NASA/TM—2002-211720

A Parametric Assessment of the Mission Applicability of Thin-Film Solar Arrays

David J. Hoffman
Glenn Research Center, Cleveland, Ohio

August 2002

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301–621–0134
- Telephone the NASA Access Help Desk at 301–621–0390
- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2002-211720

A Parametric Assessment of the Mission Applicability of Thin-Film Solar Arrays

David J. Hoffman
Glenn Research Center, Cleveland, Ohio

Prepared for the
Space Power Workshop 2002
cosponsored by the Air Force Research Laboratory, USAF Space and Missile Systems Center, and the Aerospace Corporation
Redondo Beach, California, April 22–25, 2002

National Aeronautics and
Space Administration

Glenn Research Center

August 2002

This report contains preliminary findings, subject to revision as analysis proceeds.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

A Parametric Assessment of the Mission Applicability of Thin-Film Solar Arrays

David J. Hoffman
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

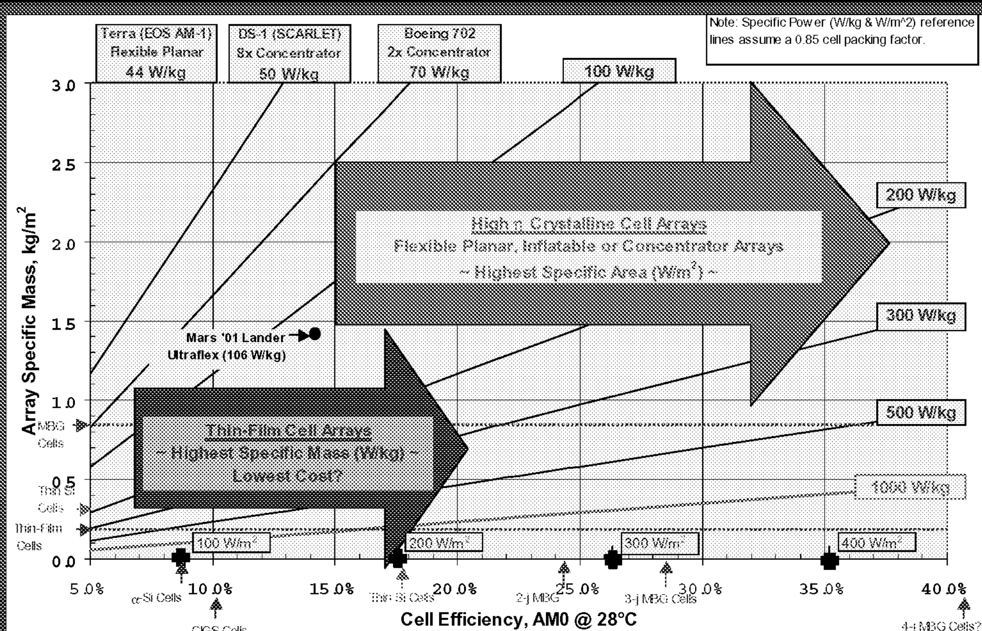
Summary

Results are presented from a parametric assessment of the applicability and spacecraft-level impacts of very lightweight thin-film solar arrays with relatively large deployed areas for representative space missions. The most and least attractive features of thin-film solar arrays are briefly discussed. A calculation is then presented illustrating that from a solar array alone mass perspective, larger arrays with less efficient but lighter thin-film solar cells can weigh less than smaller arrays with more efficient but heavier crystalline cells. However, a spacecraft-level systems assessment must take into account the additional mass associated with solar array deployed area: the propellant needed to desaturate the momentum accumulated from area-related disturbance torques and to perform aerodynamic drag makeup reboost. The results for such an assessment are presented for a representative low Earth orbit (LEO) mission, as a function of altitude and mission life, and a geostationary Earth orbit (GEO) mission. Discussion of the results includes a list of specific mission types most likely to benefit from using thin-film arrays. The presentation concludes with a list of issues to be addressed prior to use of thin-film solar arrays in space and the observation that with their unique characteristics, very lightweight arrays using efficient, thin-film cells on flexible substrates may become the best array option for a subset of Earth orbiting and deep space missions.

