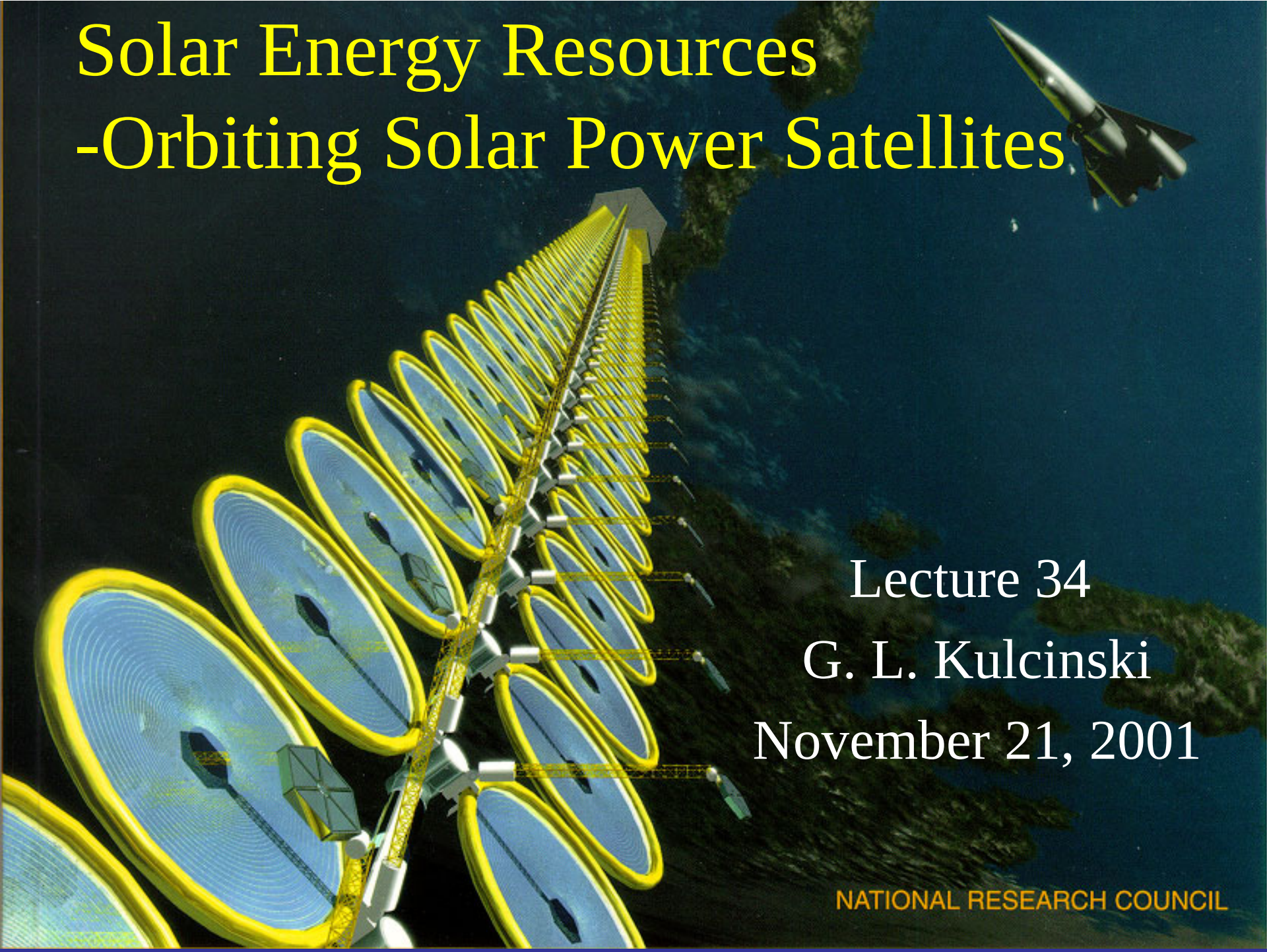
Solar Energy Resources
-Orbiting Solar Power Satellites



Lecture 34

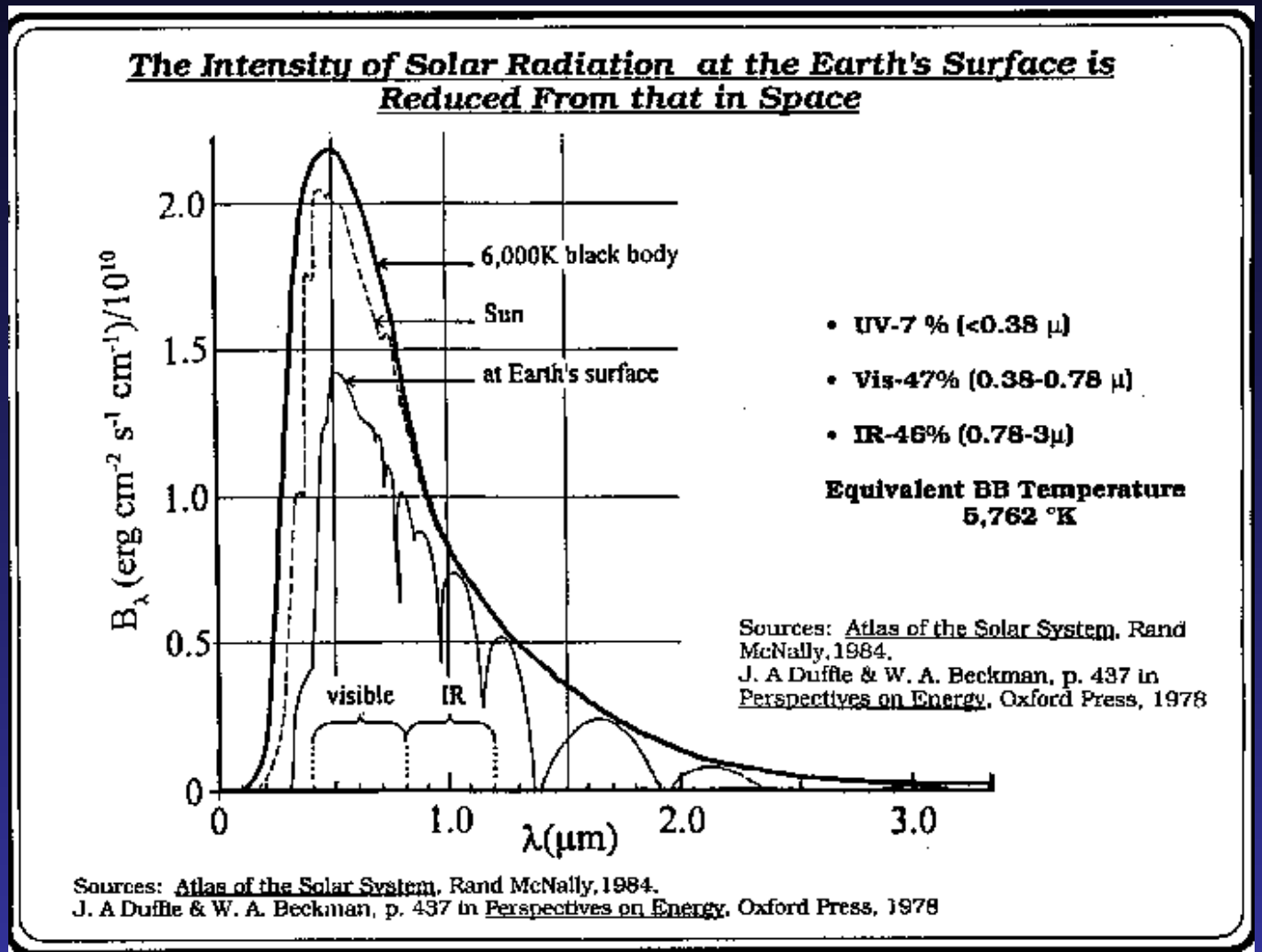
G. L. Kulcinski

November 21, 2001

Important Features of the Sun

- Total power in the Sun……3.86 x 10^{26} Watts
- Power @ surface of Sun……63 MW/m^2
- Distance Earth to Sun……147-152 x 10^6 km
- Solar power @ top of
  Earth's Atmosphere……..1,368 Watts/m^2
- Ave. solar power @ surface……Jan. -3.4 kWh/m^2-d
  Madison, WI ……July-5.6 kWh/m^2-d

The Intensity of Solar Radiation at the Earth's Surface is Reduced From that in Space



Sources: Atlas of the Solar System. Rand McNally, 1984.
J. A Duffie & W. A. Beckman, p. 437 in Perspectives on Energy. Oxford Press, 1978

