National Aeronautics and Space Administration

Propulsion options for sending a spacecraft into the interstellar medium

September 2014

Les Johnson / NASA MSFC

Catalog of Viable Propulsion Options

- Chemical (Space Launch System)
- Electric Propulsion
- Nuclear Thermal
- Solar Thermal
- Solar Sail
- Electric Sail

SLS Block 1B Shroud

Fairing Envelope

Usable Payload Static Envelope

Negotiable Envelope Below Separation/Interface Plane

Payload Attach Fitting

Acoustic Blankets

Notes:

All dimensions are in mm/in.

Acoustic blanket thickness is 114.3 mm (4.5 in.) in nose and cylindrical section.

Delta Program requires definition of payload within 51 mm (2.0 in.) of payload envelope.

Projections of spacecraft appendages below the spacecraft separation/interface plane may be permitted but must be coordinated with the Delta Program Office.

Payload Attach Fittings	
PAF	Height mm/in.
1194-5	2088/82.2
1575-5	1807/71.2
1666-5	2134/84.0

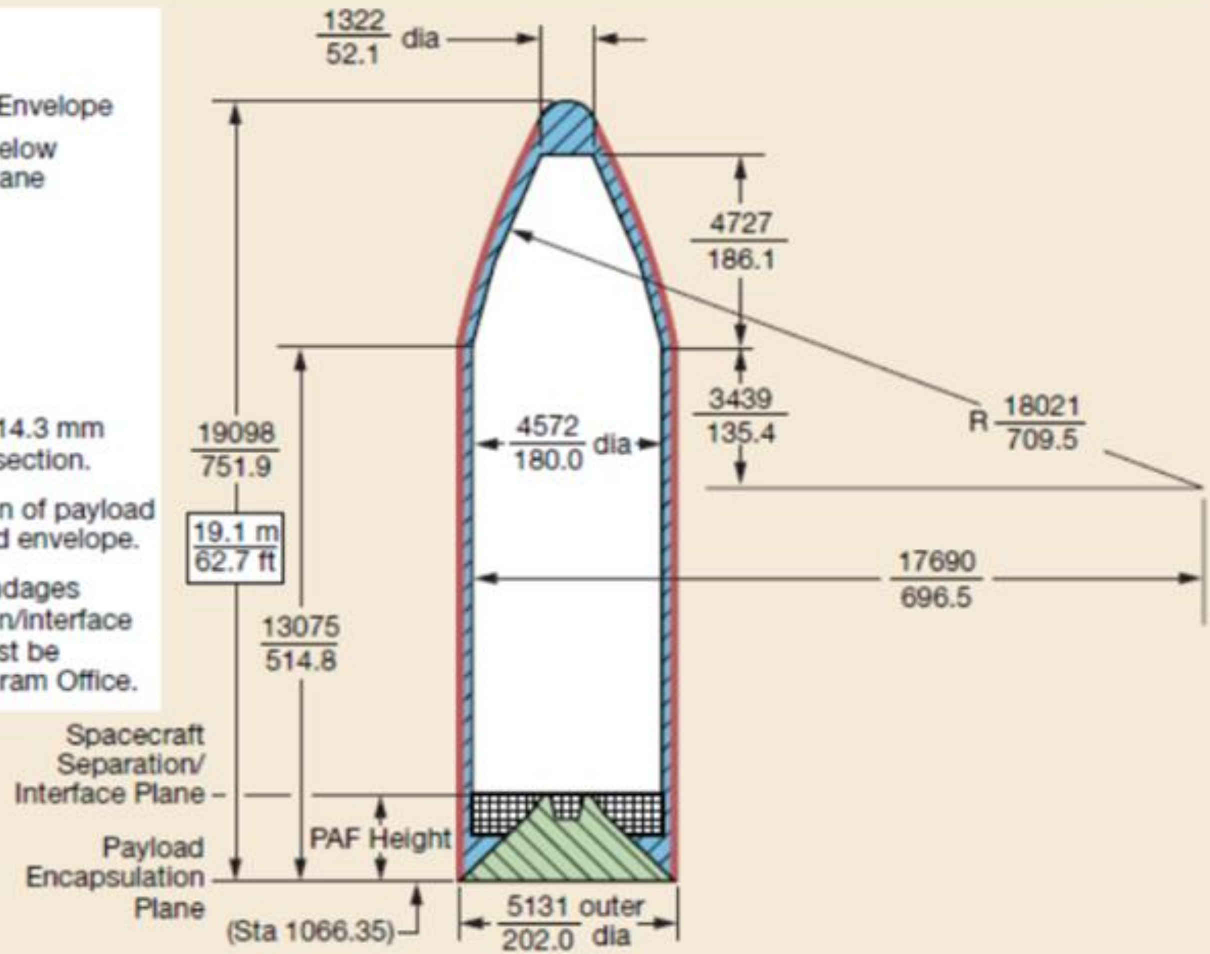
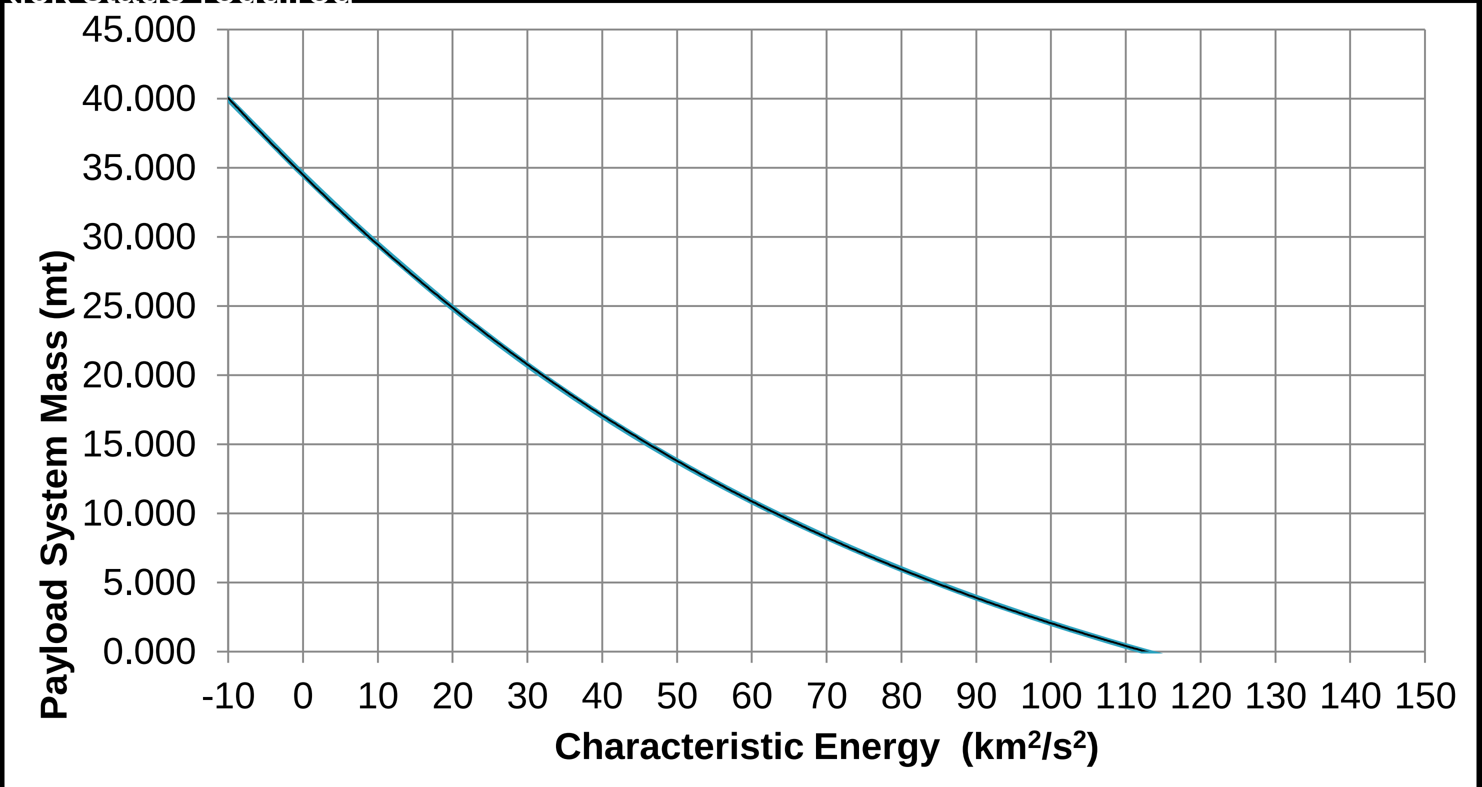