Photovoltaic Array Metrics

Feature	Which array technology will have the advantage?
• Low Cost	• Thin-film arrays: although still unproven.
• Low Mass	• Thin-film arrays: Highest Specific Power (W/kg) – Although large area results in a greater total mass penalty (array + propellant) for lower altitude LEO
• Packageability	• Thin-film arrays
• Deployability	•Crystalline-cell rigid panel arrays
• Small Deployed Area	• Crystalline-cell arrays: Highest Specific Area (W/m^2) + Always at least ½ the size of Thin-Film arrays?
• Reliable Performance	• Crystalline-cell arrays: long history of successful performance, but thin-film arrays show promise.
• Radiation	• Thin-film cells more tolerant
• Op. Temperature	• MJ GaAs cells have better thermal coefficient
• Hi-Voltage Capability	• Thin-film cells easier to isolate from plasma

Thin-film & crystalline cell arrays each have attractive features!



How efficient do thin-film cells have to be?

Arrays with *less efficient but lighter* thin-film cells can match the mass of arrays with *more efficient but heavier* MBG crystalline cells.

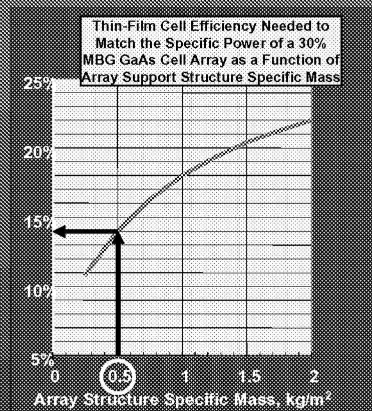
1st Order: Equate array specific power at BOL, 28° C   W/kg=(W/m^2) / (kg/m^2)

$$\Rightarrow \text{TF Cell Eff} = \text{MBG Cell Eff} \times \frac{\text{(Array Structure + TF Cell Area Sp. Mass)}}{\text{(Array Structure + MBG Cell Area Sp. Mass)}}$$

- Mass-Equivalent array with a 0.5 kg/m^2 structure:
  - 30% efficient 1.0 kg/m^2 MBG cells
  - 14% efficient 0.2 kg/m^2 thin-film cells

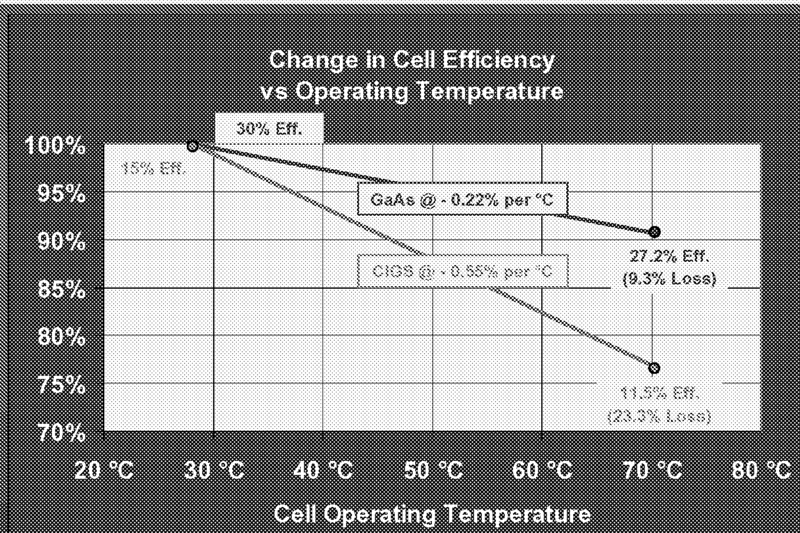
2nd Order
Support structure will be optimized for light-weight thin-film cell blankets
- 12% TF cells on 0.27 kg/m^2 structure matches the specific mass of 30% MBG cells on 0.5 kg/m^2 structure for arrays with same deployed stiffness.