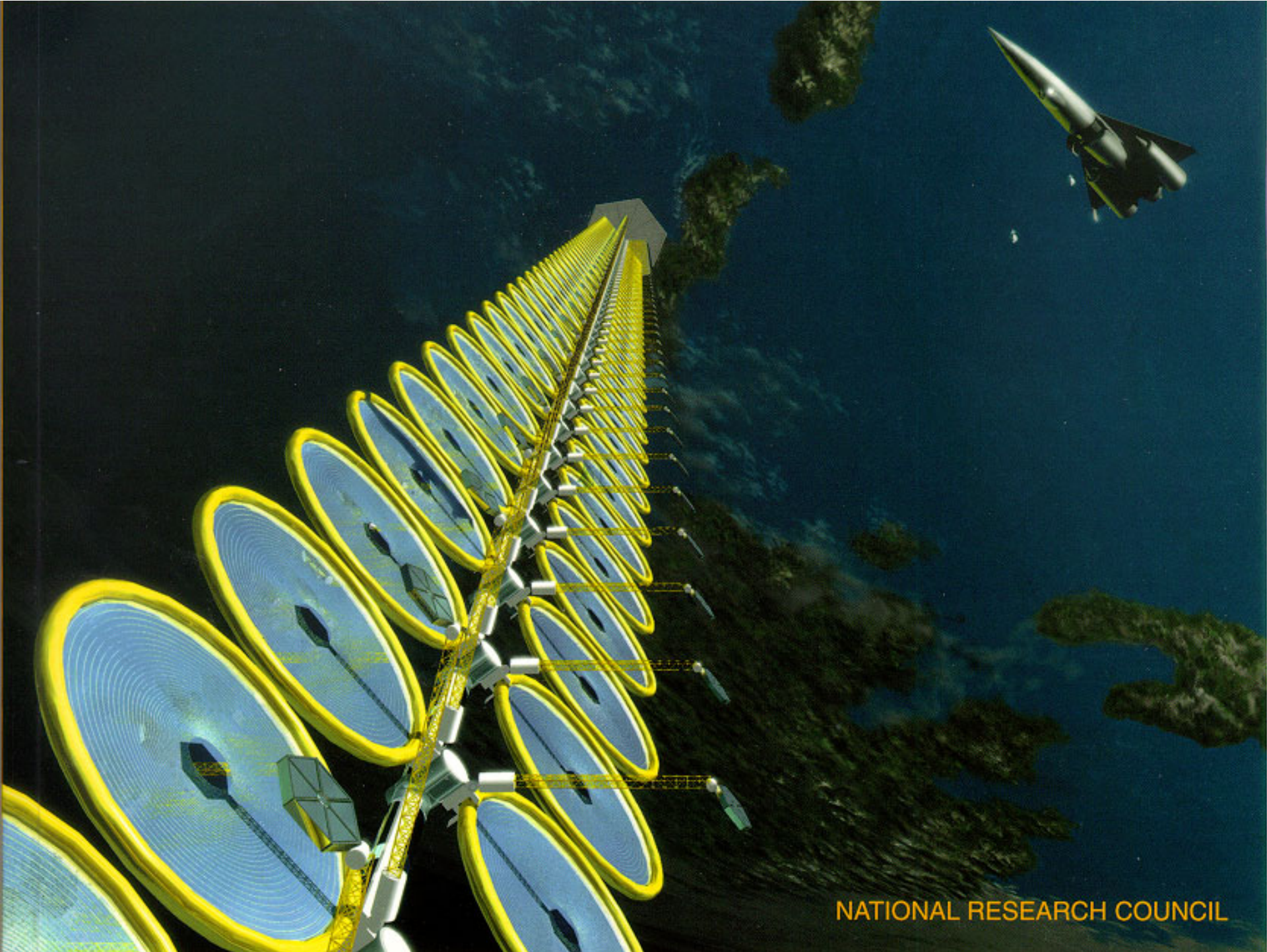
Solar Energy From Space

Solar Power Satellites

- Pioneered by Peter Glaser
- Originally proposed 1968
- Subjected to scrutiny by NASA, DOE, and National Academy of Sciences

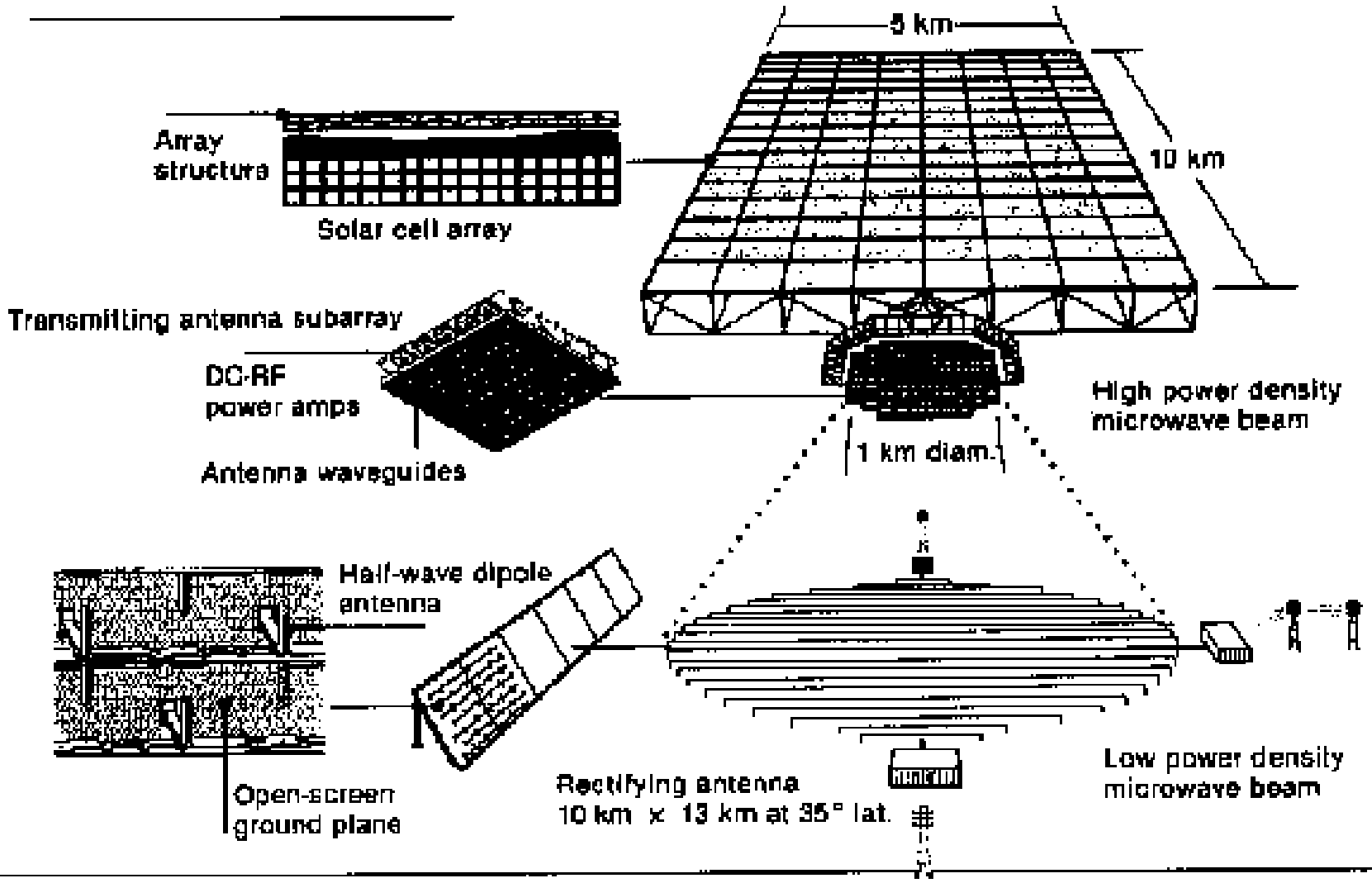
Lunar Power System

- Pioneered by David Criswell
- Originally proposed 1985
- Subjected to analysis by NASA and U. of Houston



