Evolution of ISS as Technology Development, Demonstration, and Deployment (TD**3) Infrastructure to Support Commercialization of Low Earth Orbit and Beyond

IAC SYSTEMS ENGINEERING SYMPOSIUM (D3)

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Evolution ISS to support TD^3 missions

XISP-Inc Evolving TD^3 Mission Set

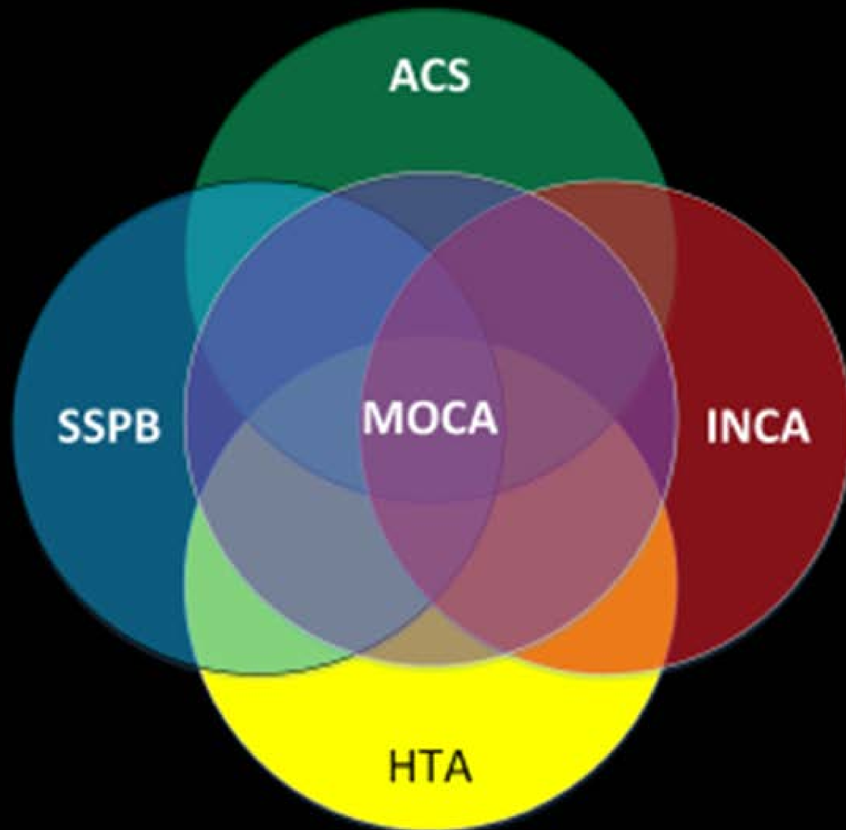
Alpha CubeSat (ACS)

Space-to-Space Power Beaming (SSPB)

Halfway To Anywhere (HTA)

Interoperable Network Communication Architecture (INCA)

Mission Operations Control Applications (MOCA)



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Space Solar Power Key Considerations

- Space Solar Power is an applied engineering problem and an economics problem.
- Applications have significant systems engineering and economic challenges in each venue that must be successfully addressed.
- Each venue has different fundamental figures of merit which define their value proposition.
- Operational capabilities are best realized by leveraging a combination of technology development "Push" and mission requirements "Pull".
- Each increment of public and/or private investment should lead to an operational capability.
- Work Vectors: Technology Development → Demonstration → Deployment and Space-to-Space → Surface-to-Surface → Space-to-Alt Surface → Space-to-Earth

Space Solar Power Key Variables

• Cost/Economics (initial cost to first power, LCOE, market viability, anchor customers),
• Frequency/Wavelength (microwave to eye-safe optical),
• Voltage/Amperage (input, output, transforms)
• Distance (near field, boundary regions, far field),
• Magnitude (power level supporting applications, scalability)
• Duration (pulsed, scheduled, continuous),
• Availability (dispatchable, on demand, scheduled, prioritized, by exception, resilience, interoperability),
• Security (misuse, interruption, destruction, safety),
• Performance (net transfer, end-to-end efficiency, piecewise efficiency, steering precision and accuracy, beam shaping, effective operational difference),
• Logistics (mass, volume, modularity, durability, maintainability),
• Environmental (temperature, radiation, degradation), and
• Technology Readiness Level [TRL] (cost, schedule, and technical risk)

Space-to-Space Power Beaming (SSPB) Hypothesis

XISP-Inc has hypothesized that unbundling/disaggregating power systems (i.e. the separation of power generation, transmission, control, storage, and loads) can:

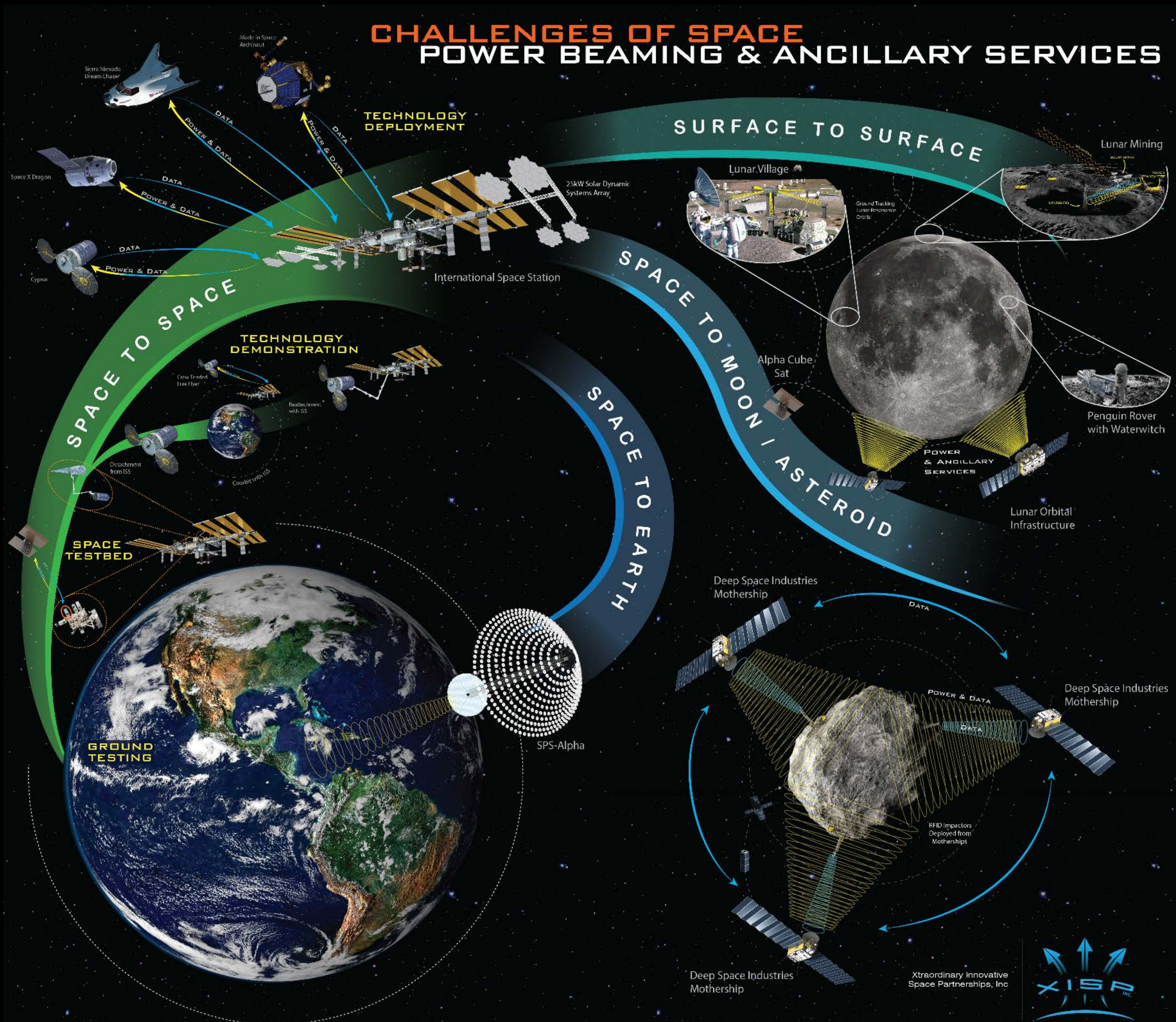
- reduce spacecraft complexity, mass and/or volume
- allow reallocation of spacecraft mass and/or volume
- alter the cadence of spacecraft mission operations
- reduce or eliminate solar pointing requirements
- impart additional delta-V to spacecraft/debris

  - indirectly (power augmentation) -
  - directly (momentum transfer)