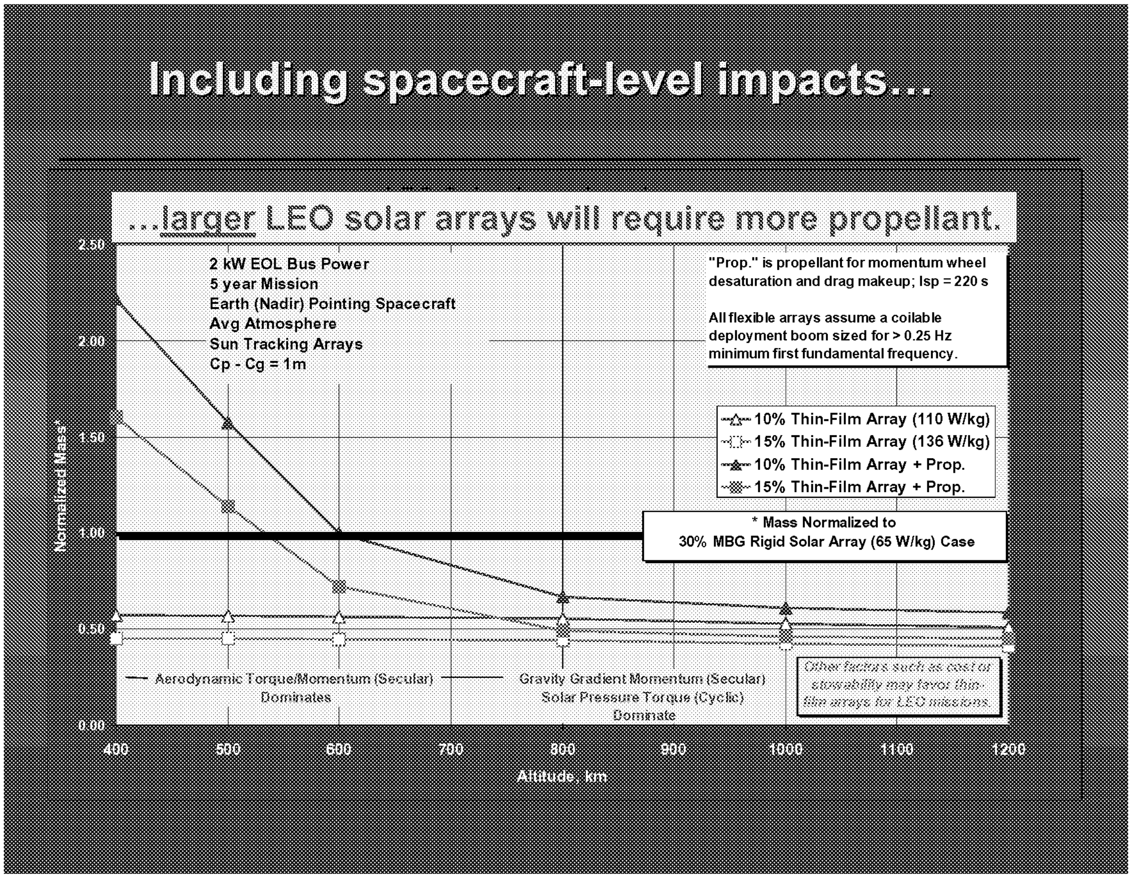
However, to meet EOL power rqmt at max op temp
- Need 17% BOL 28°C Thin-Film cells