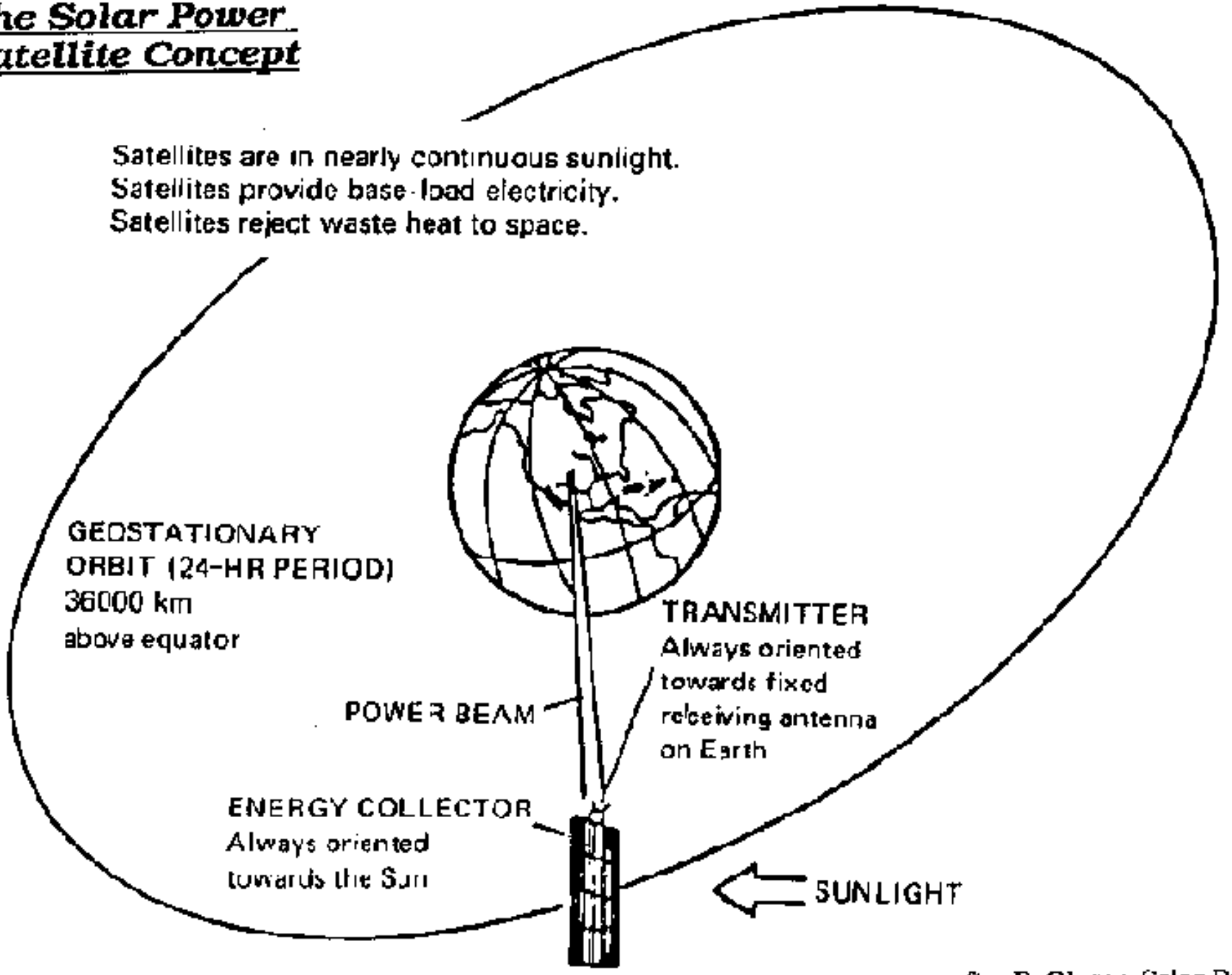
NATIONAL RESEARCH COUNCIL

Solar Power Satellite Reference Design



SOURCE: C. C. Kraft, "The Solar Power Satellite Concept," NASA publication No. JSCp 14898, July 1979.

The Solar Power Satellite Concept



after P. Glaser, Solar Power Satellites, Ellis Horwood, 1993

Overall Efficiency of Converting Solar Energy @ GEO to Electricity on Earth with SPS is ≈ 7-8%

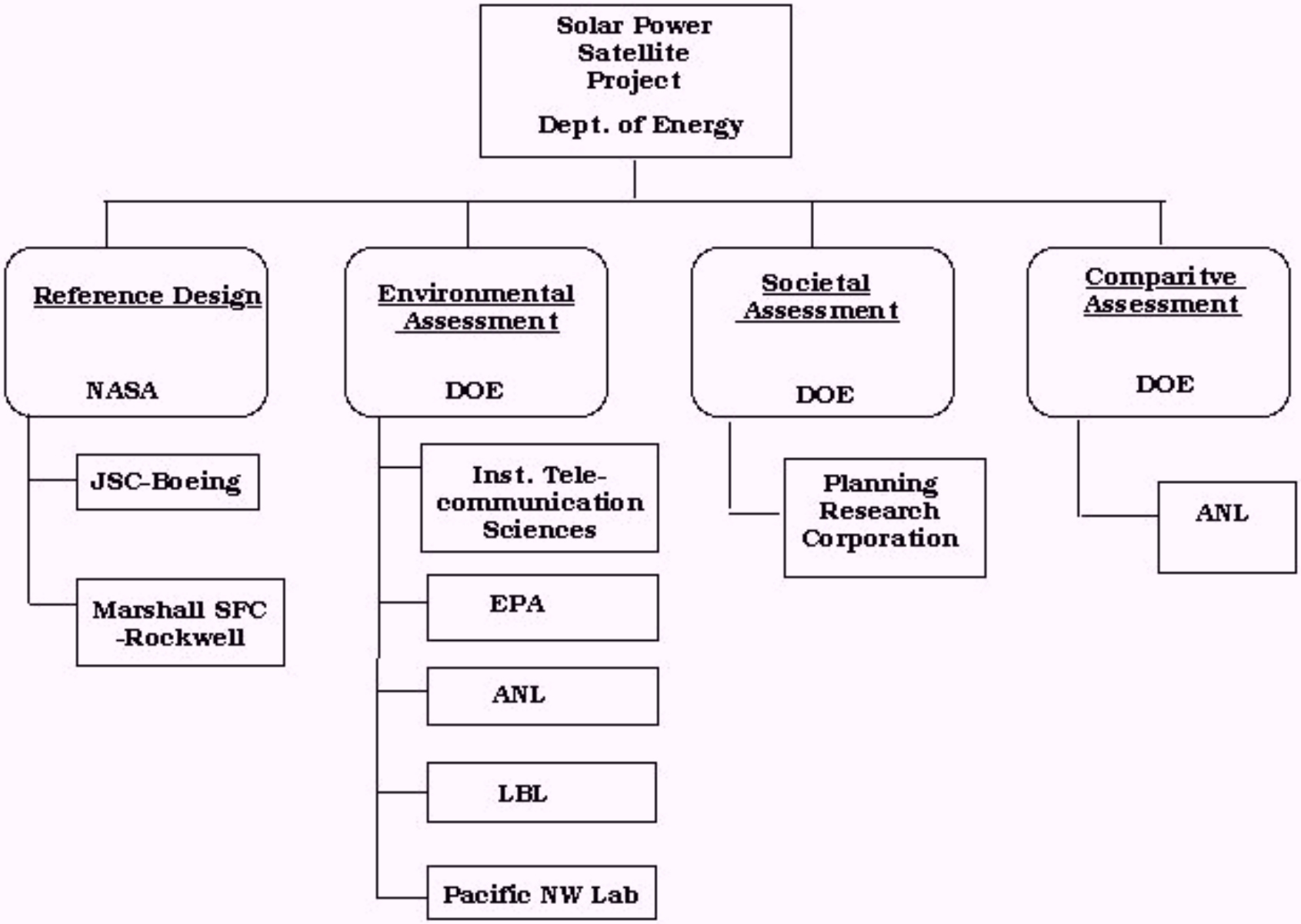
Process	Efficiency-%	Comment
Collection	88	Seasonal variations, eclipses
Conversion of Photons to Electricity (Is)	15.7	Including temperature effects, radiation, & degradation
Conditioning and Conversion	76.6	DC to RF
Antenna Transmission	96.5	
Transmission Through space	99.6	
Transmission Through Atmosphere	98	
Collection & Conversion	78.3	RF to electricity
Overall Efficiency	7.81	

The SPS Concept is Over 30 Years Old

- 1968-Peter Glaser proposes concept
- 1972-NASA/Lewis evaluates the concept
- 1973-Glaser patented the concept
- 1975-NASA demonstrates microwave power transmission
- 1977-DOE/NASA initiates Concept Dev. & Eval. Prog. (CDEP)
- 1978-9 DOE/NASA reviews
- 1980-DOE finishes review, published CDEP, terminates program
- 1981-NAS and OTA publish results of SPS critique
- 1990's renewed interest
- 1999- NASA initiates $15 M/y program on SPS technology
- 2001-NAS reassesses SPS, publishes report

Partial Source: F. A. Koomanoff and C. E. Bloomquist, p. 26 in Solar Power Satellites, Ellis Harwood, 1993

The SPS Was Examined in Considerable Detail in the Late 70's



The SPS Reference Design

System Characteristics

- Total electric power on Earth…..300 GW_e
- Single unit power ……5 GW_e
- Number of Units……60
- Design life……30 years
- Deployment rate……..2/year

Source: F. A. Koomanoff and C. E. Bloomquist, p. 26 in Solar Power Satellites, Ellis Harwood, 1993

The SPS Reference Design (continued)

Satellite Characteristics

- Overall dimensions…..10 x 5 x 0.5 km
- Structural material……..graphite composite
- Number of Units……60
- Design life……30 year
- Geo distance……35,800 km

Source: F. A. Koomanoff and C. E. Bloomquist, p. 26 in Solar Power Satellites, Ellis Harwood, 1993

The SPS Reference Design (cont.)