Work Vectors

Venues

Venues	Space Solar Power Problem Space: Technology Development — Ground	Space Solar Power Problem Space: Technology Development — Space	Space Solar Power Solution Space: Operational Capability/Applications — Technology Demonstration	Space Solar Power Solution Space: Operational Capability/Applications — Technology Deployment
Space - to - Space	• Cognitive SDR Transceiver • Converged Electro/Optics • W Band & Optical Apertures • Piecewise Efficiency • Reflectarray Rectenna • Beam Forming • Management Operations Control Applications (MOCA)	• ISS Mounted Transceiver • Deployable Rectenna • 6U Flight Test Article • Optimized Frequencies • End-to-End Efficiency • Scaling/Modularity (Gen, Trans, and Control) • Multiplexing Services • MOCA S/W & Data System	• ISS Co-orbiting Crew Tended Free Flyer Demo • Propulsion Augment Demo • Space Based Propellant Depot Operations Demo • Disaggregated Formation Flying Spacecraft Demo • Plug in/Plug Out Tech Demo	• Power & Ancillary Services Beaming Interface Kit(s) • Dispatchable Power & Ancillary Services • Cislunar Propulsion Services • Kilowatt scale services
Surface - to - Surface	• Deployable Power Generation & Relay Towers • Conformal Rectenna • Deployable Rectenna • Solar Concentrator/Reflector	• Powered Rover • Powered Prospector • Powered Miner • Volatile/Metal Separation	• Power & Ancillary Services Beaming - Survive the Night • Volatiles Mining Demo • Propellant Depot Demo • Metals Mining Demo	• Dispatchable Power & Ancillary Services • 24x7 Operations Support • Kilowatt to Megawatt Scale Services
Space - to - Moon / Asteroid	• Disaggregatable Flight Systems Technology • Scalable Transceiver • Scalable/Printable Rectenna • Management Operations Control Applications (MOCA)	• Mothership with deployable sensors/rovers • Distributable Rectenna • Lunar Resonant Orbits • Beam Steering (Phased Array & Gimbals)	• Power & Ancillary Services Beaming Demo • Lunar Assay & Mining Demo • Asteroidal Assay & Water/ Volatiles Mining Demo • Asteroidal Optical Drilling, Volatiles Mining & Demo • Metal Refining Demo • Planetary Defense	• Synergistic impact of Cislunar Development • Dispatchable Power & Ancillary Services • 24x7 Operations Support • Megawatt to Gigawatt Scale Services
Space - to - Earth	• Lunar Resource Model • Asteroidal Resource Model • Drive launch costs down to $100/kg to LEO • Atmospheric Transparency • Beam Management -- Frequency/Control/Security • MOCA Authentication, Authorization and Control System	• Modular Structure I/Fs (mechanical/robotic/ control/thermal) • Thermal Management • Pointing Large Structures • Electro-Magnetic/Optical Alignment • Solar Dynamic Modules • Non-Iridium Based Concentrated Photovoltaic	• Power & Ancillary Services Beaming to UAVs & Others • Power & Ancillary Services Beaming to Forward Bases • Power & Ancillary Services Beaming to Terrestrial Grid	• Synergistic impact of Cislunar Development • Dispatchable Power & Ancillary Services • National and International Geopolitical High Ground • Gigawatt to Terawatt Scale Services


CHALLENGES OF SPACE
POWER BEAMING & ANCILLARY SERVICES
Sierra Nevada Dream Chaser
Made in Space Archinaut
TECHNOLOGY DEPLOYMENT
Space X Dragon
Cygnus
DATA
POWER & DATA
2.5kW Solar Dynamic Systems Array
International Space Station
SURFACE TO SURFACE
Lunar Village
Lunar Mining
SPACE TO SPACE
TECHNOLOGY DEMONSTRATION
SPACE TO MOON / ASTEROID
Alpha Cube Sat
Penguin Rover with Waterwitch
POWER & ANCILLARY SERVICES
Lunar Orbital Infrastructure
SPACE TO EARTH
SPACE TESTBED
GROUND TESTING
SPS-Alpha
Deep Space Industries Mothership
Deep Space Industries Mothership
Deep Space Industries Mothership
RFID Impactors Deployed from Motherships
Xtraordinary Innovative Space Partnerships, Inc
XISP

Session 1 – Energy Key Considerations

Sectors ➔ There are no unilateral sector options

Products/Services ➔ Cislunar Electrical Utility that leverages the economies of scale

Customers ➔ Near term service degraded systems
➔ Mid term enhanced new systems
➔ Long term immortal systems infrastructure

Supplier/Resources ➔ Trading the state-of-the-art vs. Satisfactory & Sufficient vs. optimal both a systems engineering and an economics challenge. Robotics and advanced automation are essential to meeting both challenges

Transportation ➔ Foster the market – government(s) role as NACA/IACA and first customers

Investment/R&D ➔ Matching investment tranches, staging, perceived & actual cost/schedule/technical risk, and returns

Infrastructure ➔ Elements, linkages, and operational procedures must be defined

Regulation ➔ Create a regulatory framework that is informed and driven by the confluence of interests necessary to grow the market

Session 2 – Energy TD^3 Milestones

Technology Development → Technology Demonstration → Technology Deployment

Space Solar Power	2018	2020	2024	2029	2038	2047
	ISS TD^3	LEO TD^3	GEO TD^3	GEO TD^3	GEO TD^3	SSP's >
	3-6 KW	~100 KW	~100 MW	~2 GW	10 GW	50 GW
	SSP Testbed	SSP LEO Demo	SSP GEO Demo	Full SSP		
• **Space-to-Space**	NASA/DOD	NASA/DOD/DOE	NASA/DOD/DOE	Electrical Utility		
• **Space-to-Luna**	Commercial	Commercial	Commercial	Commercial		
• **Space-to-Earth**						
• **Space-to-NEO**	Co-orbiting Test	ComSats Recovery	ComSats Primary	→ $$$	→ $$$$	
• **Space In situ**	Platform Model	Platform TD^3	Platform Ops	→ $$$	→ $$$$	
• **Luna-to-Luna**	Spectrum Model	Spectrum Apply	Spectrum Allocation			
• **Earth-to-Earth**	Orbit Slot Model	Orbit Slot Apply	Orbit Slot Allocation			
	LP&L Seed/Angel	LP&L Series A/B/C	LP&L IPO	→ $$$	→ $$$$	
	Co-orbiting Tests	Co-orbiting Labs	Co-orbiting Facilities	→ $$$	→ $$$$	
		Lunar Test(s)	Lunar Operations	→ $$$	→ $$$$	
		NEO Test(s)	Asteroidal Assay	→ $$$	→ $$$$	

Session 3 – Energy Challenge Questions

Sectors → Orchestration is essential in a cooperative+collaborative+competitive market.
Products/Services → Cislunar Electrical Utility demand will scale with demonstrated supply.
Customers → As soon as energy is available it will be used - Are customers really ready?
Supplier/Resources → Establish standards, make economic sense and scale - reality check!?
→ Robotics, advanced automation, and human involvement needed.
→ System trades require iterative and recursive Technology Development, Demonstration, and Deployment (TD^3)
Transportation → Match to mission requirements, be sustainable, and affordable to use.
Investment/R&D → Each increment of investment needs to lead to actual customer use.
Infrastructure → Elements, linkages, and operational procedures need definition & buy-in.

Regulation → Consistent long term government commitment to foster the market and help mitigate perceived and actual cost, schedule, and technical risk.

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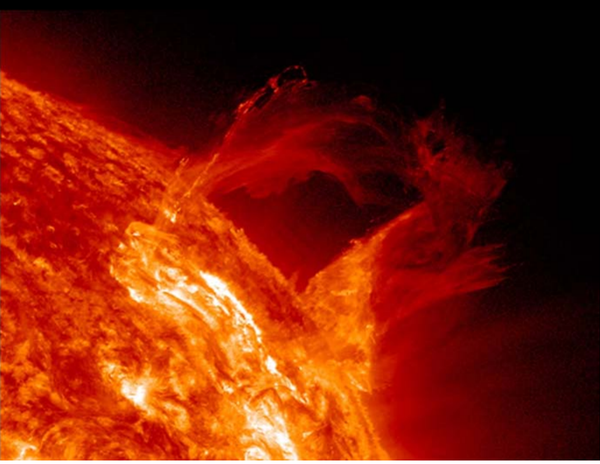
What’s Next?

Lunar Power & Light Company

an XISP-Inc Consortium



Don’t wait for the future, help us build it!

www.xisp-inc.com

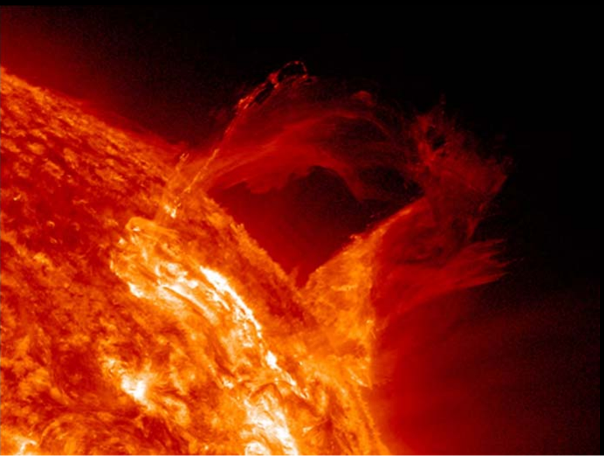
BACKUP CHARTS - Energy

- Sectors
- Products/Services
- Customers
- Supplier/Resources
- Transportation
- Investment/R&D
- Infrastructure
- Regulation

BACKUP - SECTORS

- International Governmental Consortia
- Government Consortia
- Government-Commercial Consortia
- Government-Not for profit Consortia
- Commercial Consortia

➔ ***THERE ARE NO UNILATERAL SECTOR OPTIONS***



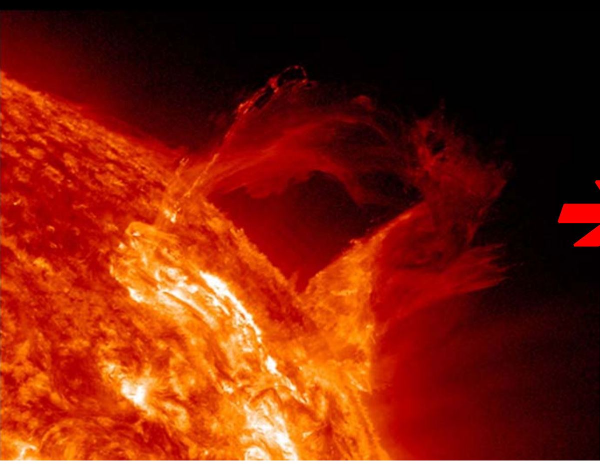
BACKUP – PRODUCTS/SERVICES

Cislunar Electrical Utility

- Earth-to-Earth Wireless Energy
- Space-to-Earth Wireless Energy
- Space-to-Space Wireless Energy
- Space-to -Luna Wireless Energy
- Space-to-Asteroid Wireless Energy
- Space Power Generation (insitu)

Product Catalog

- Emergency Power
- Backup Power
- Auxiliary Power
- Primary Power
- Indirect/Direct Momentum Transfer
- Allied Utilities (Comm, Nav, Data, etc.)



