoenix	Cleveland
Annual average of available sunshine, percent	85	50
Daily input of average radiation[a]:		
langley	520	335
$kW\text{-}hr/ft^2$	0.56	0.36
Array daily output[b]:		
$kW\text{-}hr/ft^2$	0.0668	0.0428
$kW\text{-}hr/(mile)^2$	18.6×10^5	12.0×10^5
Maximum array output[b], $kW/(mile)^2$	2.76×10^5	2.52×10^5

[a]Ref. 6.

[b]Assuming cell efficiency of 14 percent and a cell packing factor of 85 percent.

Solar Cells/Arrays

Based on current technology, a 2-centimeter by 4-centimeter silicon solar cell nominally costs about $6 when obtained in large quantities. Then, at a cost of about $5 more, the cell is mounted on a substrate with interconnects, glass cover, ultraviolet filter, antireflection coating, and the various adhesives required to hold the package together.

The optimistic technology cost estimate for a cell of 8-square-centimeter area with an efficiency of 14 percent is $1.60. The assembly cost using automated assembly is estimated at $1.75 per cell and includes the substrate, cover, interconnections, solder, inspection, and overhead (private communication with solar cell manufacturers and array assemblers).

Power Conditioning

Power conditioning must be considered unless the solar power can be supplied to a nearby user who can employ the dc power directly and also tolerate the fluctuating nature of the solar power supply. For current technology, conditioning equipment will use rotating inverters with the auxiliary equipment required to collect the power and to prepare it for transmission. At high powers, power conditioning costs level out at $154 per kilowatt (General Electric and Westinghouse catalogs for April 1971). Presently, the output of rotary inverters is limited by the size of dc motors available to drive the generators. Even with three or four 1000-horsepower dc motors driving the generator, a maximum of only 2500 kilowatts is achieved. Based on optimistic technology, using solid-state inverters, a cost of $33 per kilowatt is projected (ref. 7). Solar cell farms will use solid state together with the collection and transformer equipment (at a cost of $13 per kilowatt) needed to transmit the power at high voltage levels. The current technology limits of solid-state inverter size is 250-kilovolt-amperes (at a cost of $250/kW). Recently, however, a static inverter in the gigawatt range was put into service for the Extra High Voltage direct-current line between the Dalles Dam in Oregon and Sylmar, California (refs. 7 to 9). When the present solar cell system is ready for operation, there will no doubt be inverters available in the range intermediate between the gigawatt static inverter and the 250-kilovolt-ampere solid-state inverter.

Because of the diurnal and seasonal variation of the energy source, the inverter must operate over a large load range without significant efficiency loss. Multiple unit inverters together with an appropriate switching system will probably be employed to maintain the required high-efficiency power conditioning performance. The cost of such a switching system has not been considered here.

FACILITY

Site Construction

Several types of site construction were examined taking into account considerations such as wind loads, rainfall, replacement, and maintenance. One type of construction consists of poles and lightweight trusses to carry the array load. The overall cost of this construction is considered to be too high, namely, $8 per square foot. A second type consists of poles and cables. The cost of this construction is also high, estimated to be $1.75 per square foot. A third type - possibly the lowest in cost - is a blacktop surface with drainage with the solar arrays cemented to steel bands set in the blacktop. This type of construction together with fencing and the installation costs is estimated to cost $0.76 per square foot (private communications with Ohio State Highway Department, Cleveland, Ohio, and Mr. D. F. Larson of Lewis Research Center).

In more detail, the blacktop is laid on a layer of crushed stone. Six-inch-high mounds of blacktop approximately 10 inches wide by 100 feet long are placed on 5-foot centers. The solar arrays in 100-foot by 10-foot panels are cemented to 1/2-inch steel bands stapled to the mounds. Figure 2 gives a schematic layout of this type of construction. The area utilization factor for the arrays mounted on site is 81 percent. The solar panels are interconnected electrically using plug-in straps to achieve any desired series-parallel arrangement. When trouble develops, a replacement panel may be substituted by stripping out the old panel and cementing in a new one.