Energy Conversion System

- Photovoltaic Cells……..Si, or GaAlAs
- D. E. to RF Conversion……..klystrons
- Transmission Antenna Diameter…….1 km

Source: F. A. Koomanoff and C. E. Bloomquist, p. 26 in Solar Power Satellites, Ellis Harwood, 1993

The SPS Reference Design (cont.)

Ground Base Energy Conversion System

- Receiving Frequency……...2.45 GHz
- Rectenna dimensions (@ 35°lat.)

  Active 10 x 13 km

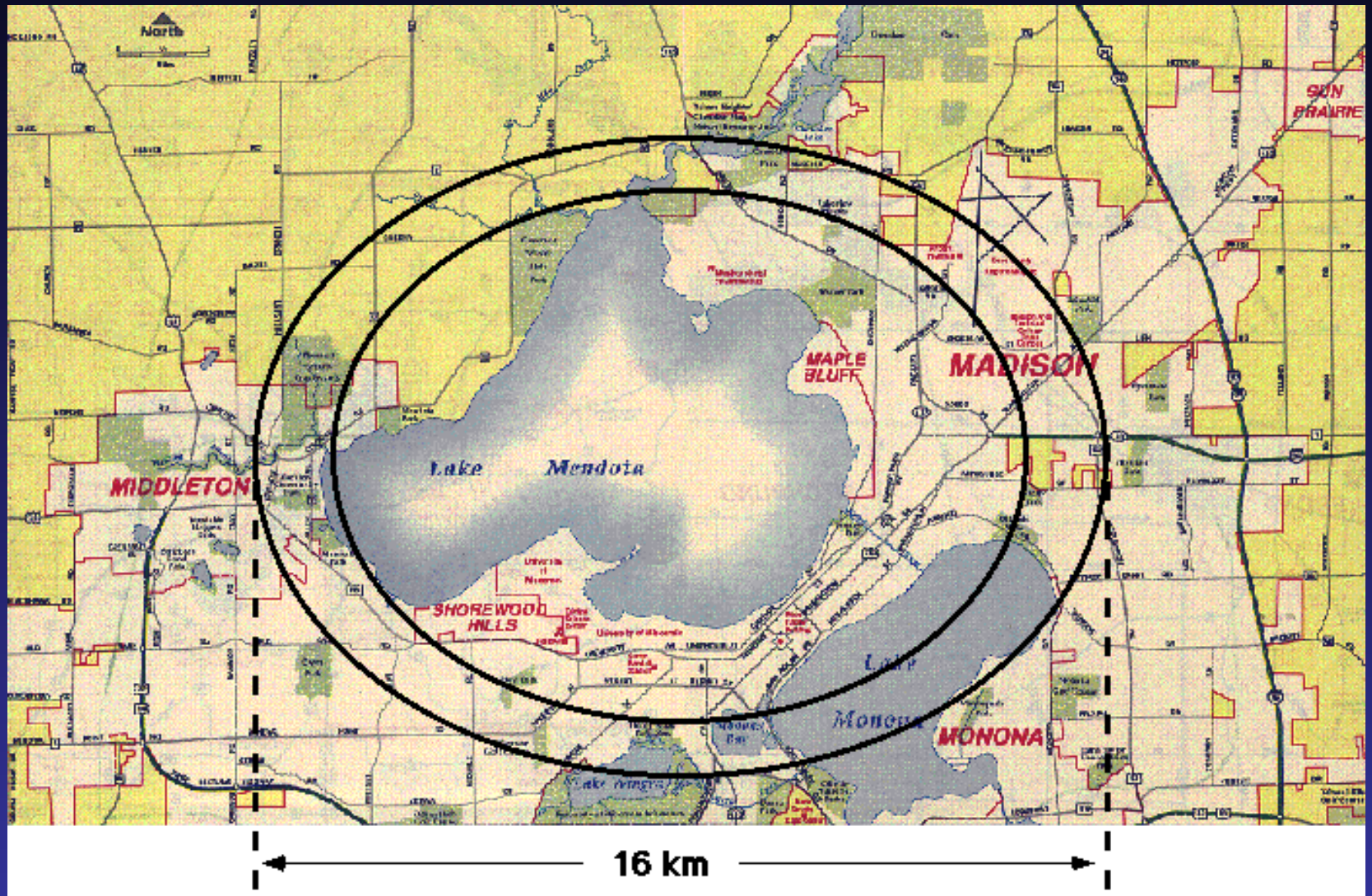
  Including Exclusion Area 12 x 15.8 km
- Rectenna power density peak…… 230 W/m^2

  @ edge……10 W/m^2

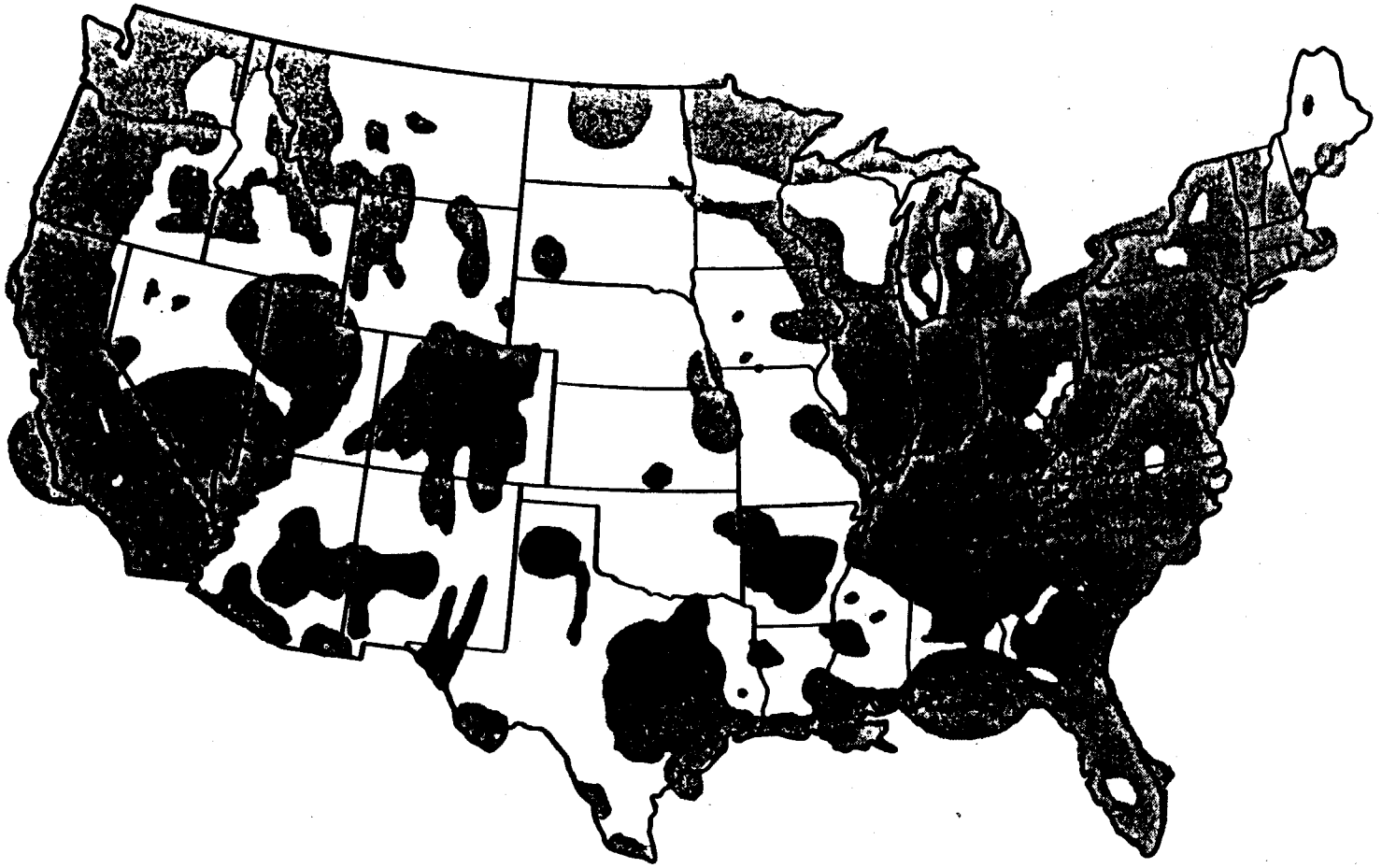
  @edge of exclusion zone……..1 W/m^2

Source: F. A. Koomanoff and C. E. Bloomquist, p. 26 in Solar Power Satellites, Ellis Harwood, 1993

The "Footprint" of the Solar Power Collector is Reasonable for a 300 GW_e Unit



Approximately 40% of the U. S. is Suitable for SPS Retenna Siting



SOURCE: *Satellite Power System (SPS) Rectenna Siting: Availability and Distribution of Nominally Eligible Sites,* DOE/ER-10041-T10, November 1980.