→ ***Leverage Economy of Scale***

BACKUP – CUSTOMERS "Earth"

Earth

- Other Electrical Utilities (existing & new) → less than 10 cents/kwh delivered to the grid
  → environmentally benign
  → scalable to meet world demand
  → accessible near where it is needed
  → limited security issues

- Military Logistics →cost per kwh is fungible provided that the required power is available where it is needed, when it is needed, with no exceptions
- Emergency Response Logistics → readily deployable, reasonable to operate, relatively low cost,
- Remote Infrastructure Alternative → where SSP is a cost effective alternative to other available options
- Transportation Vehicles → where SSP is a cost effective mission appropriate options
- Kinetic storage, water desalination, synthetic fuel production → very low cost surplus power

The baseload power market is driven by the delivered cost per kwh to the grid.

All other categories of power demand trade off cost to some extent to accommodate one or more other objectives.

BACKUP – CUSTOMERS "Space"

Space

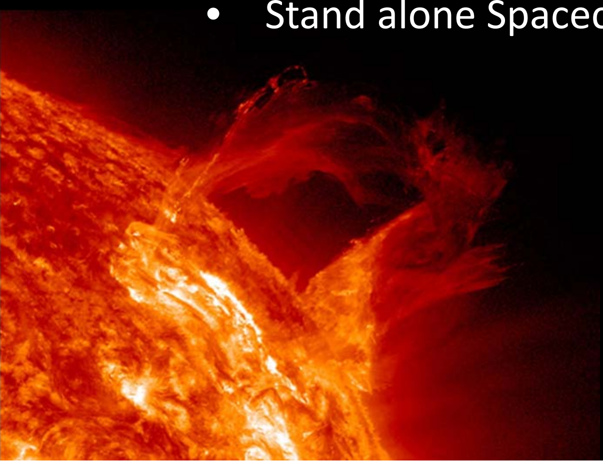
- Transportation Vehicles
- Propulsion Augment (resistojets, etc.)
- Debris Mitigation

Bit Gathering/Processing/Transfer

- Constellation Systems
- Fractionated Systems
- Multi-Use/Customer Platforms
- Integrated Platforms
- Stand alone Spacecraft

Human and/or Robotic Facilities

- R&D Facilities
- Manufacturing Facilities
- Intermodal Facilities
- Processing Facilities (fuel, ores, etc.)
- Mining Facilities (water, ores, etc)
- Hospitality Facilities (tourist)
- Habitation Facilities



Near term - Degraded Legacy Systems
Mid Term - Enhanced Systems
Long Term - Immortal Systems

XISP INC.

BACKUP – CUSTOMERS "Lunar"

Lunar

- Electrical Relay Infrastructure (new)
- Exploration Vehicle Support
- Emergency Response Logistics
- Remote Infrastructure Alternative
- Transportation Vehicles

Bit Gathering/Processing/Transfer

- Allied Utilities (Comm, Nav, Data, etc)

Human and/or Robotic Facilities

- R&D Facilities
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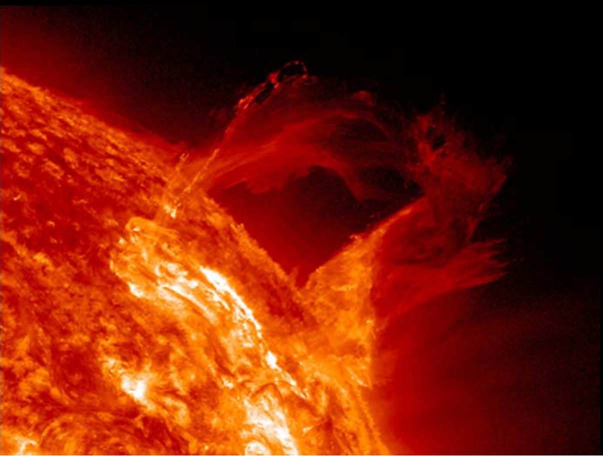


All services are mission enhancing
if not mission enabling

XISP INC.

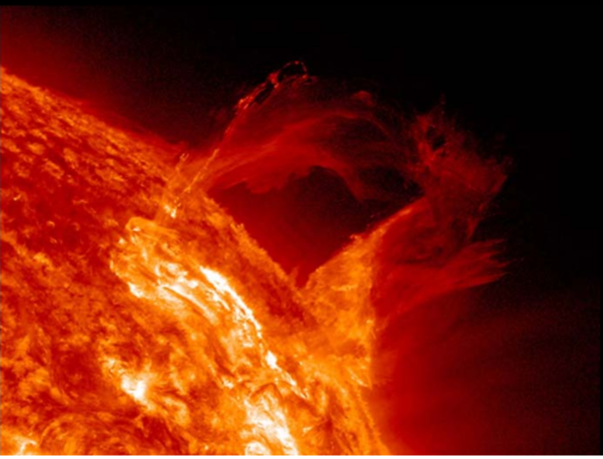
BACKUP – Suppliers/Resources

Logistics
- Earth Launch Systems
- Transfer Systems
- Luna Launch Systems

Low Mass Power Generation
- Photovoltaic
- Solar concentrator
- Solar Dynamic

Radiant Energy Beaming
- Microwave
- Frequency Agnostic
- Laser

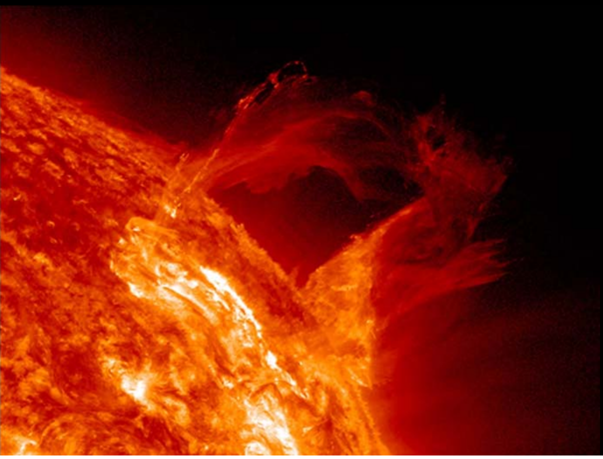
Other Technologies
- Robotic Assembly Assets
- Control & Damping of Large Structures
- Piece Part Manufacturing in Space
- High temperature tolerant electronics
- Radiation tolerant electronics
- Modular structures
- Network Control Architectures



Trade State-of-the-art vs. satisfactory and sufficient vs. optimal

BACKUP – Transportation

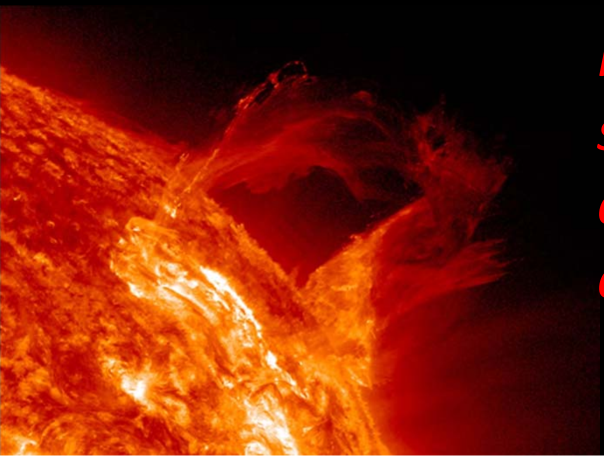
- Earth to LEO
- LEO to Earth
- LEO to LEO/MEO/HEO
- LEO to GEO
- LEO to Lunar Orbit
- LEO to NEO
- GEO to GEO
- GEO to LEO
- GEO to Lunar Orbit
- Lunar Orbit to Luna
- Lunar Orbit to Lunar Orbit
- Lunar Orbit to GEO
- Lunar Orbit to LEO
- Lunar Orbit to NEO
- NEO to NEO
- NEO to Lunar Orbit
- NEO to GEO
- NEO to LEO
- Luna to Lunar Orbit
- GEO to NEO



Foster the market – Government(s) as the NACA/IACA and first customers

BACKUP – Investment/R&D

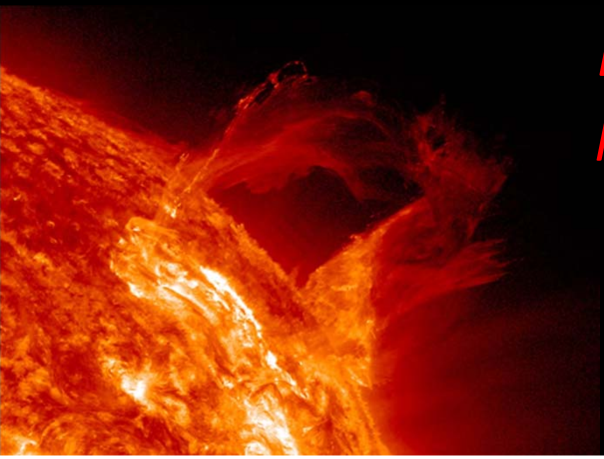
- Low cost launch
- Low cost transfers
- Low cost mass production
- High efficiency solar power generation
- Control and Damping of large structures
- Demonstration of Power Beaming
- High Temperature Solar Cells
- Luna/Lunar manufacturing



Match between traunches of investment, staging of effort, perceived and actual cost/schedule/technical risk and returns is critical to success.