Figure 3-5. Payload Static Envelope, 5-m-dia by 19.1-m Composite Fairing

SLS Block 1B Performance

- 250 AU
- Assume Voyager mass
- Requires C3 of about 150 km^2/s^2
  - Performance curve shows that SLS has no capability at this high C3
    - Kick stage required



Conclusions

- No trajectories found that meet the desired 20-30 year outbound total trip time
  - Jupiter gravity assist the best case
    - 42 year total trip time
    - Simpler flyby targeting since a single planet
  - Saturn-Uranus
    - 40 year trip time required two 4 km/s powered flybys, which results in stages that are too heavy for the SLS Block 1B
- These analyses were not optimized. Better performance is likely.

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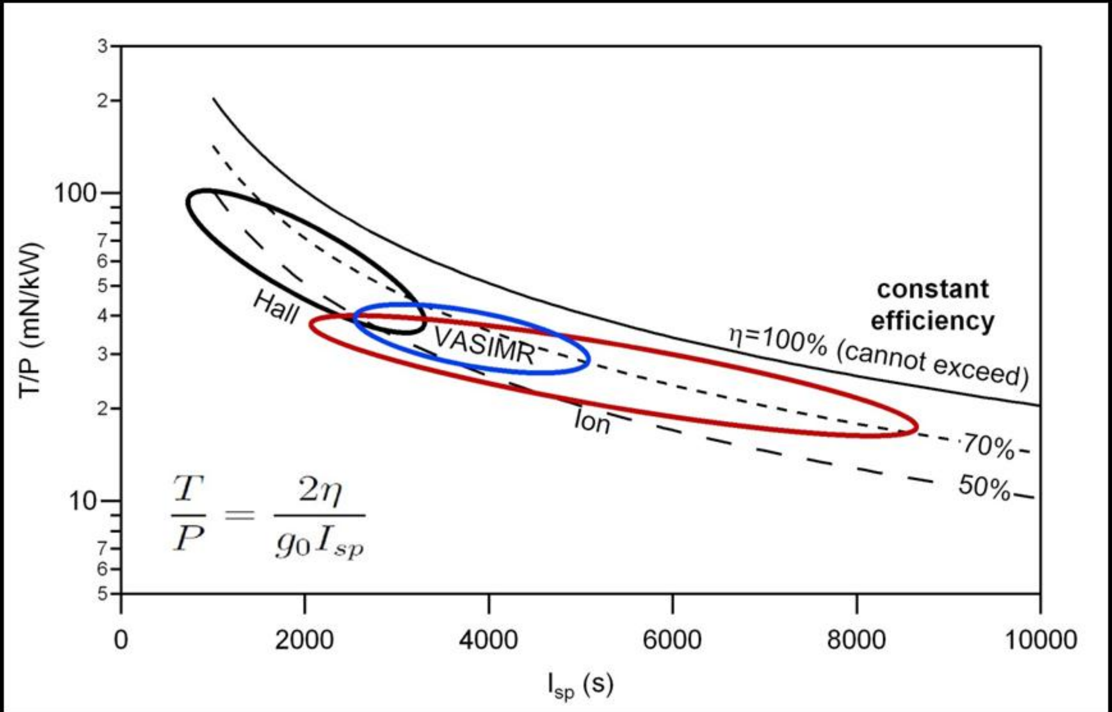
Electric Propulsion Technology Survey Thrust-to-Power and Isp