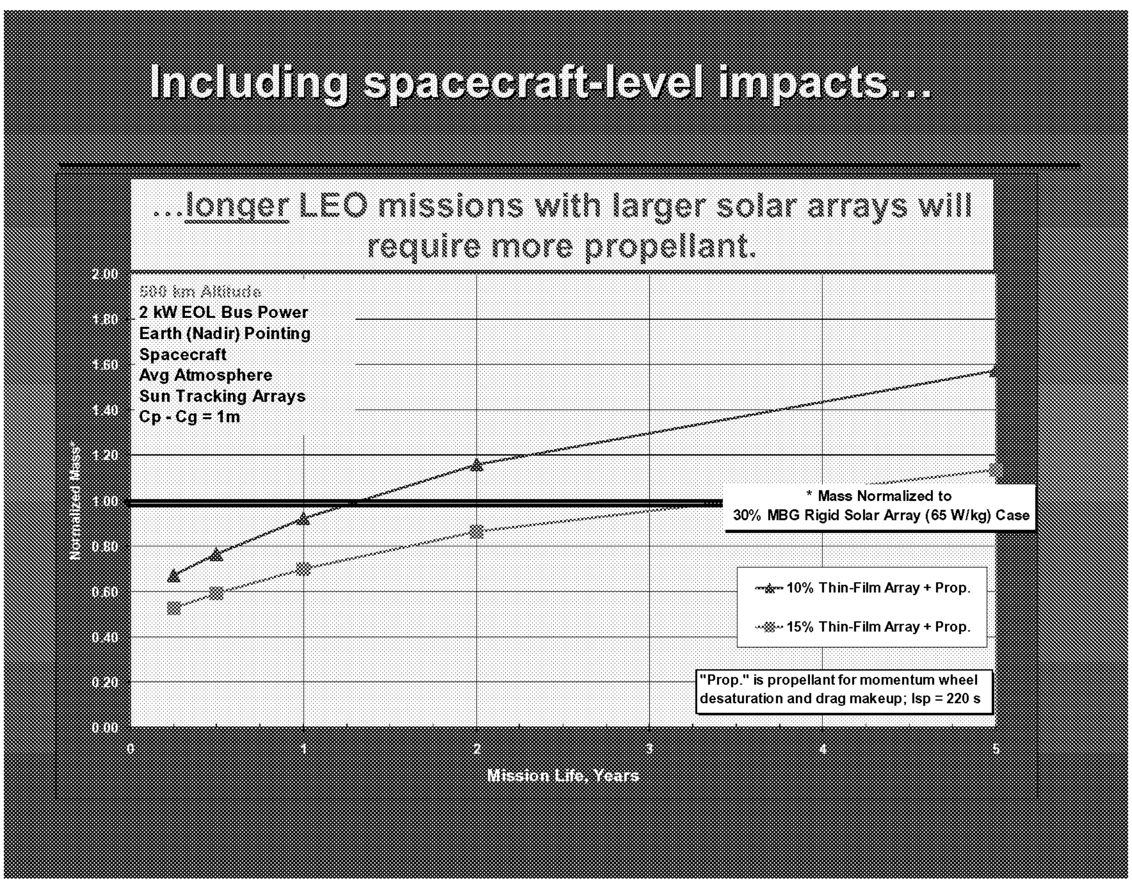
Solar Cell Operating Temperature

The lightweight, radiation tolerant advantage of thin-film CIGS is offset by its temperature coefficient for efficiency