BACKUP – Infrastructure

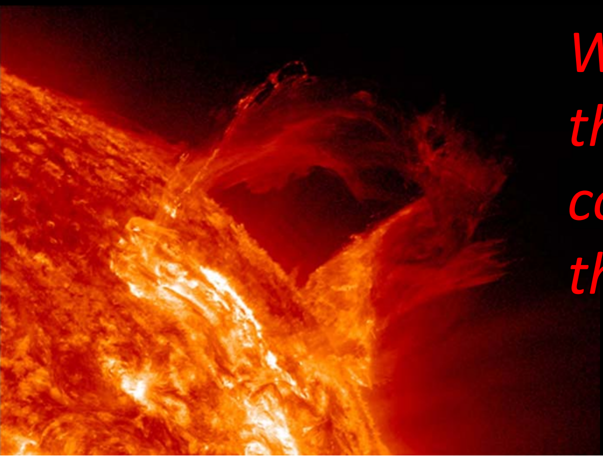
- Transportation System
- Network of Space Solar Powered Satellites
- Ground Station "Rectennas" (receiving antennas)
- Maintenance Capability
- (As an exception) crewed teams for repairs
- Asteroid Manufacturing
- Lunar Manufacturing



Elements, linkages, and operational procedures must be defined and built.

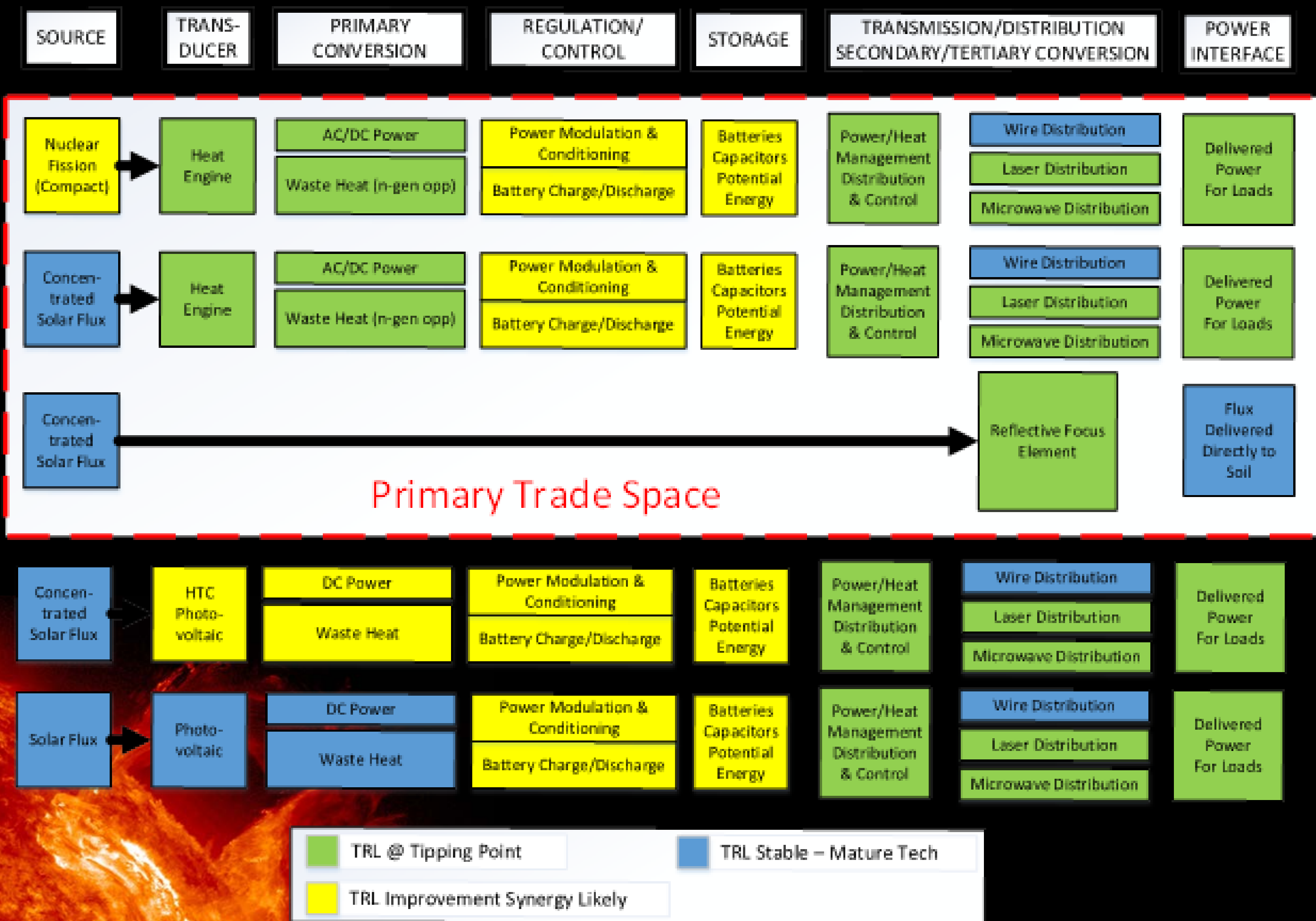
BACKUP – Regulation

- Spectrum regulation
- Inspection of System for Compliance with Outer Space Treaty
- Space traffic Control
- International Indemnification
- Debris Management and Mitigation
- Zoning on Earth Rectennas
- WHO compliance for Health and Safety

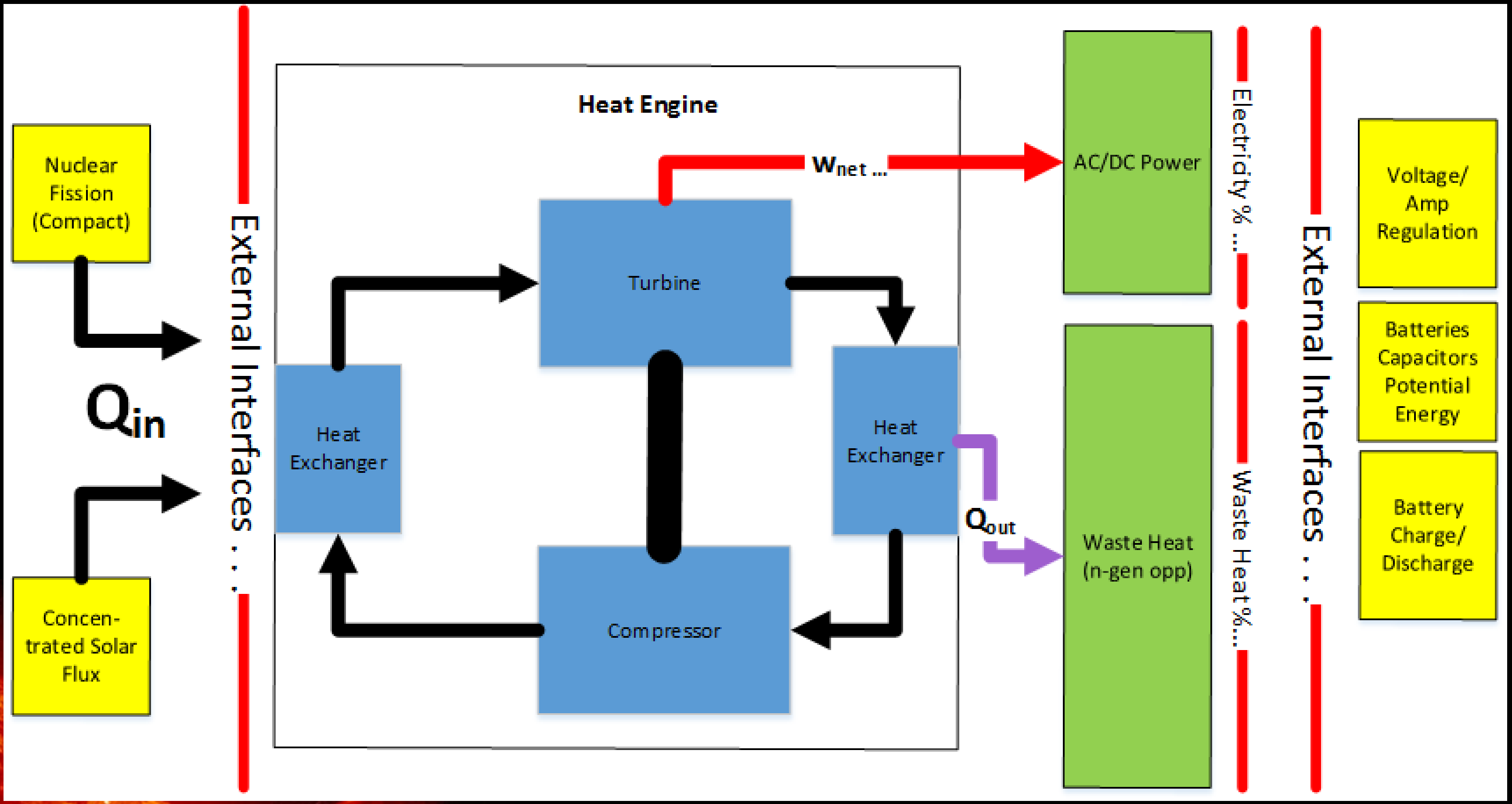


We need to create a regulatory framework that is informed and driven by the confluence of interests necessary to grow the market.