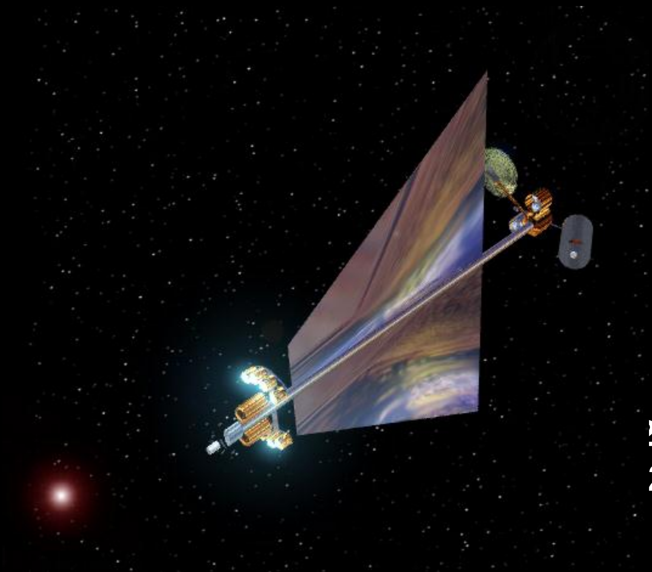
- In an electric propulsion system there is an inverse relationship between high thrust-to-power and high Isp
  - At fixed power and efficiency, the trade-off is between thrust (driving trip time) and Isp (driving system mass)
  - At fixed Isp and efficiency, the only way to increase thrust is to increase the power.



EP Technologies (SEP or NEP)

- Gridded Ion Thrusters
  - NASA's Evolutionary Xenon Thruster (NEXT)
  - Nuclear Electric Xenon Ion System (NEXIS)
- Hall Effect Thrusters at generic power levels of: 4.5, 10, 20, and 50 kW
- Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

Nuclear Electric Propulsion Previous Study Summary

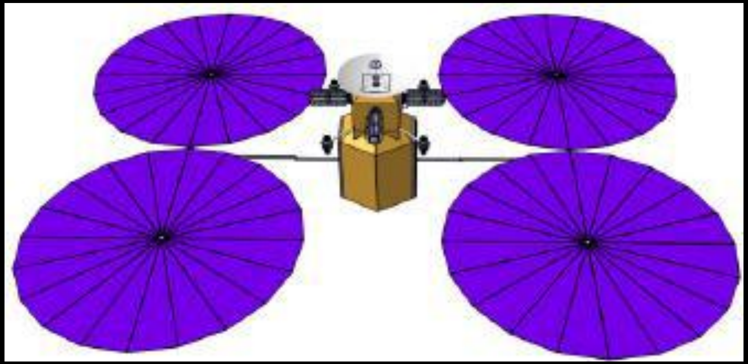


2010
2022

- **Transportation Approach**
  - Depart from 2500 km circular LEO
  - Spiral out to escape in about 96 days
  - Heliocentric direct trajectory
    - 200 AU in 15 years (Vinf = ~13.3 AU/Year)
  - Vehicle Parameters: Payload = 191 kg, Overall System α = 10.15, Power System α = 8.15 kg/kW, Tankage Fraction = 5% of Propellant, Power = 500 kW, Isp = 8,550 seconds, overall eff. = 70%

- **Assessment Results**
  - IMLEO: 13.2 mt
  - Departure: 2015
  - Trip Time ~15 yrs
  - Mission Duration : 20+ yrs
- **Issues**
  - Ion propulsion system required does not exist
    - Need to run new analysis using NEXT engine
  - Necessary power system technology does not exist:
    - High inlet turbine temperature: 1500 K
    - Low radiator areal mass: 3 kg/m^2
    - High distribution voltage: 1000 V
    - High conversion system lifetime
  - Cost: Last attempt to field NEP system (JIMO) was extremely expensive
- **Reference**
  - Farris, B., et al. "Integrated In-Space Transportation Plan." NASA STI/Recon Technical Report N 3 (2002): 00623.