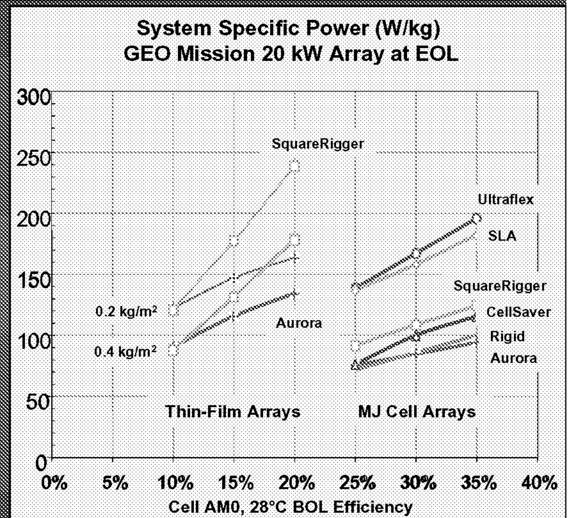
Including spacecraft-level impacts…
…larger LEO solar arrays will require more propellant.
2 kW EOL Bus Power
5 year Mission
Earth (Nadir) Pointing Spacecraft
Avg Atmosphere
Sun Tracking Arrays
Cp - Cg = 1m
"Prop." is propellant for momentum wheel desaturation and drag makeup; Isp = 220 s
All flexible arrays assume a coilable deployment boom sized for > 0.25 Hz minimum first fundamental frequency.
10% Thin-Film Array (110 W/kg)
15% Thin-Film Array (136 W/kg)
10% Thin-Film Array + Prop.
15% Thin-Film Array + Prop.
* Mass Normalized to
30% MBG Rigid Solar Array (65 W/kg) Case
Aerodynamic Torque/Momentum (Secular) Dominates
Gravity Gradient Momentum (Secular)
Solar Pressure Torque (Cyclic)
Dominate
Other factors such as cost or stowability may favor thin-film arrays for LEO missions.
Normalized Mass*
2.50
2.00
1.50
1.00
0.50
0.00
400
500
600
700
800
900
1000
1100
1200
Altitude, km

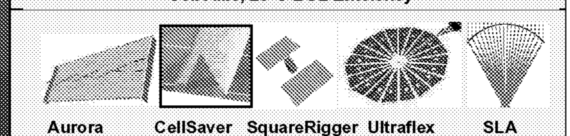


Including spacecraft-level impacts…
…longer LEO missions with larger solar arrays will require more propellant.
500 km Altitude
2 kW EOL Bus Power
Earth (Nadir) Pointing Spacecraft
Avg Atmosphere
Sun Tracking Arrays
Cp - Cg = 1m
* Mass Normalized to
30% MBG Rigid Solar Array (65 W/kg) Case
10% Thin-Film Array + Prop.
15% Thin-Film Array + Prop.
"Prop." is propellant for momentum wheel desaturation and drag makeup; Isp = 220 s
Normalized Mass*
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
1
2
3
4
5
Mission Life, Years

NASA/AFRL Sponsored Comprehensive Solar Array Study by AEC Able

- Missions:
  - LEO, MEO, GEO, SEP Transfer, Interplanetary
- PV Cell Technologies:
  - MJ Crystalline at 25%, 30% & 35% Eff.
  - Thin-Film at 10%, 15% & 20% Eff.; 0.2 and 0.4 kg/m^2
- Array Technologies:
  - Rigid Panel, CellSaver, Stretched Lens Array, Aurora, Ultraflex, SquareRigger
  - Evaluation of complete systems incl. launch restraints, yokes, wire harnesses, deployment synchronization etc.
- Environments:
  - Deployed & Stowed Stiffness
  - Cell operating temperature
  - Radiation degradation





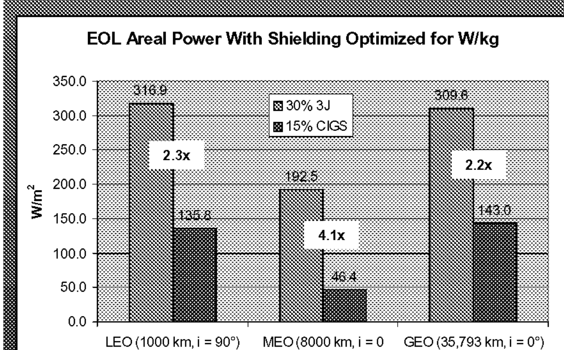
Preliminary Array Study Results

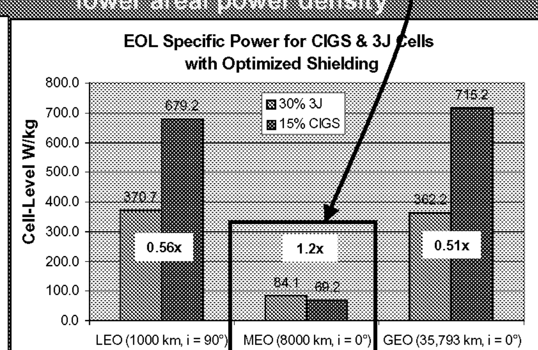
Performance of Shielded Thin-Film & 3J Crystalline PV in Various Earth Orbits