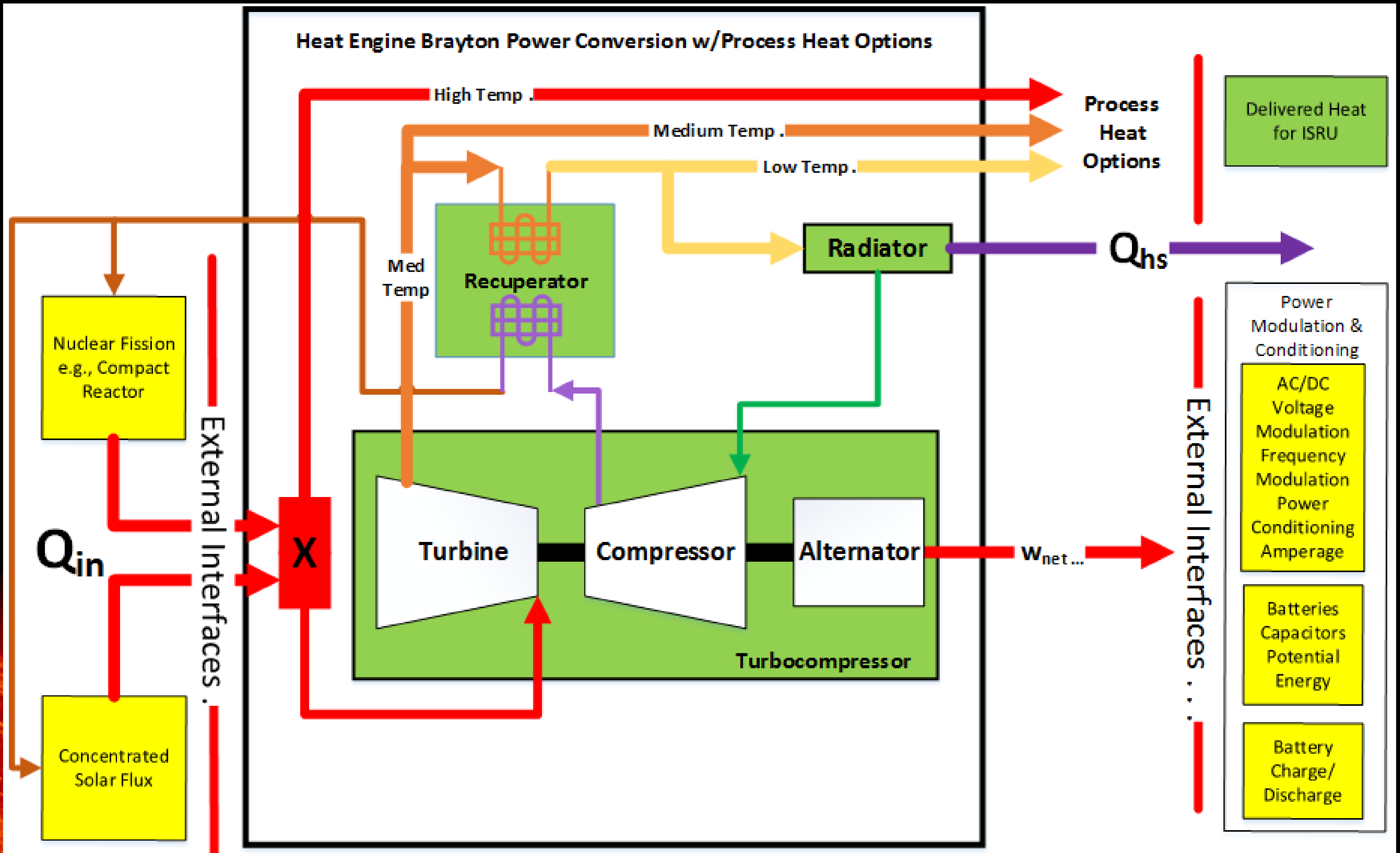
Power Generation, Storage, and Distribution



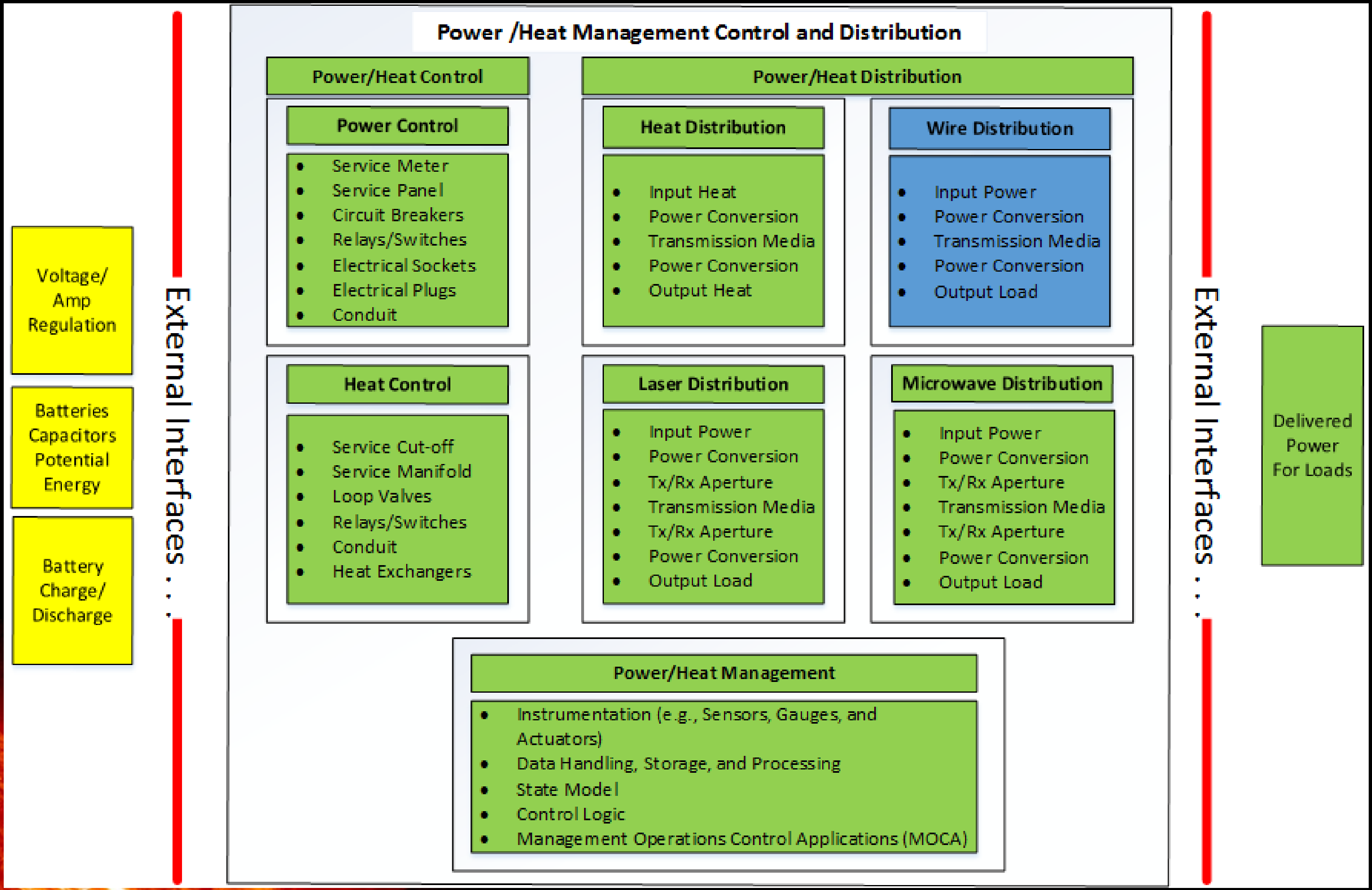
Brayton Cycle Heat Engine Block Diagram (Simple)