Solar and Radioisotope EP Previous Study Summary



- **Assessment Results**
  - Initial Mass to Earth Escape 1692 kg
  - Trip Time 28 yrs
- **Issues**
  - Ion engines do not exist
  - Availability and cost of multiple RTG's
- **Reference**
  - Loeb, H.W., Schartner, K.H., Dachwald, B., and Sebodt, W., "Interstellar Heliopause Probe, Электронный журнал «Труды МАИ». Выпуск № 60

- Transportation Approach
  - SEP used in inner solar system and on outbound until burnout
    - 6 ion engines (Isp = 7300 s)
    - >50 kW solar array power,
  - REP used after SEP stage is jettisoned
    - Isp = 3800 sec, ~600 W radioisotope power
    - 4 Radioisotope Thermoelectric Generators (RTG's)
  - Jovian Gravity Assist assumed
  - Launce to C3 > 0 assumed

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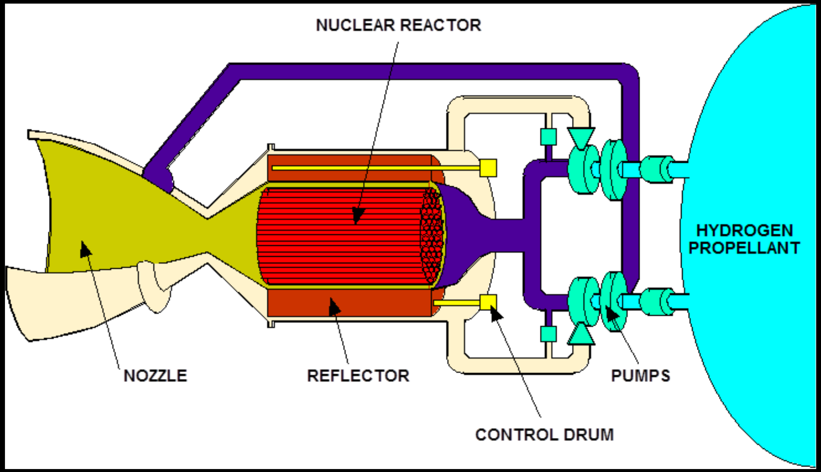
Nuclear Thermal Propulsion (NTP)



Major Elements of a Nuclear Thermal Rocket

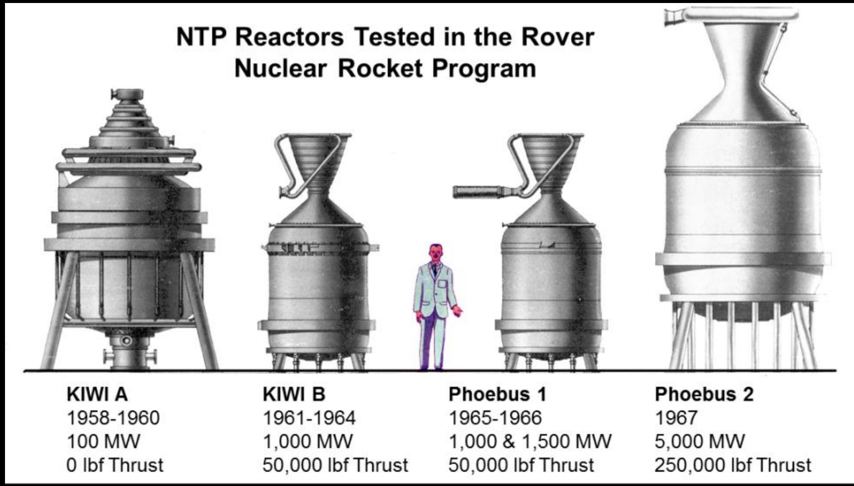
Nuclear Thermal Rocket Prototype from ~1970

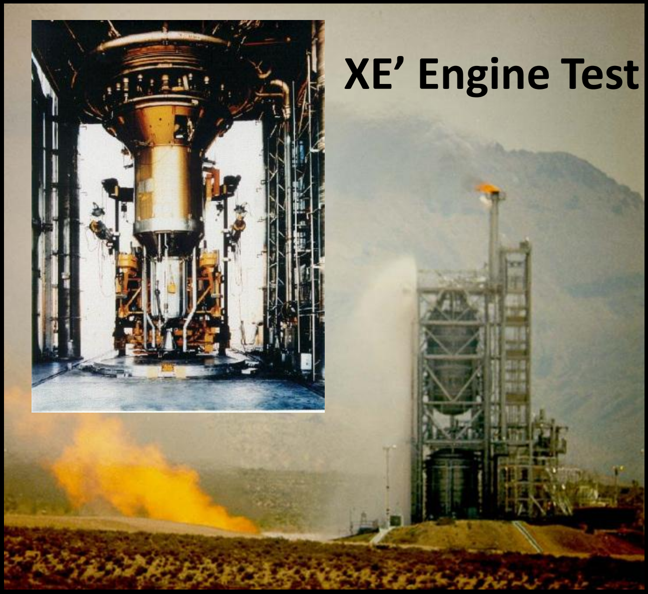
- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: 50,000 N ≈ 225 MW_{th} at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O_2/H_2 engine runs hotter than NTP)

Nuclear Thermal Propulsion (NTP)