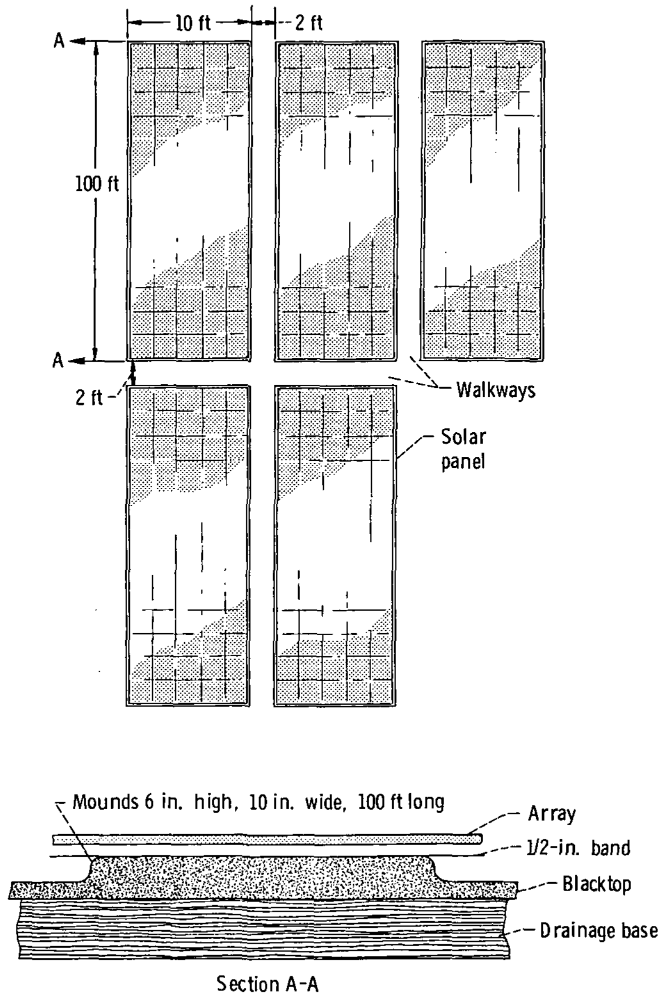

Figure 2. - Solar array site construction. Total array area, 2.79×10^7 square feet per square mile; array packing factor, 81 percent; blacktop area, 3.42×10^7 square feet.

The blacktop surface and drainage system (1) protect the array from innundation or being covered with mud during storms, (2) minimize dust formation, and (3) provide access for maintenance. Other ground treatment schemes with a somewhat lower cost potential may involve the use of packed crushed stone or chemical treatment of the soil. However, the question of long-term durability and support of arrays would still have to be dealt with. No further consideration is given to these schemes in this study.

Maintenance and Operation

The maintenance and operation of this facility is calculated on the basis of two shifts per day. Each shift would include an operator and an electrician whose duties would include the operation of the generators, phasing the generators into and out of the system, maintaining the motor generator sets, and replacing and repairing the solar cell panels. The labor costs plus a small amount of money for miscellaneous supplies is projected to be about $1 per kilowatt-year. This cost estimate is probably on the low side, since it is less than that incurred by power-producing facilities using coal or nuclear fuels, namely, $2 to $4 per kilowatt-year (ref. 3).

Buildings

The building to house the control room and power conditioning equipment is a single-story Butler-type metal building with a 14-foot ceiling and a concrete floor. Total area of the building is 22 000 square feet, which includes space for the power conditioning equipment, a control room, and a work area. Basic costs for the erected building are $15 per square foot in Cleveland and $20 per square foot in Phoenix. These costs include the concrete floor and metal building plus air conditioning for the control room, heat, lights, and a restroom for the staff.

Life

The useful life is assumed to be 30 years for the power conditioning equipment, site construction, and buildings and 10 years for the solar array. Two cases of array degradation are considered in this study. In one case, no degradation in output is assumed; in the other case, a linear degradation in power output to 50 percent of the original is assumed over the 10-year useful lifetime. For this second case, the array power and area are initially increased by one-third so that the integrated output would be the same as for the undegraded case over the 10-year lifetime.

Electricity Production Cost

The cost per kilowatt-hour of electricity is computed by summing the maintenance and operating costs and the cost to retire the debts for the initial investments and dividing by the kilowatt-hours of electricity produced. Debt retirement is based on equal monthly payments over the useful lifetimes of the item and a 7 percent per annum interest on the outstanding debt (ref. 10). Land costs, taxes, and profits are not included in this study because it was found difficult to provide good generalized estimates of these items. They can be expected, however, to add 10 percent or more to the overall production cost.

SOLAR CELL SYSTEM POWER COST

In table III is shown the average daily solar radiation incident on Phoenix and Cleveland in langleys per day and converted to kilowatt-hours per square foot per day. Assuming a silicon solar cell conversion efficiency of 14 percent and a cell packing factor of 85 percent, the average daily output of the solar array will be 18.6×10^5 and 12.0×10^5 kilowatt-hour per square mile, respectively. The maximum array output power for both locations is calculated from the maximum recorded insolation values. The values for Phoenix and Cleveland are 2.76×10^5 and 2.52×10^5 kilowatts per square mile, respectively. These maximum values are used to size and estimate the costs of the power conditioning equipment. Using these figures the cost of a solar power system can be estimated for optimistic technology as shown in table IV. The cost breakdown, for the cases of no solar cell degradation and 50-percent degradation in 10 years, is made by category of array, power conditioning, and facility.