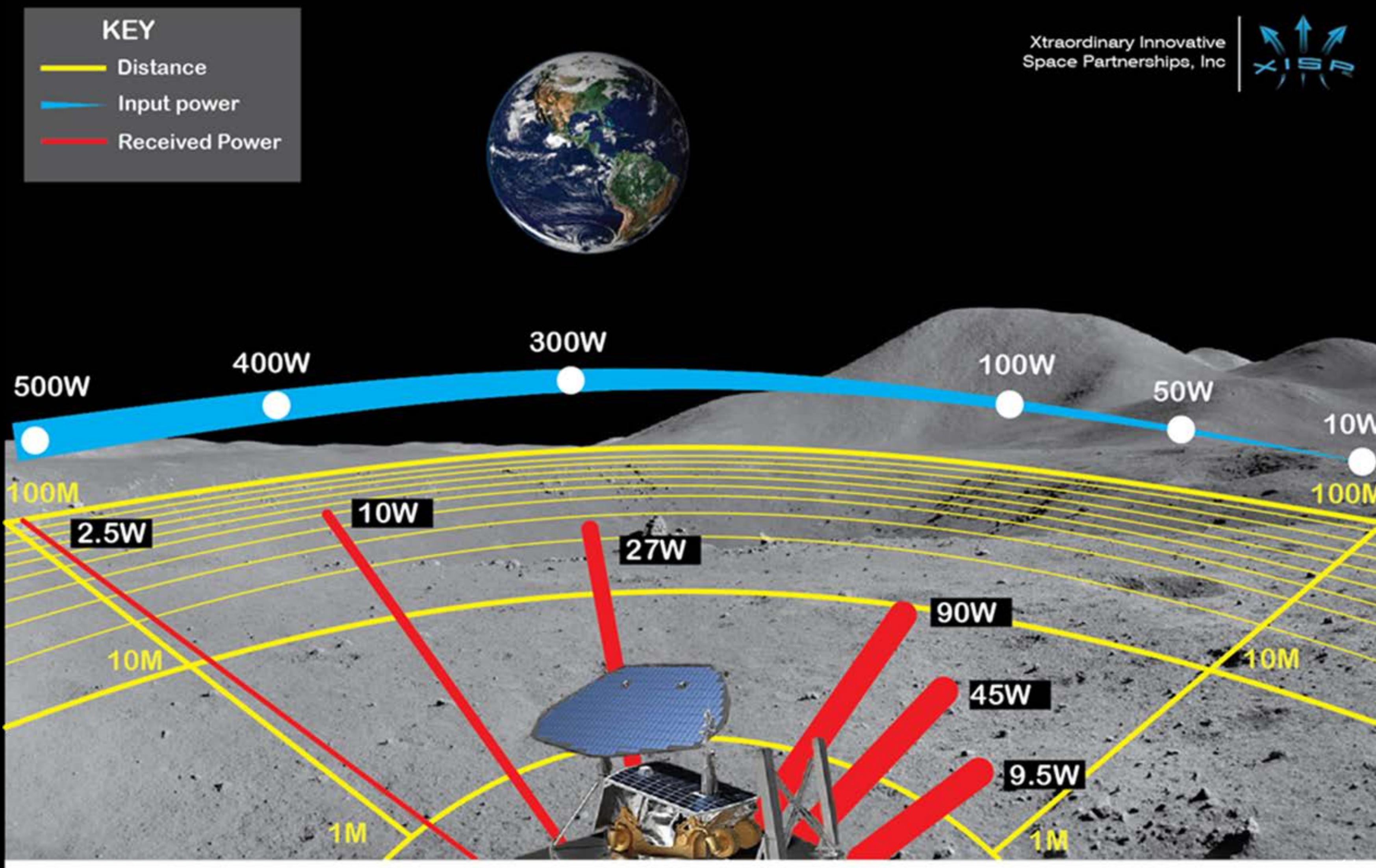
Brayton Cycle Hear Engine Block Diagram w/Process Heat Options



SSPB Transceiver Preliminary Design Isometric

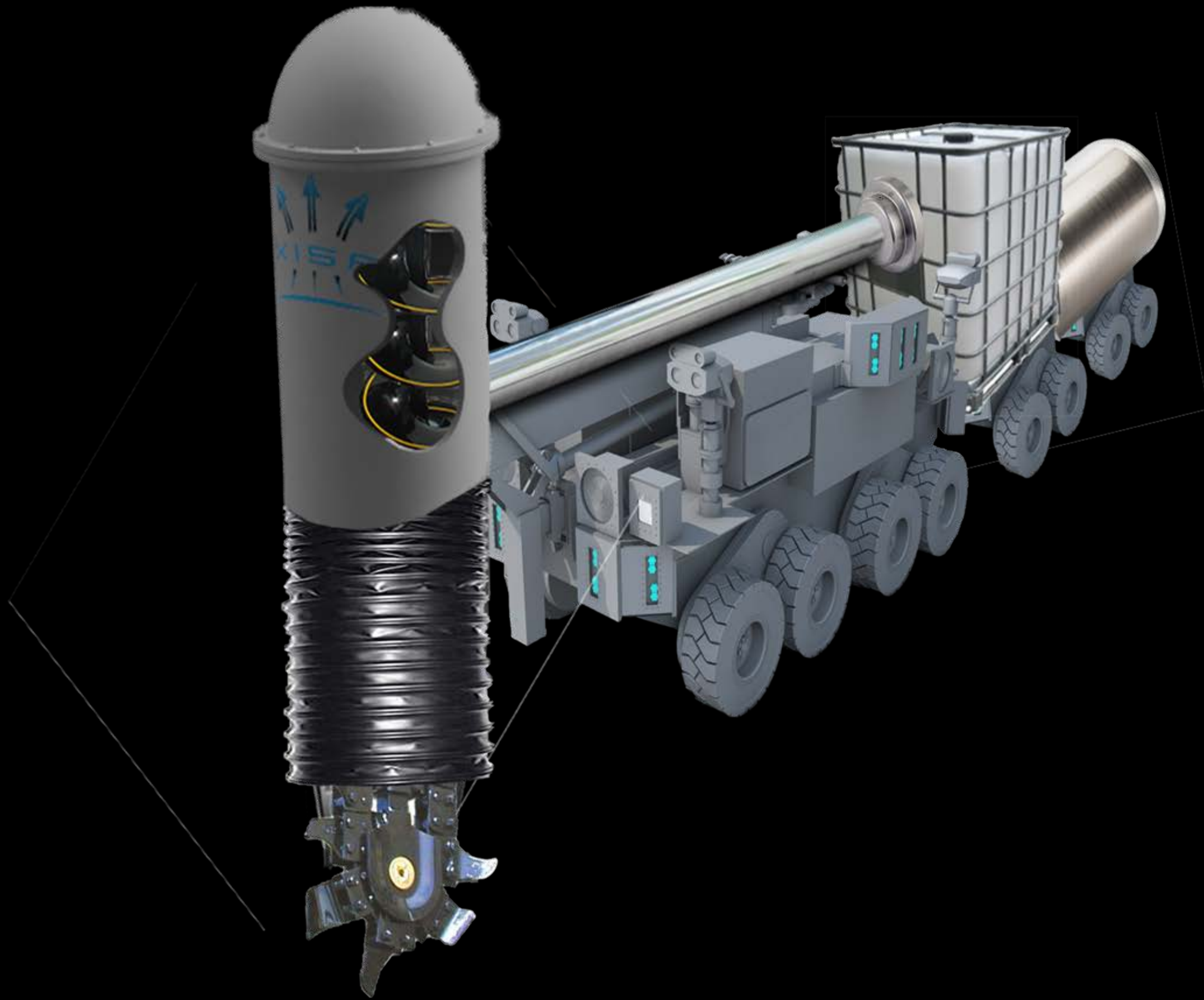


CLPS 15 Kg Power Beaming Testbed
XISP-Inc/Raytheon Proposal submitted for SMD LSITP 2019