- **20 NTP / reactors designed, built and tested at the Nevada Test Site in the 1960's and early 1970's for the Rover/NERVA program**
- **Engine sizes tested**
  - 25, 50, 75 and 250 klb_f
- **H_2 exit temperatures achieved**
  - 2,350-2,550 K (in 25 klb_f Pewee)
- **I_{sp} capability**
  - 825-850 sec ("hot bleed cycle" tested on NERVA-XE)
  - 850-875 sec ("expander cycle" chosen for NERVA flight engine)
- **Burn duration**
  - ~ 62 min (50 klb_f NRX-A6 - single burn)
  - ~ 2 hrs (50 klb_f NRX-XE': 27 restarts / accumulated burn time)

**** NERVA: Nuclear Engine for Rocket Vehicle Applications***





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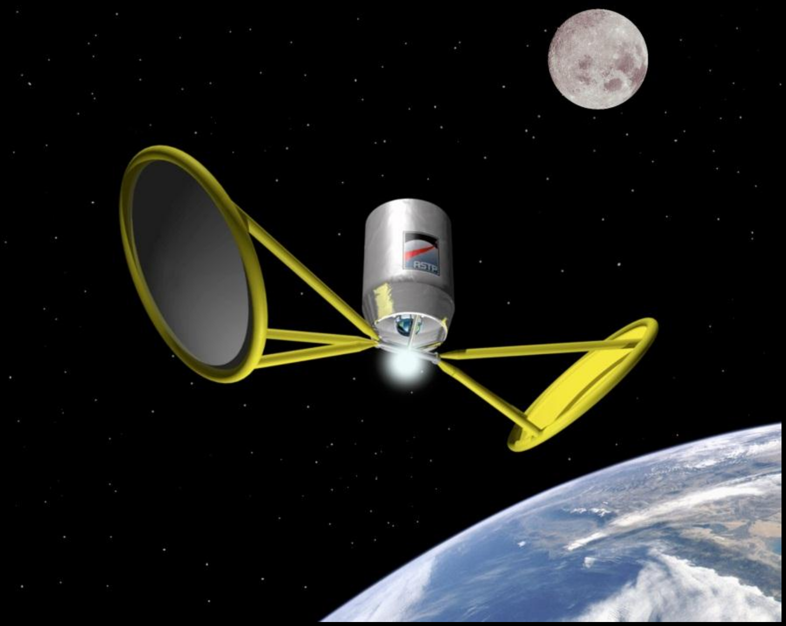
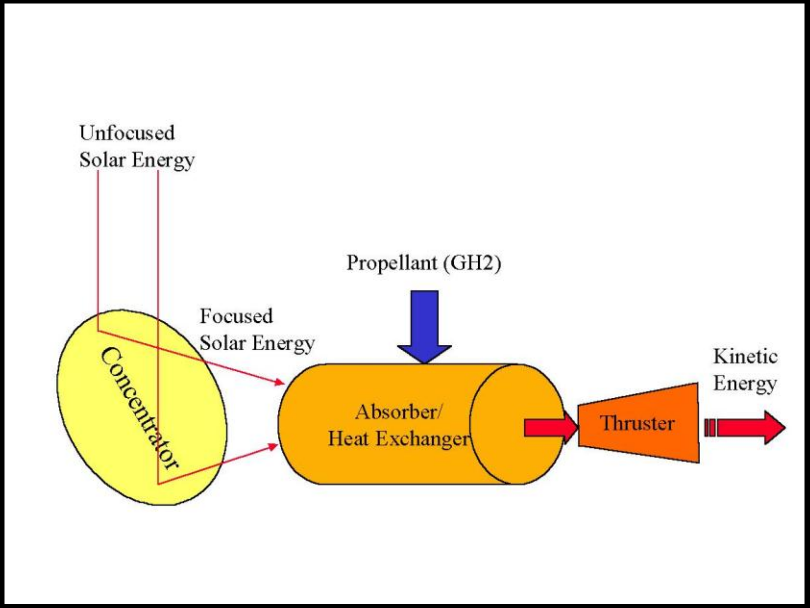
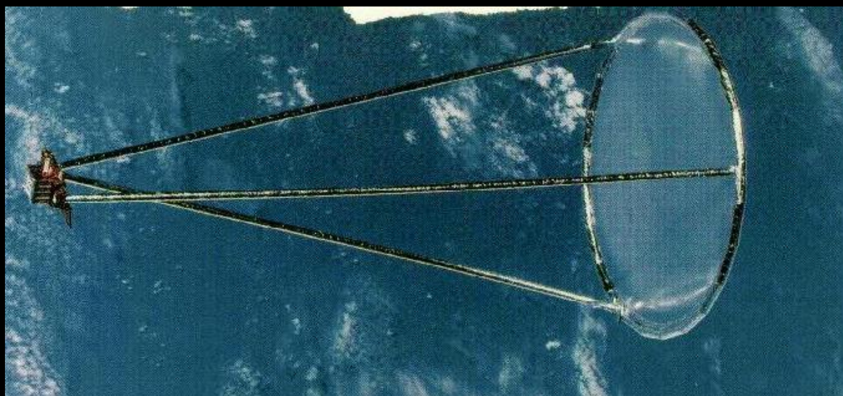
Solar Thermal Propulsion (STP)





The STP system takes the sunlight impinging on a large collector/concentrator and focuses it into the absorber cavity of the thruster for either direct heating of the propellant or indirect heating via heat exchanger to extremely high temperatures and specific impulse >900 seconds using hydrogen as propellant.