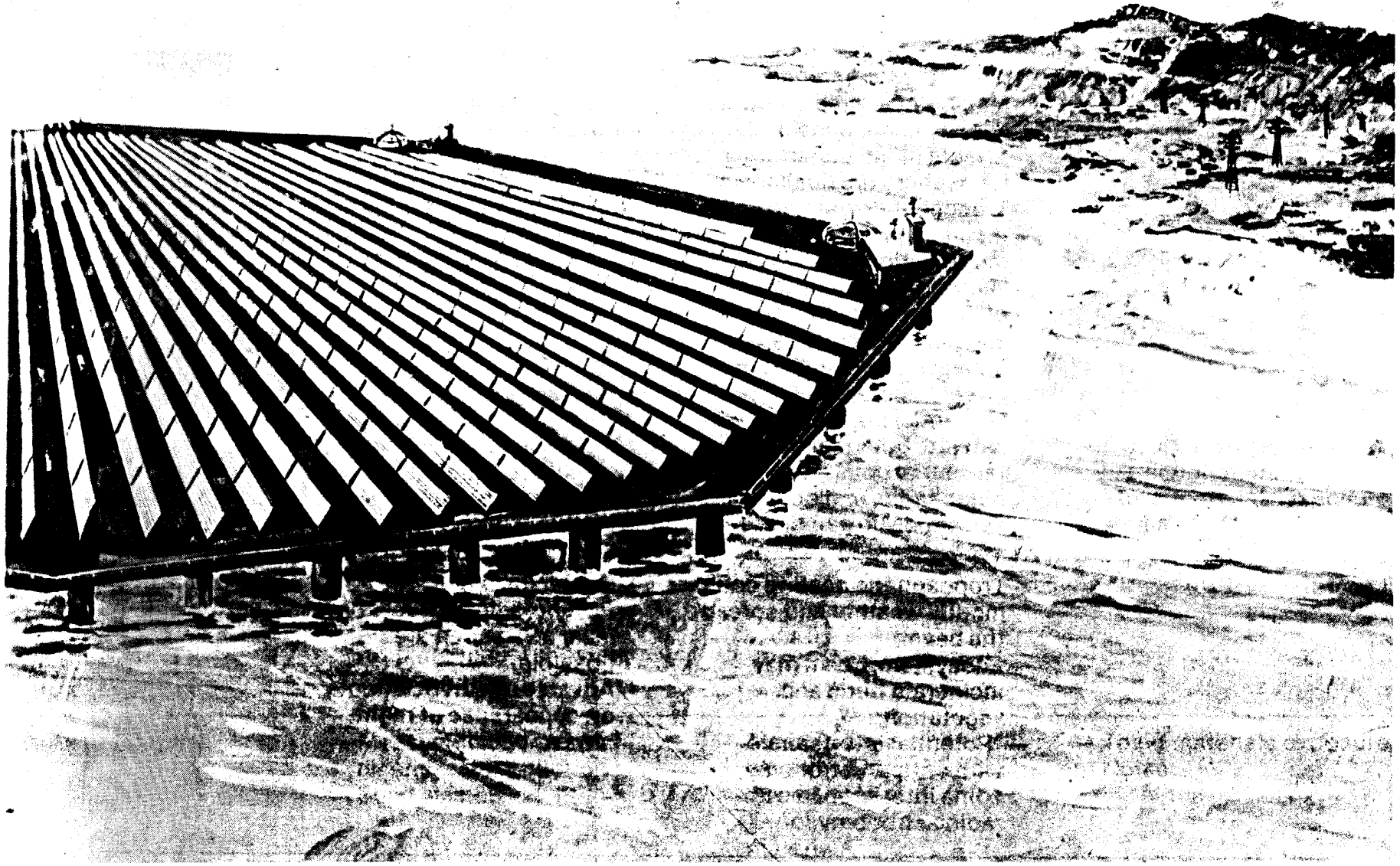


Photo credit: National Aeronautics and Space Administration

An artist's concept of an offshore antenna that would receive microwave energy beamed from a large space solar power collector in geosynchronous orbit

radiation to assess the health risks associated with SPS microwave systems. The information

tional standards. Even more stringent microwave standards could increase land require-

The SPS Reference Design (cont.)

Ground Base Energy Conversion System

- Receiving Frequency……..2.45 GHz
- Rectenna dimensions (@ 35°lat.)

  Active 10 x 13 km

  Including Exclusion Area 12 x 15.8 km
- Rectenna power density peak…… 230 W/m^2

  @ edge……10 W/m^2

  @edge of exclusion zone……..1 W/m^2

Source: F. A. Koomanoff and C. E. Bloomquist, p. 26 in Solar Power Satellites, Ellis Harwood, 1993

The SPS Reference Design (cont.)

Space Transportation System

- Earth to LEO……Cargo: vertical take-off, winged 2 staged (425 tonne payload)
  Personnel: modified shuttle
- LEO to GEO……Cargo: electric orbital transfer vehicle
  Personnel: 2-staged liquid O_2 + H_2

Source: F. A. Koomanoff and C. E. Bloomquist, p. 26 in Solar Power Satellites, Ellis Harwood, 1993

The SPS Reference Design (cont.)

Space Construction

- Staging base…….LEO: 480 km
- Final construction….. GEO: 35,800 km
- Satellite construction time….6 months
- Constriction crew…..600
- System maintenance crew:……240

Source: F. A. Koomanoff and C. E. Bloomquist, p. 26 in Solar Power Satellites, Ellis Harwood, 1993

There are 5 Key Technical Areas Where Advances are Required for the SPS to Succeed

1.) Energy Conversion and On-Board Power Distribution
   - A. Lightweight solar cell blanket lifetime-annealing T, cost
   - B. Solar Brayton and solar Rankine cycles
   - C. High voltage, high current, high speed switchgear
   - D. Effect of space plasma on high-voltage operation

There are 5 Key Technical Areas Where Advances are Required for the SPS to Succeed-(cont.)

2.) Power transmission and reception

- A. Beaming accuracy
- B. DC to RF converters
- C. Materials-efficiency, vibration,and thermal cycling
- D. Rectenna-Microwave scattering and harmonic generation

There are 5 Key Technical Areas Where Advances are Required for the SPS to Succeed-(cont.)

3.) Space Structures, Controls, and Materials

- A. Interaction between structural, thermal, & mechanical loads
- B. Fatigue resistance,ease of automated construction

There are 5 Key Technical Areas Where Advances are Required for the SPS to Succeed-(cont.)

4.) Construction, Operation, and Maintenance

- A. Rates, costs, and safety of SPS construction & operation
- B. Cost reductions from automated construction
- E. Practicality of off-shore rectenna siting

There are 5 Key Technical Areas Where Advances are Required for the SPS to Succeed-(cont.)

5.) Space Transportation

- A. Need to lower launch costs to $75/kg in LEO (1995$)
- B. Reusable vehicles and components
- E. Increased engine life and maintainability
- D. Scalability of ion engine technology
- E. Possibility of MPD engines