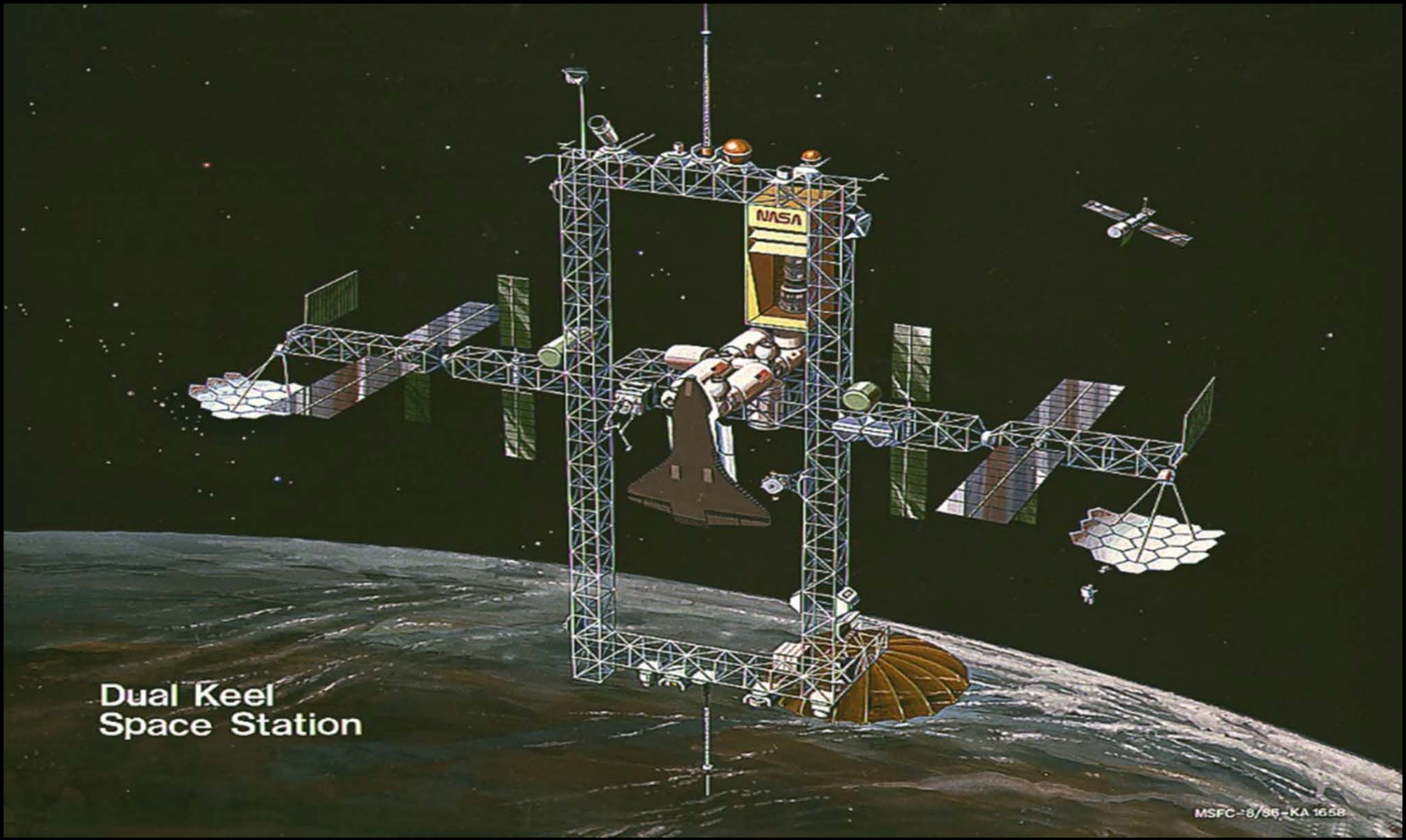



Lunar Village

XISP-Inc WaterWitch Lunar Regolith Volatiles and Ore Prospecting

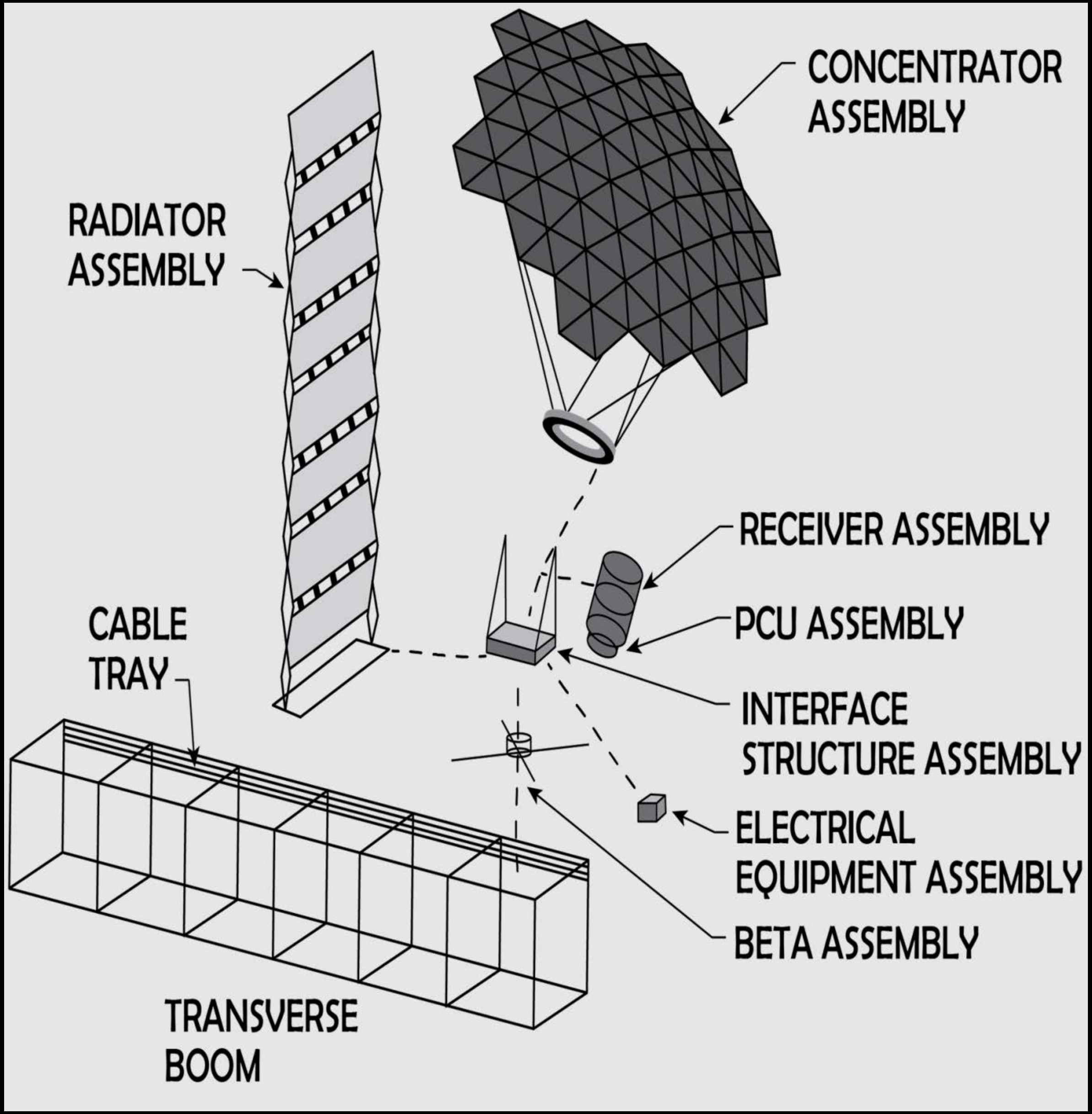


Early Space Station Design w/Solar Dynamic



LaRC/GRC 2kW Solar Dynamic Test

Solar Dynamic Components

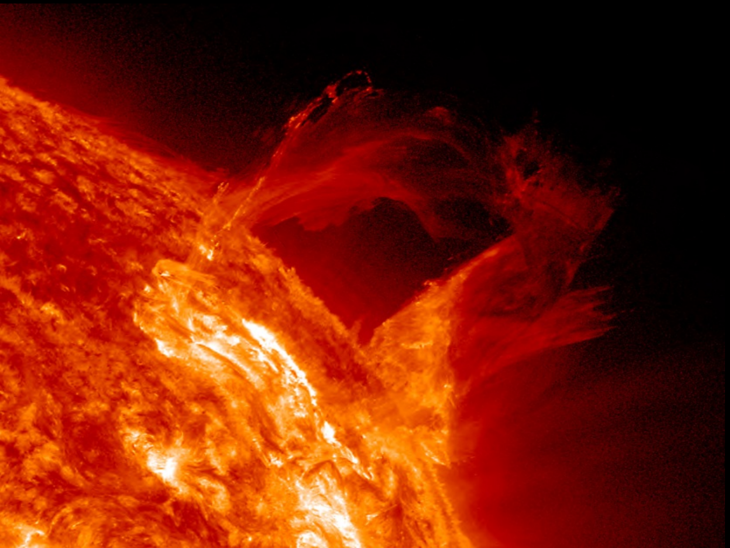


Conclusion

- SSPB one of multiple examples has transitioned from a conceptual mission pregnant with opportunity to a commercial mission with recognized standing.
- There is now a defined confluence of interests biased toward successful execution of the mission as public private partnership.
- Successful demonstration of space solar power beaming will:
  1. Reduce the perceived cost, schedule, technical risk of SSP
  2. Pave the way for SSP use in space-to-space, space-to-lunar/infrastructure surface, and space-to-Earth
- Commercial space applications include:
  1. enabling expansion of operational mission capabilities,
  2. enhanced spacecraft/infrastructure design flexibility, and
  3. out-bound orbital trajectory insertion propulsion, and
  4. pave the way for the Lunar Power & Light Company.

Don’t wait for the future, help us make it!

Backup Slides



SSPB Test Bed Experiments

- End-to-End & Piecewise Efficiency Optimization
    - DC ===> Microwave,
    - Beam Forming, Transmission, Rectenna
    - Microwave ===> DC
    - Advanced Development of eye safe Optical
- Transmitter & Rectenna Scalability using Cubesats
- Far/Near Field Effects & Boundaries
- Formation Flying/Alignment/Loosely Coupled Structures
- Optimization/Scaling/Efficacy of the Solution Set

Where does it make sense to use the technology?