- Assumed photovoltaic only mass:
  - CIGS = 0.2 kg/m^2 (On 30 µm titanium foil)
  - 3J GaInP/GaAs/Ge = 0.75 kg/m^2 (140 µm thick Ge wafer)
  - Radiation shielding optimizes array specific power (W/kg)

Results do not include array structural support mass!

- EOL W/m^2 always higher for 3J cell compared to CIGS
- EOL W/kg for shielded cell higher for CIGS *except in MEO*
  - Due to on-negligible shielding and lower areal power density





Solar Array Specific Power

What's in the numerator & denominator?

Mass Specific Power W/kg	BOL		EOL	
	1 AU 28° C	1 AU Op. Temp.	1 AU 28° C	1 AU Op. Temp.
Cell Blanket (0.22 kg/m²)				
10% CIGS	523	395	404	305
15% CIGS	785	604	605	466
Array Level				
10% CIGS	123	92	95	71
15% CIGS	193	149	149	115

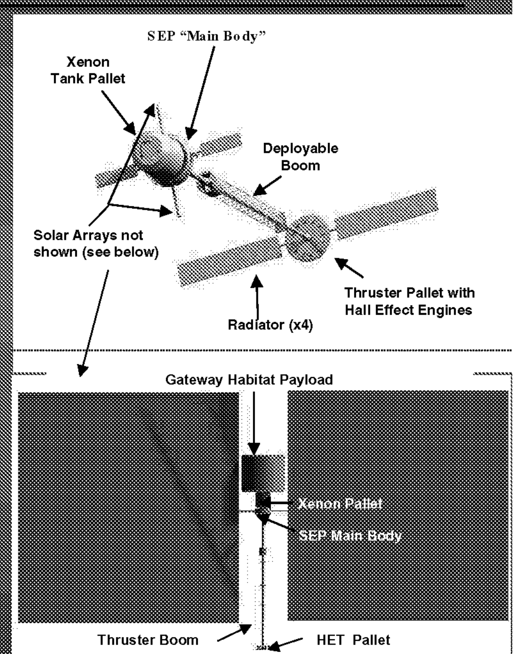
Lunar L1 "Gateway" SEP Stage

Features

- 180-day trip time, 400 km 28.5° LEO-Lunar L1
- 46-day return, Lunar L1 - 400 km 28.5° LEO
- 584 kW SEP Stage Power (2 round trips)
- 7,300 m² High-Voltage Thin-Film Solar Arrays (2 wings)
- 12 Direct-Drive Hall Effect 50 kW Engines (incl. 1 spare)

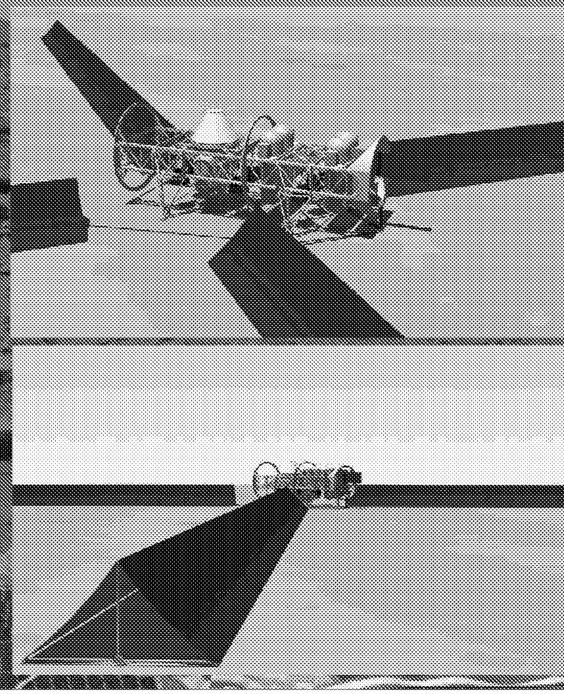
Mass Characteristics

- 15.0 MT SEP Stage Dry Mass (w/ 20% margin)
- 20.0 MT Xenon propellant
- 30.0 MT Payload
- 65.0 MT Vehicle Initial Mass LEO