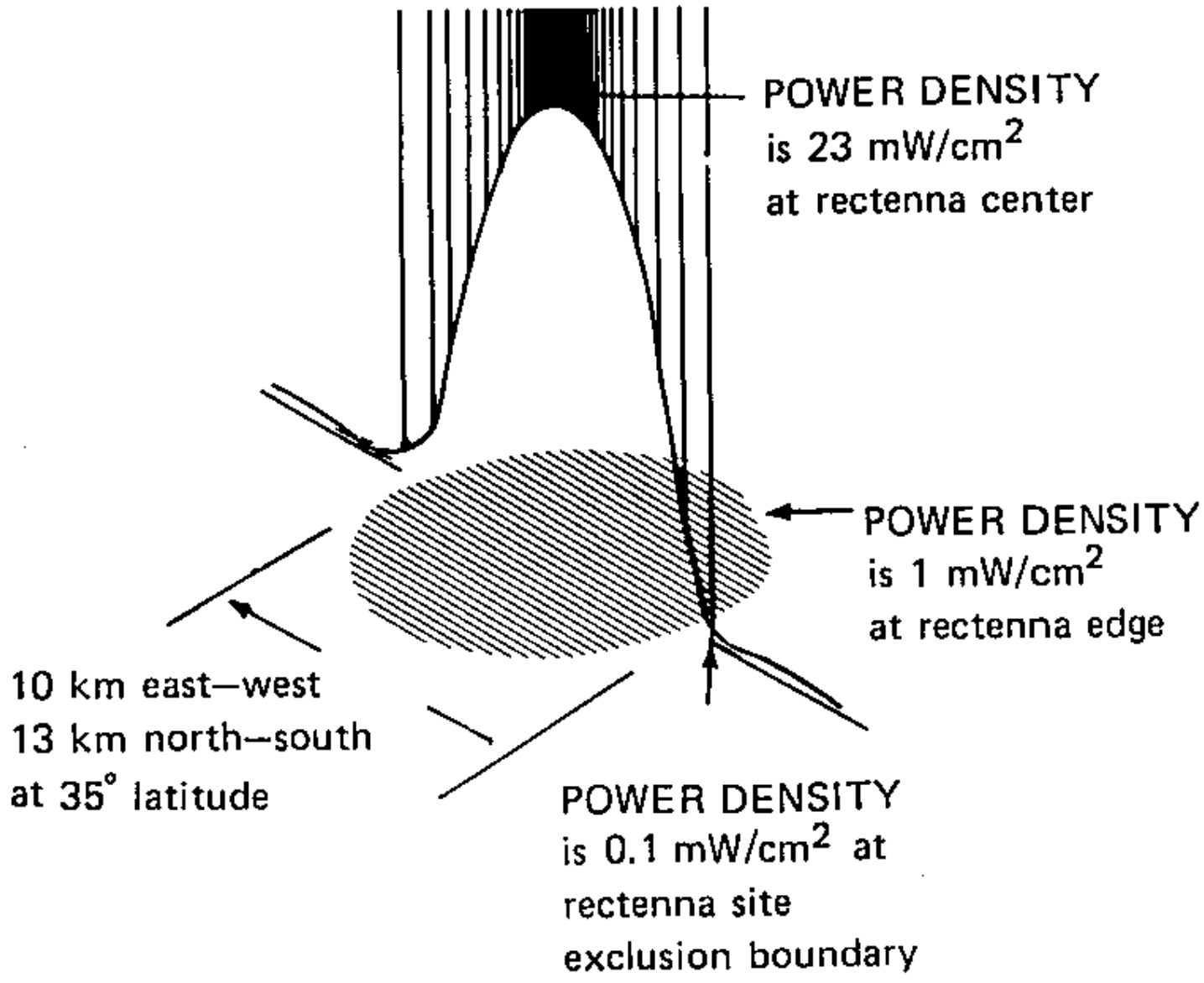
There are 5 Areas of Environmental/Safety Effects Associated with the SPS Project

- 1.) Microwave exposure effects on health and ecosystems
- 2.) Non-microwave effects on health and ecosystems
- 3.) Atmospheric effects
- 4.) Ionosphere heating effects
- 5.) Effects on Astronomy

Microwave Exposure Effects on Health and Ecosystems

- Microwaves @ 2.45 GHz do not have enough energy to ionize atom, they can only agitate them
- If radiation intensity is high enough, ≈ 10's of W/m^2, one can experience body heating
- Adverse effects to animals have been reported at 40-300 W/m^2

The Power Distribution From a 5 GW_e SPS



after P. Glaser, Solar Power Satellites, Ellis Horwood, 1993

Microwave Exposure Effects on Health and Ecosystems (cont.)

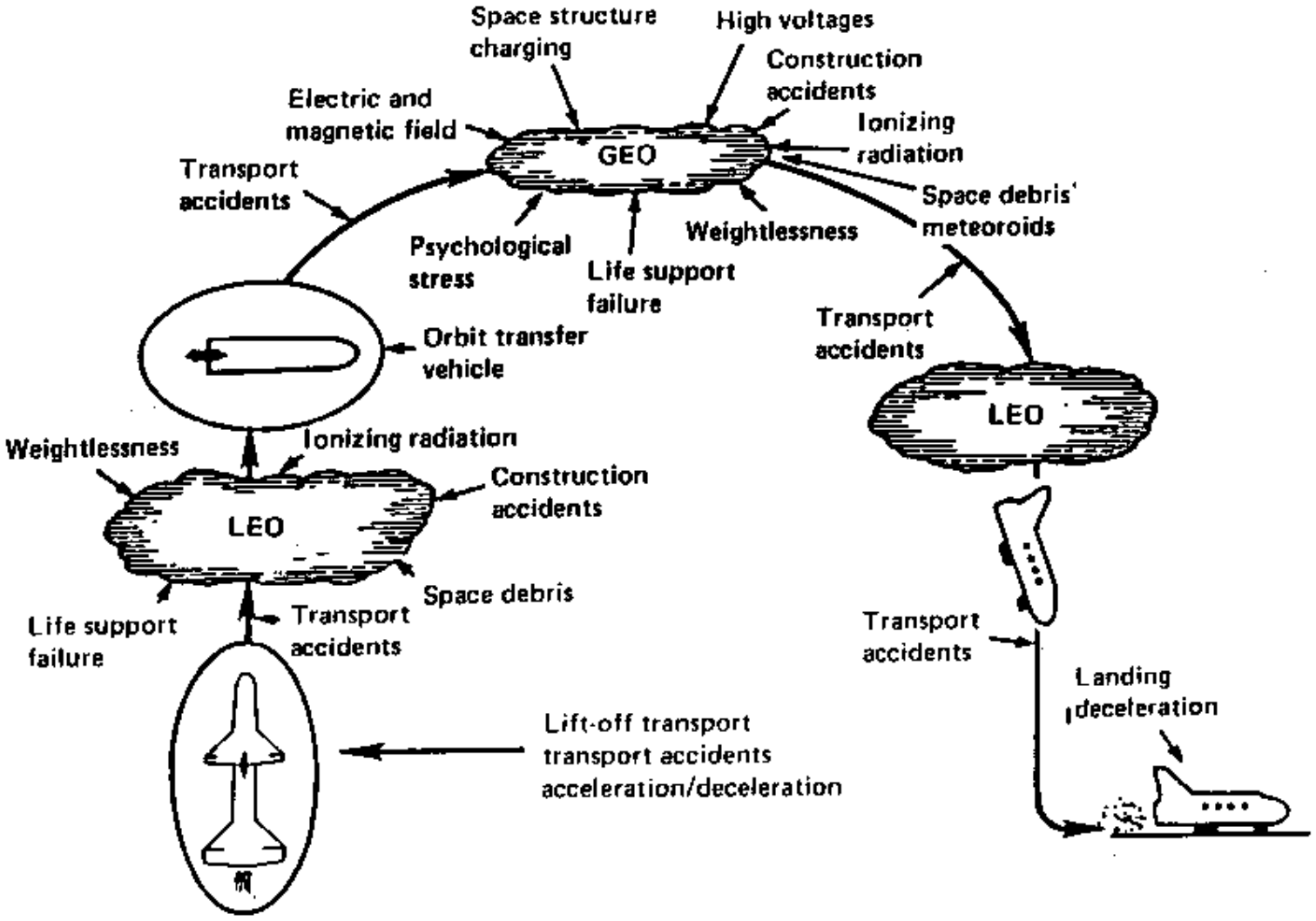
- If the SPS electricity delivered to Earth was 300 GW_e, 88% of the 1995 production, (60 sites with 5 GW_e rectenna at each site), they would have to be placed an average of 300 km apart.

- Given the current beam profiles, the minimum microwave flux between sites would be 0.001 W/m^2. Background is 0.0001 W/m^2.