SSPB & Commercial Evolution

- Repurpose Cygnus Pressurized Logistics Carriers as crew tended co-orbiting labs with fault tolerant power and auxiliary services for some number of cycles.
- Support other co-orbiting crew-tended space manufacturing elements
- Lunar Power & Light Company – a Cislunar utility
  - Enhanced ISS power & co-orbiting community
  - LEO Independent power generation & ancillary services distribution
  - MEO/HEO/GEO power generation & ancillary services distribution
  - Libration point/lunar orbit/lunar surface power generation & ancillary services distribution

SSPB & Commercial On-Ramps

- ISS Co-orbiting Free-flyers
  - Micro-g manufacturing cells
- Asteroidal Assay
  - Co-orbiting motherships with landed sensors
- Propulsion (delta-V augmentation)
  - Out bound & cycling spacecraft
  - Debris management
- Plug-In/Plug-Out Infrastructure Platforms
  - Communications, Navigation, Power, etc.
  - Earth facing, space operations, and space exploration
- Operational Cadence/Cycle Evolution
  - International Lunar Decade Support

SSPB Mathematics & Efficiency

Technologies for wireless power transmission include:

- Microwave
- Laser
- Induction

Each of these methods vary with respect to:

- End-to-End Efficiency
- Effective distance/Range
- Power handling capacity/scalability
- Pointing & Targeting Requirements
- Safety Issues
- Atmospheric Attenuation

SSPB Microwave Efficiency Data

DC to Microwave Conversion	Beam Forming Antenna	Free Space Transmission	Reception Conversion to DC
Circa 1992 80%–90% Efficient **Circa 2016** ~95 % Efficient** @ < 6 GHz 10%-60% @ Higher Freq.	**Circa 1992** 80 – 90 % Efficient **Circa 2016** Comparable @ < 6 GHz 50%-80% @ Higher Freq.	**Circa 1992** 80 – 90 % Efficient **Circa 2016** Comparable @ < 6 GHz 1%-90% @ Higher Freq.	**Circa 1992** 80 – 90 % Efficient **Circa 2016** ~95 % Efficient** @ < 6 GHz 37%-72% @ Higher Freq.

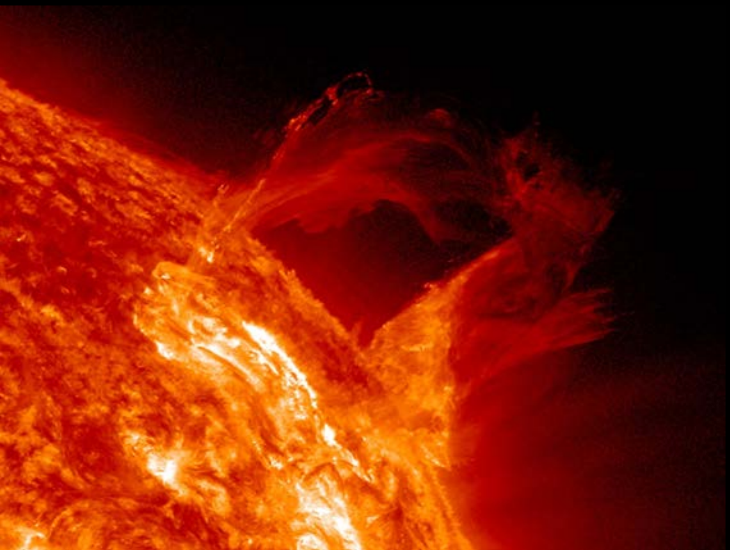
Theoretical Maximum Possible DC to DC Efficiency
Circa 1992 ~76%
Circa 2016 85-95%*** @ < 6 GHz and TBD @ Higher Frequencies
Experimental DC to DC Efficiency Circa 1992 ~54 %, Circa 2016 TBD but significantly higher

*William C. Brown, Life Fellow, IEEE, and E. Eugene Eves, Beamed Microwave Power Transmission and its Application to Space, IEEE Transactions On Microwave Theory and Techniques, Vol. 40, No. 6. June 1992
**depending on voltage multiplier ratio
***using one cycle modulation instead of pulse width modulation
Current High Frequency values based on input from current researchers (see paper for references)

SSPB Recent Fiber Laser Data

2013 – Propagation efficiencies of 90%, at 1.2km, 3kW CW – U.S. NRL
2013 – 10kW CW individual, single-mode, fiber lasers – U.S. NRL
2014 – 3kW three-fiber array, 80% efficiency – Northrup Grumman
2015 – 30kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army
2017 – 60kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

Demonstrated source power to beam efficiency of 43 percent



SSPB Recent Fiber Laser Data

2013 – Propagation efficiencies of 90 percent, at a range of 1.2 kilometers (km), with transmitted continuous-wave power levels of 3 kilowatt (kW) – U.S. Naval Research Laboratory

2013 – 10kW individual, single-mode, fiber lasers continuous power – U.S. Naval Research Laboratory

2014 – Three-fiber array combining results, showing a constant 80% efficiency across a broad range of input powers (0–3000W). – Northrup Grumman Two straightforward changes appear likely to increase the combining efficiency from 80% to 90% or more. First, combining more fibers increases Diffractive Optical Element (DOE) diffraction efficiency, leading to greater combining efficiency as well as higher combined power. We successfully fabricated DOEs with fiber channel counts ranging from 9–81, leading to diffraction efficiencies of 97–99%, compared with only 92% for our three-fiber DOE. Second, standardizing the design of the fiber amplifiers would reduce losses arising from mode field and power mismatches and should also be relatively simple.

2015 – 30kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

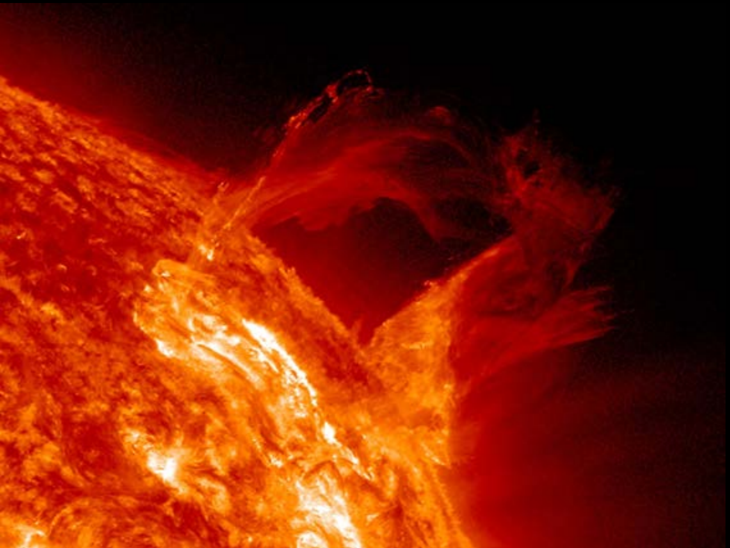
2017 – 60kW combined fiber laser mobile system fielded – Lockheed Martin & U.S. Army

Demonstrated source power to beam efficiency of 43 percent

SSPB Mathematics & Efficiency

Theoretical Limits & Other Considerations

- Diffraction
- Thermal capacity/heat tolerance
- Electromagnetic Environment
- Navigating Frequency Allocation & Use Issues



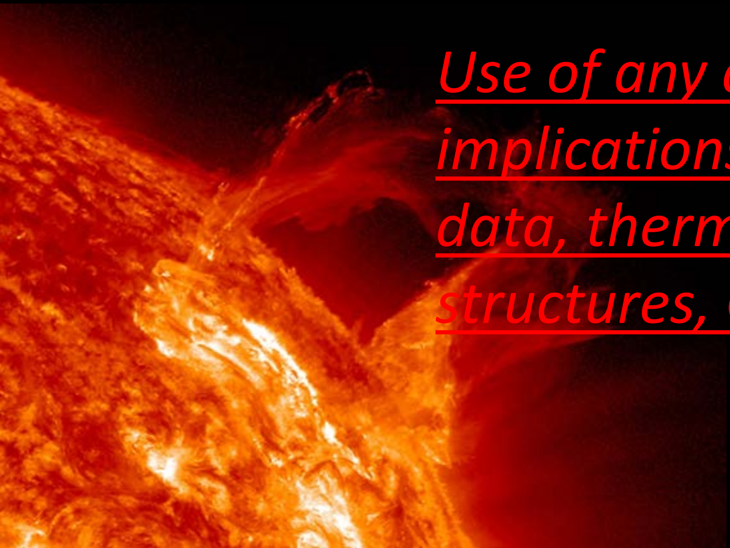
Technological Challenges

- Physics of near field/ far field energy propagation understood.
- Use of radiant energy to transfer: power, data, force, &/or heat, either directly and/or by inducing near field effects at a distance, are not well understood
- Moreover, there is very limited engineering knowledge base of practical applications.
- Accordingly, this is applied engineering work, (a.k.a. technology development), not new physics.

To optimize beaming applications we need to better understand how each of the components of radiant energy can be made to interact in a controlled manner.

Technological Challenges -2

- Radiant energy components include
  - Electrical
  - Magnetic
  - Linear & Angular Momentum
  - Thermal
  - Data
- There are potential direct and indirect uses for each beam component



Use of any combination of these components has implications for all spacecraft systems (e.g., power, data, thermal, communications, navigation, structures, GN&C, propulsion, payloads, etc.)

Technological Challenges - 3

- In theory, the use of the component interactions can enable:
  - Individual knowledge of position and orientation
  - Shared knowledge loose coupling /interfaces between related objects
  - Near network control (size to sense/proportionality to enable desired control)
  - Fixed and/or rotating planar beam projections
  - Potential for net velocity along any specified vector

In theory, there is no difference between theory and practice – but in practice, there is.

– Jan L.A. van de Snepscheut
computer scientist

Additional Challenges - 3

- Economics

– Map the financing to terrestrial electrical power and ancillary services utility analog that just happens to be in space.

– Each addressable market has different fundamental figures of merit.

- Public/Private Partnerships

– Drawing out the confluence of interests that can support substantive agreements

- GeoPolictical

– Make International Cooperation/Collaboration real.