In the array category the cost of the single-crystal cell as projected for optimistic technology is $1.60 for an 8 square-centimeter cell. With an 85-percent cell packing factor, the cell cost per square foot of array is $160. To this must be added interest

TABLE IV. - ESTIMATE OF SOLAR CELL SYSTEM POWER COST:

OPTIMISTIC TECHNOLOGY

	No degradation		50-Percent degradation in 10 years	
	Cleveland	Phoenix	Cleveland	Phoenix
	Power cost, dollars/kW-hr			
Array:				
Cells[a]	1.40	0.90	1.85	1.20
Assembly[a]	1.55	1.00	2.05	1.30
Subtotal	2.95	1.90	3.90	2.50
Solid-state power conditioning[b]	.0023	.0015	.0030	.0020
Facility:				
Site construction[b]	.0039	.0025	.0050	.0033
Buildings[b]	.0001	.0001	.0001	.0001
Maintenance, operation[c]	.0004	.0002	.0005	.0003
Subtotal	.0044	.0028	.0056	.0037
Total[d]	2.96	1.90	3.91	2.51

[a]Depreciated over 10 years; interest rate, 7 percent.
[b]Depreciated over 30 years; interest rate, 7 percent.
[c]Current revenues.
[d]Land cost, taxes, and profit not included

charges, which brings the cell cost total to $220 per square foot. The cost of assembling cells into an array, taking advantage of flexible substrates and covers and automated assembly techniques, is estimated to be $170 per square foot. With interest charges the array assembly total cost is $240 per square foot. The total array cost is then $460 per square foot. From this, the solar cell array contribution to the power generation cost is found to be $2.95 and $1.90 per kilowatt-hour in Cleveland and Phoenix, respectively. If a 50-percent performance degradation in 10 years is assumed, the solar cell array power generation cost increases by about 30 percent. In either case, however, the cost contributed by the array alone is two to three orders of magnitude greater than electric utility power costs.

The power conditioning and facility costs are derived from the dollar numbers given in an earlier section of this study. The higher costs in the 50-percent degradation case for power conditioning, site construction, and maintenance reflect the approximately 30-percent increase in array area involved. The power conditioning contribution to the power generation cost for no array performance degradation is about 2 mills per kilowatt-hour. The facility cost contribution is about 3 to 5 mills per kilowatt-hour, or about equal to the cost of present electric utility power.

CONCLUSION

Even using assumptions based on optimistic technology, it is evident that the power generation cost of a large-scale solar cell powerplant is far from competitive with central station powerplants. The major costs reside in solar cell fabrication and in assembly; these costs alone are estimated to be two to three orders of magnitude greater than the total cost of central station power generation. Additionally, the site construction cost of the solar cell power system is estimated to be about equal to the total cost of central station power generation. A major technological breakthrough in solar cell fabrication and in array assembly is required, as well as a breakthrough in site construction, in order to alter this picture.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 16, 1971,
113-33.

REFERENCES

1. Gaucher, Leon P.: Energy in Perspective. Chemical Technology, Mar. 1971, pp. 153-158.
2. Anon.: Proceedings of the Round Table Discussion on the Ground Application of Photovoltaic Power Sources, Boston College, Nov. 27, 1970.
3. Anon.: Coal-Fired Plants Not Doomed by Pollution Threats. Environ. Sci. Tech., vol. 2, no. 10, Oct. 1968, p. 729.
4. Anon.: Electric Power and the Environment. Energy Policy Staff, Office of Science & Technology, Aug. 1970.
5. Stites, J. G., Jr.: Environmental Effects of Producing Electric Power. Hearings before Joint Commission on Atomic Energy, U.S. Congress, 2nd Session, Jan.-Feb. 1970, Part 2, vol. I, p. 1732.
6. Anon.: Climatic Atlas of the U.S. Environmental Science Service Administration, June 1968.
7. Lawrence, R. F.: Transmission in the 70's. Westinghouse Engineer, vol. 30, no. 6, Nov. 1970.
8. Gould, W. R.: Environmental Effects of Producing Electric Power. Hearings before Joint Commission on Atomic Energy, U.S. Congress, 2nd Session, Jan.-Feb. 1970, Part 2, vol. I, p. 1677.
9. Mahoney, William M.: EHV-DC System Ties Los Angeles to Northwest. J. Power Div., Proc. ASCE, vol. 97, no. P0-1, Jan. 1971, pp. 181-201.
10. Minrath, William R.: Handbook of Business Mathematics. Second ed., D. Van Nostrand Co., Inc., 1967.

NATIONAL AERONAUTICS AND SPACE ADMISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

U.S.MAIL

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

---

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546