Solar Thermal Propulsion (STP)



1996 L'Garde Inflatable Antenna Experiment (IAE) (14 meter diameter antenna) seen from STS-77

MSFC Solar Thermal Propulsion Test Facility ~10kW

A lot of STP work done by the AFRL and NASA in the mid-1990's. Improvements needed in optical concentrator accuracy and performance (improving from 50-60% to 85-90%), system/stage packaging, sun pointing, inflatable deployment, controlled cryogenic boil-off, and engine performance. An integrated overall system test has never been performed. STP is currently limited by payload shroud volume when considering liquid hydrogen LH2 for propellant. An option to overcome this limit involves utilizing high temperature carbides with melting point ~4000K and provide specific impulse >1200 seconds.

STP thruster made of 100% Tungsten

MSFC Advanced Concepts

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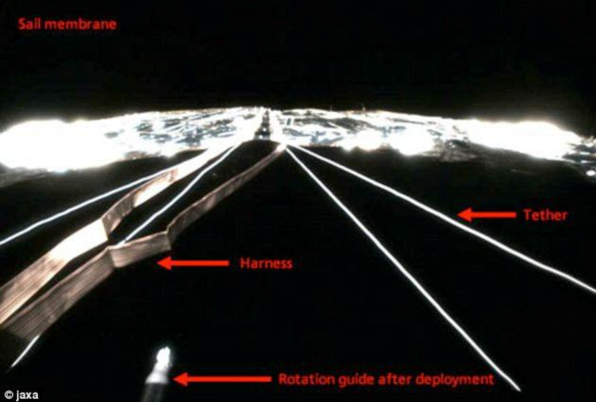
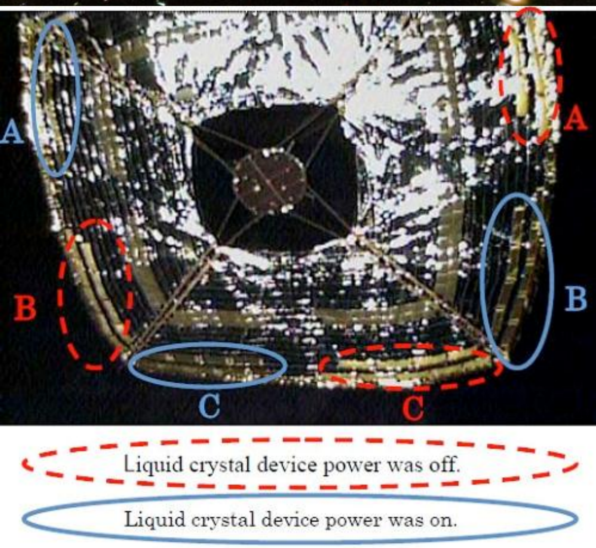
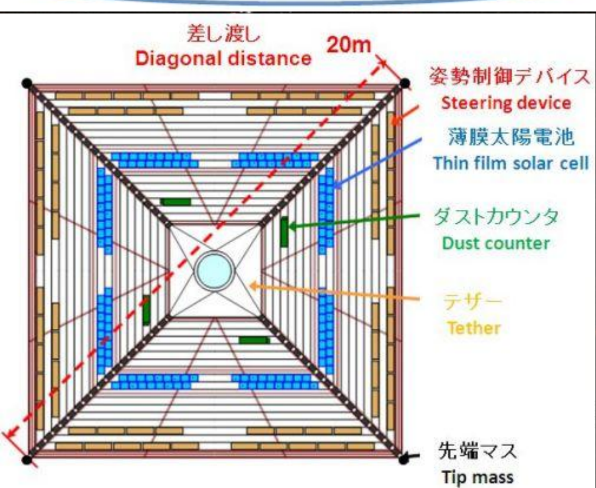
Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)







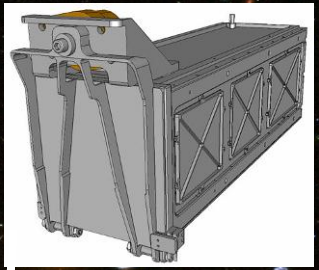
- IKAROS was launched on May 21, 2010
- The Japan Aerospace Exploration Agency (JAXA) began to deploy the solar sail on June 3, 2010.
- IKAROS has demonstrated deployment of a solar sailcraft, acceleration by photon pressure, and attitude control.
    - Deployment was by centrifugal force

Configuration / Body Diam.	1.6 m x Height 0.8 m (Cylinder shape)
Configuration / Membrane	Square 14 m and diagonal 20 m
Weight	Mass at liftoff: about 310 kg

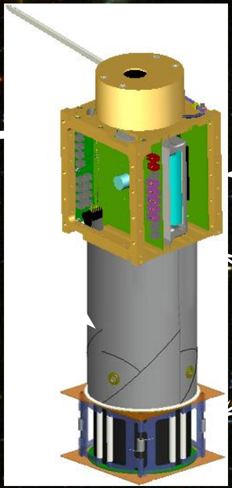

JAXA

NanoSail-D2 Mission Configuration (2010)

Boom & Sail Spool (ManTech SRS)



PPOD Deployer
(Cal-Poly)



Spacecraft Bus (Ames Research Center)

Bus interfaces Actuation Electronics (MSFC/UAH)