Living and Working in Space can be Hazardous to Your Health

- For the reference system proposed in the late 70's, it was estimated that it would take 600 workers, working full time, 30 years to construct sixty-5 GW_e SPS's in GEO.
- It was assumed the workers would live in LEO and be transported to GEO
- Total exposure ≈ 18,000 person-years
- This does not include maintenance

There Are Several Factors to Consider When Assessing Worker Saftey



after Koomanoff and Bloomquist, Solar Power Satellites, Ellis Horwood, 1993

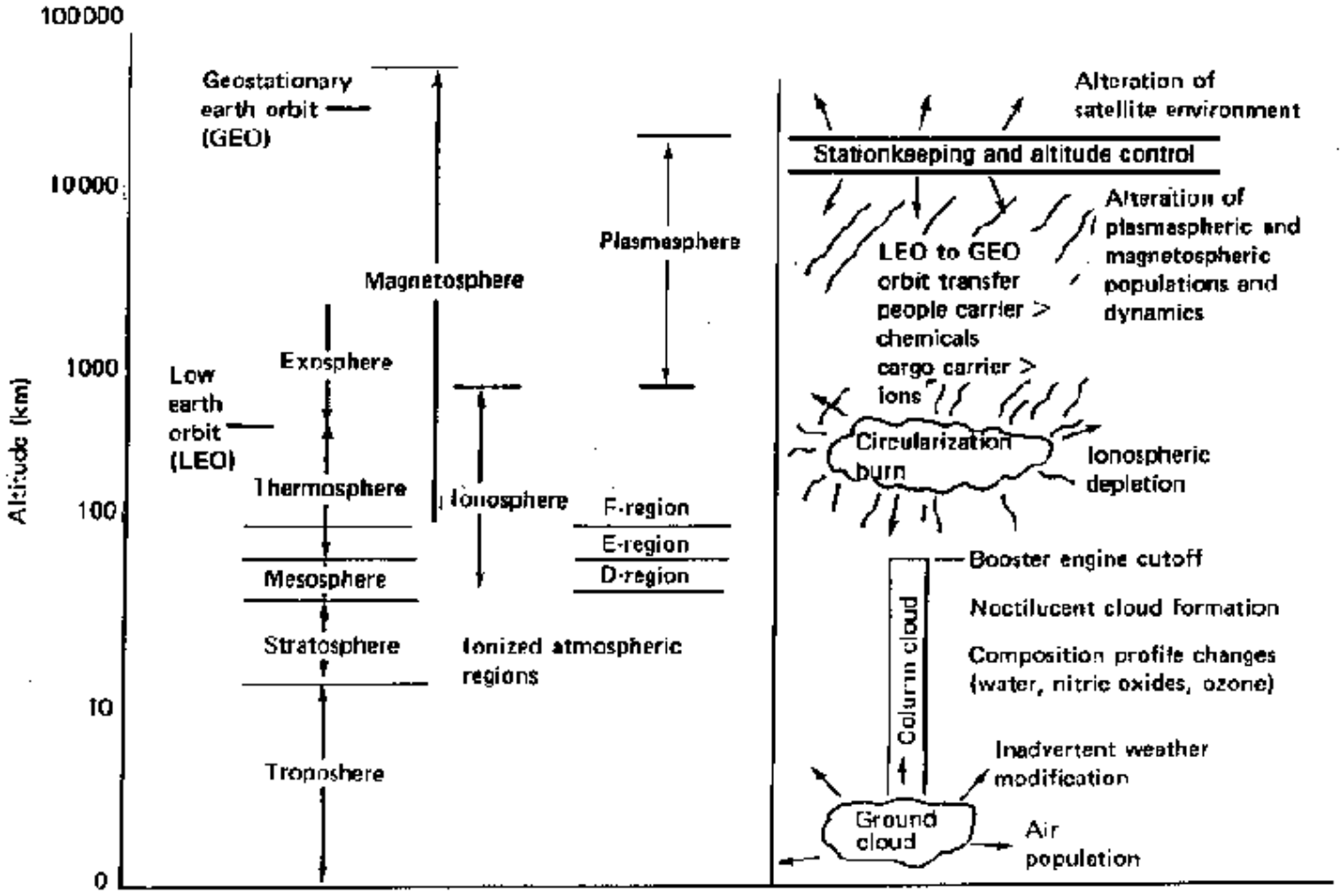
The High Level of HLLV Activity Associated with SPS's Could impact the Earth's Atmosphere

- The troposphere weather could be modified due to water and thermal energy injection
- Effluents from fuel combustion could change local air quality
- Deposition of large quantities of water and H_2 into the thermosphere will alter composition (calculations indicate that effect could be 8% @ 80 km and a factor of 100 @ 120 km)

The High Level of HLLV Activity Associated with SPS's Could impact the Earth's Atmosphere-(cont.)

- Injection of water vapor @ 80-90 km could form Noctilucent clouds
- Operations in LEO/GEO could result in injection of substantial mass and energy in the magnetosphere and plasmasphere
- Areas effected:
  - Telecommunications and terrestrial interference
  - Enhanced airglow
  - Weather and climate modifications

Potential Atmospheric Effects From SPS Activity



after Koomanoff and Bloomquist, Solar Power Satellites, Ellis Horwood, 1993

Ionospheric Heating Effects

- Transmission of microwave power through the ionosphere could increase the temperatures of electrons in the D- and E-regions
- Hot D- or E- region electrons could cause a degradation in telecommunications

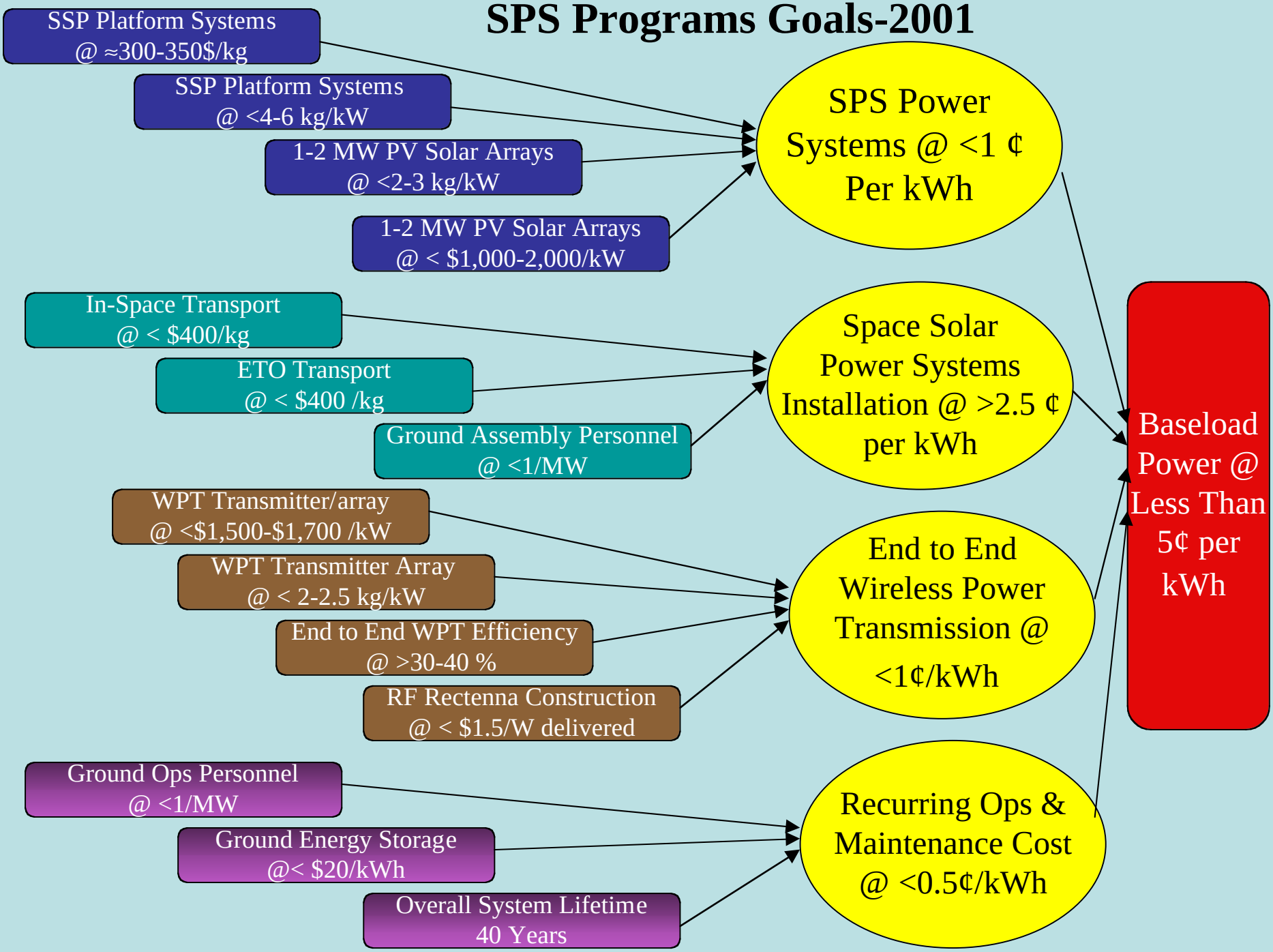
Astronomy Effects

- Currently Astronomers attempt to detect the faintest optical and electromagnetic signals reaching the Earth.
- It is estimated that a SPS would be optically as bright as Venus at its brightest
- Increased sky brightness from 60 SPS units would interfere with optical observations in a 10° to 70° band centered on the line of satellites.