Far Term Thin-Film Application
Humans on Mars

- 1100-Day Surface Mission
  - Operate ISRU Plant (400-days)
  - Support Crew (500-days)
- 5000-m2, 100 kW Class Array
- Auto-Deploy Tent Structures
  - 4.5-m Height by 100-m Length
- Thin Film PV on Thin Polymer Membrane Enabling
  - Small Packaging Volume
  - Low Mass



Thin-Film Array Mission
Applicability Summary

- Once designed, tested and space-qualified, very lightweight solar arrays using moderate to relatively high efficiency thin-film cells on lightweight flexible substrates will offer significant mass and cost benefits.
  - > 10% to 15% (1-Sun AM0) efficient >10-cm^2 thin-film cells with on low-mass substrates (1-mil metallic, 5-mil pre-preg composite ply, 2-mil polymer, open-weave polymer) resulting in solar cell "blankets" at 0.2 to 0.3 kg/m^2.

- **Attractive Earth-Orbiting applications for Thin-Film arrays include:**
  - LEO missions above 500 km to 800 km but below 4,000 km
  - LEO missions of short duration at lower altitudes
  - LEO sun-sync missions with array normal perpendicular to velocity vector
  - LEO-to-GEO transfers
  - GEO missions
  - Certain very small micro/nanosat missions

- **Beyond Earth orbit applications include:**
  - LEO-to-L1 SEP Transfers
  - LEO-to-? SEP Transfers
  - Large Surface Power Systems

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2002	Technical Memorandum

4. TITLE AND SUBTITLE

A Parametric Assessment of the Mission Applicability of Thin-Film Solar Arrays

5. FUNDING NUMBERS

WU–755–1A–16–00

6. AUTHOR(S)

David J. Hoffman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–13471

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2002-211720

11. SUPPLEMENTARY NOTES

Prepared for the Space Power Workshop 2002 cosponsored by the Air Force Research Laboratory, USAF Space and Missile Systems Center, and the Aerospace Corporation, Redondo Beach, California, April 22–25, 2002. Responsible person, David J. Hoffman, organization code 6920, 216–433–2445.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories: 18 and 20 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Results are presented from a parametric assessment of the applicability and spacecraft-level impacts of very lightweight thin-film solar arrays with relatively large deployed areas for representative space missions. The most and least attractive features of thin-film solar arrays are briefly discussed. A calculation is then presented illustrating that from a solar array alone mass perspective, larger arrays with less efficient but lighter thin-film solar cells can weigh less than smaller arrays with more efficient but heavier crystalline cells. However, a spacecraft-level systems assessment must take into account the additional mass associated with solar array deployed area: the propellant needed to desaturate the momentum accumulated from area-related disturbance torques and to perform aerodynamic drag makeup reboost. The results for such an assessment are presented for a representative low Earth orbit (LEO) mission, as a function of altitude and mission life, and a geostationary Earth orbit (GEO) mission. Discussion of the results includes a list of specific mission types most likely to benefit from using thin-film arrays. The presentation concludes with a list of issues to be addressed prior to use of thin-film solar arrays in space and the observation that with their unique characteristics, very lightweight arrays using efficient, thin-film cells on flexible substrates may become the best array option for a subset of Earth orbiting and deep space missions.

14. SUBJECT TERMS

Space power; Power generation; Photovoltaics; Solar array; Solar panel

15. NUMBER OF PAGES

13

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102