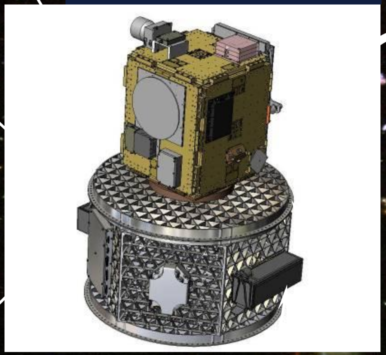
NanoSail-D
(Aluminum Closeout Panels Not Shown)

Stowed Configuration

HSV-1

AFRL Satellite (Trailblazer)

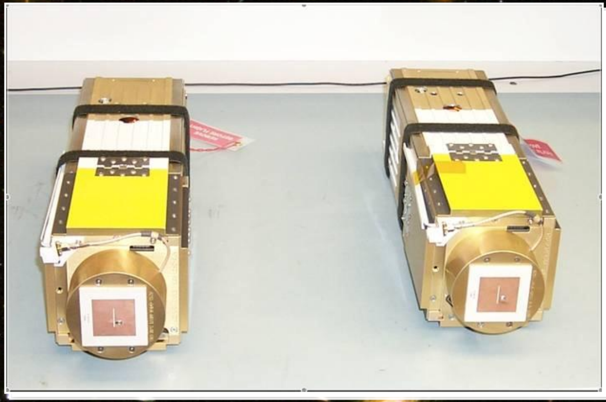
Adapter



PreSat (ARC)

NanoSail-D (MSFC)

Ride Share Adapter
(Space Access Technology)



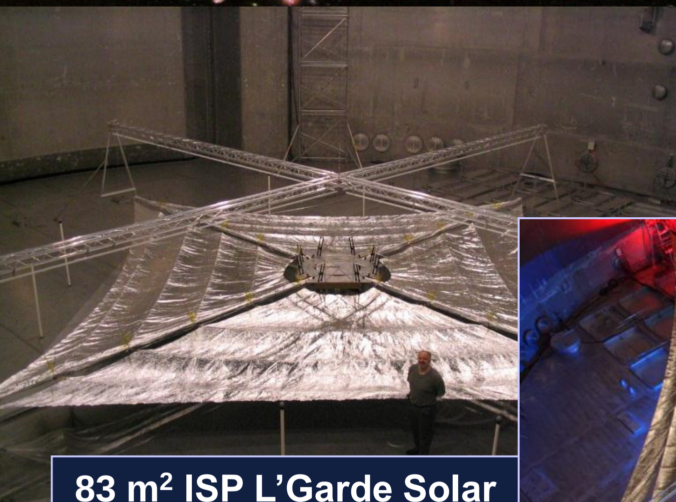
NSD-002 NSD-001

- 3U Cubesat: 10cm X 10cm X 34cm
- Deployed CP-1 sail:10 m^2 Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF & S-Band communications

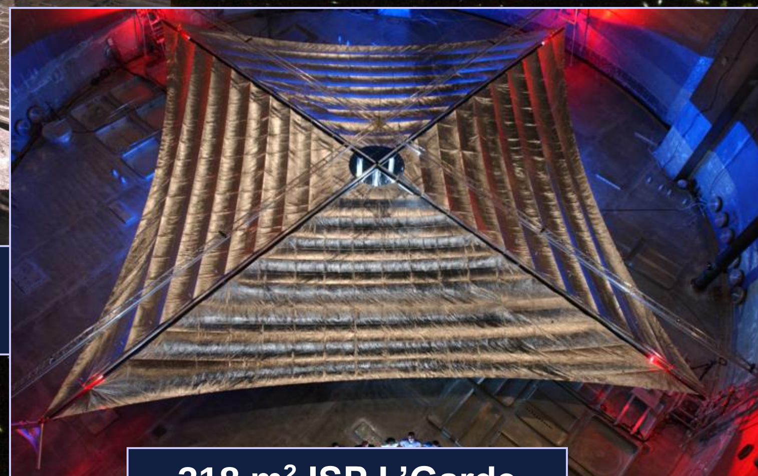
Sunjammer Solar Sail Demonstration Mission

Design Heritage

- Cold Rigidization Boom Technology
- Distributed Load Design
- Aluminized Sun Side
- High Emissivity Eclipse Surface
- Beam Tip Vane Control
- Spreader System Design



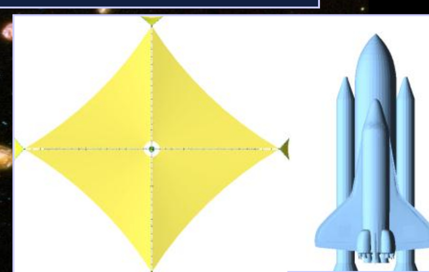
83 m^2 ISP L'Garde Solar Sail 2004



318 m^2 ISP L'Garde Solar Sail 2005

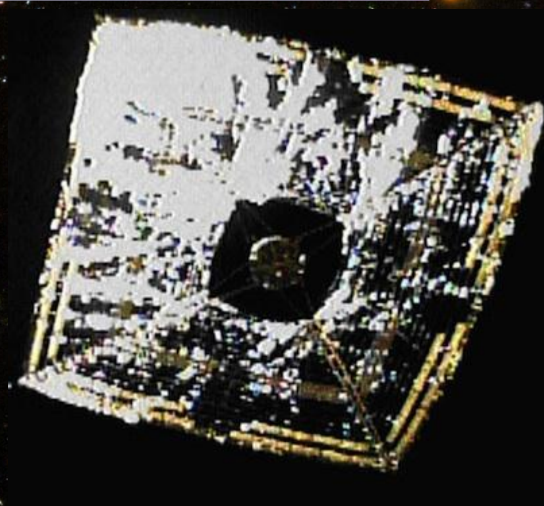
Design Features

- High Density Packagability
- Controlled Linear Deployment
- Structural Scalability
- Propellantless Operation
- Meets Current Needs