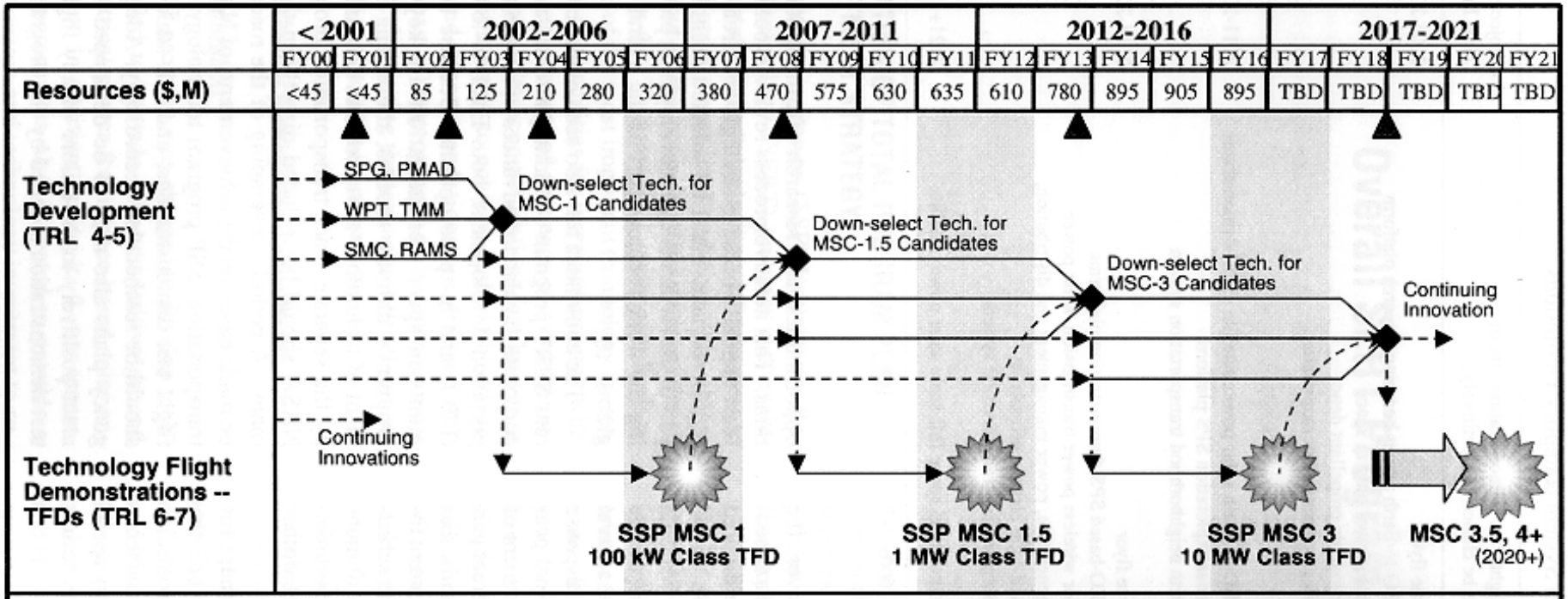
Societal Impacts

- 1.) Land resources
  - 40% of U. S. is suitable for SPS rectenna siting
  - Requires ≈ 150 km2 of contiguous land
  - May have an effect on bird fly-ways
- 2.) Local social and economic
- 3.) Allocation of SPS-GEO slots will require extensive negotiations
- 4.) Military applications of SPS' s are possible
- 5.) Modifications to Public Institutions will be required

SPS Programs Goals-2001



Space Solar Power
Research & Technology Schedule of Milestones Roadmap



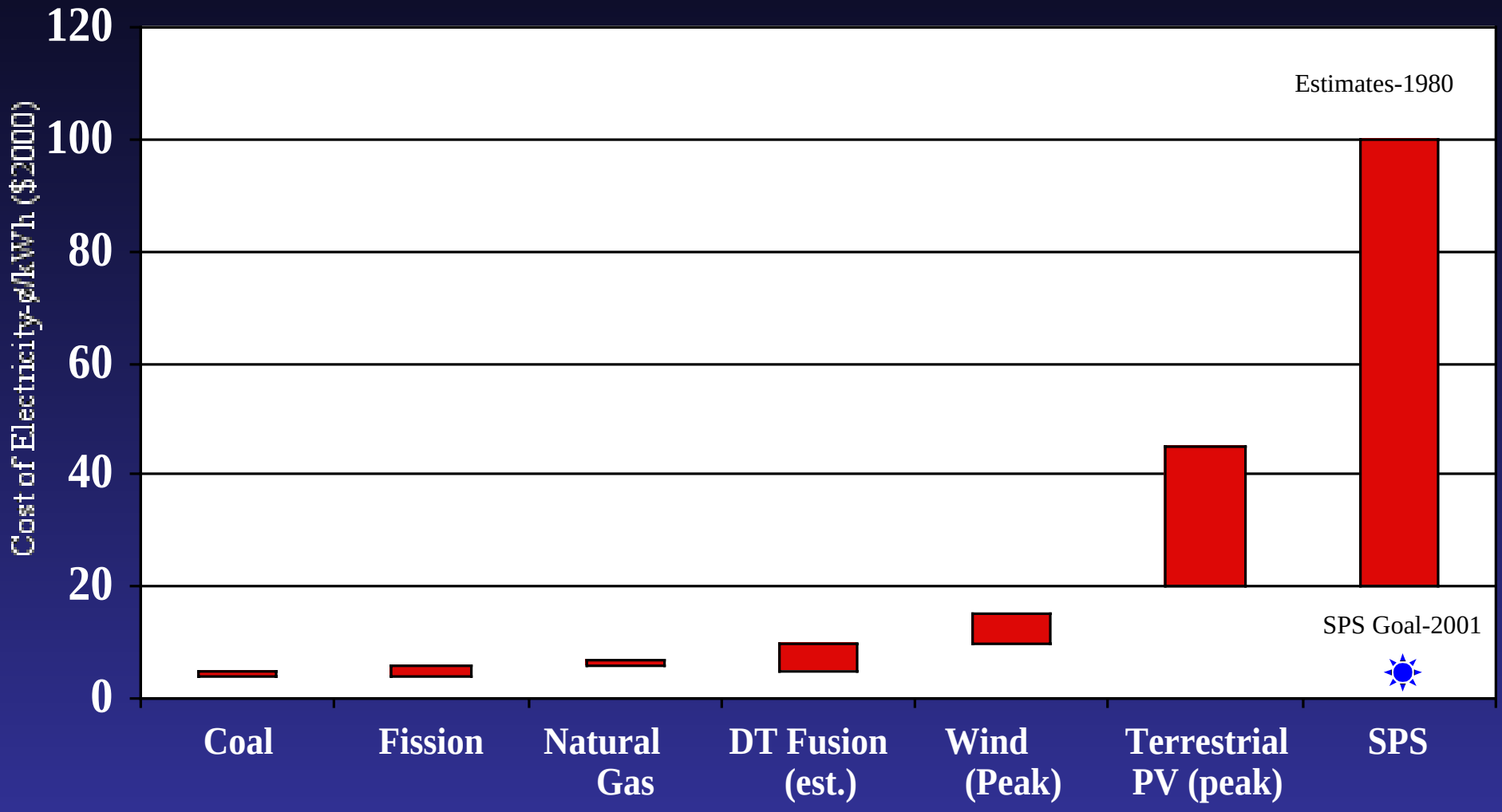
Schedule of Milestones

- '99-'00 Complete initial Space Solar Power Exploratory Research and Technology (SERT) Program
- 2001 Identify/refine top 2-3 systems concepts/architectures for each MSC Demonstration opportunity; refine interim applications
- 2002 Establish/Integrate SSP test beds at participating organizations
- 2003 Down-select technologies for initial 100kW class TFD
- 2004 >200 W/kg Solar Power Generation (Array Level) in a Test Bed
  High-efficiency WPT (>10kW level) in a Test Bed
- 2005 50 M class structures & controls flight experiments
- '06-'07 100KW Space-to-Ground & Space-to-Space SPG/WPT Demo
- 2008 >400W/kg Solar Power Generation (Array Level in the Lab
  50 kW Solar Electric Propulsion/Generation Flight Test
  High-efficiency WPT (>100kW level) in a Test Bed
- 2008 Down-select technologies for 1 MW class TFD
- '11-'12 1 MW Class Space to Space SPG/WPT Demo
- '12-'13 >600W/kg Solar Power Generation (Array Level)
- 2013 Down-select technologies for initial 10MW class TFD
- 2017 >1000W/kg Solar Power Generation (Array Level)
- '16-'17 10 MW CLASS INTEGRATED SSP SYSTEM FLIGHT DEMO

LEGEND ◆ Strategic Research and Technology Decision Point ▲ Major Technology Development Milestone ✹ Major Technology Flight Demonstration

FIGURE 2-1 NASA's SERT program: research and technology schedule of milestones roadmap. NOTE: Figure reprinted in original form. SOURCE: Mankins and Howell, 2000b.

The Present Cost of Electricity for SPS is Not Economical



Conclusions-SPS

- Designed to meet global electric energy needs
- Technology is all available now but cost is too high
- Critical to get launch costs (to GEO) down to < $360/lb or < $800/kg