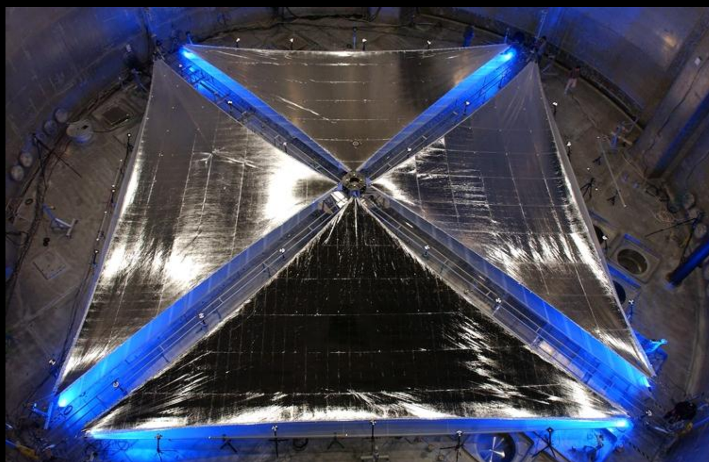
~1200 m^2 L'Garde Sunjammer Launch 2015

Solar Sails TODAY – Many Players



- **NASA and L'Garde's *Sunjammer***
  - ~1200 square meters
- **The Planetary Society's *LightSail-A* planned to launch in 2015. –B in 2016**
  - 32 square meters
- **The University of Surrey's CubeSail, DeorbitSail (2015), and InflateSail (2015)**
  - 16 square meters
- **ESA and DLR's *Gossamer 1* and Gossamer-2**
- **NASA's Near Earth Asteroid Scout (2017) and Lunar Flashlight (2017)**
  - 85 square meters

Solar Sail Propulsion
Previous Study Summary



- **Assessment Results**

Initial Mass to Earth Escape	0.6 mt
Areal Density (g/m^2)	1.0
Square Sail Side (m)	350
Trip Time	15 yrs
Mission Duration :	30 yrs
Total Mission Ops Time:	30 yrs

- **Issues**
  - Sail areal density and size required exceeds technology projections for 2020
  - Thermal control at near-sun (0.25 AU) approach
- **Reference**
  - Farris, B., et al. "Integrated In-Space Transportation Plan." NASA STI/Recon Technical Report N 3 (2002): 00623.

- Transportation Approach
  - Launch Vehicle delivers to $C_3 = 0$
  - Sail (122 kg) spun-up / deployed
    - Sail deployment mech. (286 kg = ~2x sail) jettisoned after deployment
  - Sail flies near sun to build up speed (higher light pressure) - Rmin = 0.25 AU
  - Sail jettisoned ~ 5 AU
  - Spacecraft (191 kg) coasts through the outer Solar System to the heliopause and into interstellar space
    - 200 AU in 15 years (Vinf = 14.13 AU/Year)

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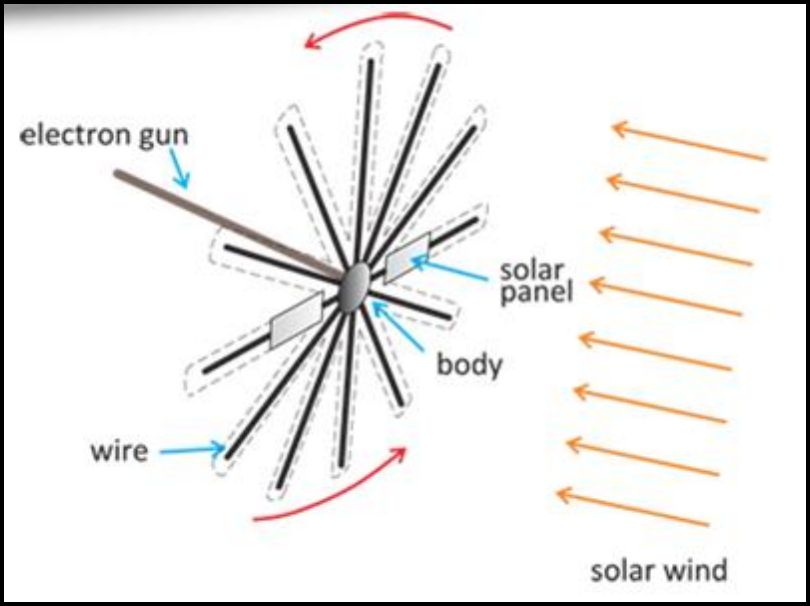
Electric Sail Propulsion

- Electric sail utilizes charged tethers to repel solar wind protons to gain momentum
- Tethers are centrifugally stretched and charged to a high voltage using an onboard electron gun



Electric Sail Propulsion Status

- Technology developed and studied extensively by Dr. Pekka Janhunen of the Finnish Meteorological Institute
- Calculations show that the thrust drops as $1/r^2$ for the solar sail and $1/r^{7/6}$ for the electric sail
- NIAC Phase 1 awarded to Bruce Wiegmann (NASA MSFC) to study the mission technology/concept for Heliopause mission