Future Directions for Space Transportation and Propulsion at NASA

5th International Symposium on Liquid Space Propulsion
Long-Life Combustion Devices Technology
Chattanooga, TN
October 27-30, 2003

Robert L. Sackheim
Assistant Director and
Chief Engineer for Propulsion
NASA Marshall Space Flight Center
The NASA Mission:

To understand and protect our home planet,

To explore the universe and search for life,

To inspire the next generation of explorers . . .

. . . as only NASA can.
Space Is Critical to the World

The New International “Ocean”

- **Scientific Discovery**
  - The Search for Life Beyond Earth
  - Understanding our Planet
  - Understanding our Universe
  - Exploration of the Planets and Beyond

- **The Ultimate High Ground for National Security**
  - Intelligence, Communications, Rapid Response, GPS . . . World Wide

- **“Space-Based” Commerce**
  - Communications and Earth Observing

Yet it Remains the Last, Largely Untapped Frontier
MSFC’s Heritage – Complex Programs Requiring a Strong Systems Engineering Focus
Stepping Stones Overlay on Space Transportation Regimes

Human, LEO

Human, Human, HEO to Lunar

Civil Robotic, LEO to Inner Planets

Robotic, near Sun

Human, Inner Planets

Human, Outer Planets

Robotic, Outer Planets

Robotic, Beyond Planets
## Regime Descriptors and Needs

<table>
<thead>
<tr>
<th>Regime</th>
<th>Descriptors and Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R1</strong></td>
<td>Human Earth Orbit</td>
</tr>
<tr>
<td><strong>R2</strong></td>
<td>Robotic LEO to near planets</td>
</tr>
<tr>
<td><strong>R3</strong></td>
<td>Human HEO and lunar</td>
</tr>
<tr>
<td><strong>R4</strong></td>
<td>Robotic near-Sun</td>
</tr>
<tr>
<td><strong>R5</strong></td>
<td>Human near planets</td>
</tr>
<tr>
<td><strong>R6</strong></td>
<td>Robotic outer planets</td>
</tr>
<tr>
<td><strong>R7</strong></td>
<td>Human outer planets</td>
</tr>
<tr>
<td><strong>R8</strong></td>
<td>Robotic beyond planetary system</td>
</tr>
</tbody>
</table>
End-to-End Regimes Capture Mission Requirements

Equal emphasis over all Regimes favors NASA-Wide Propulsion Requirements

Some Regimes have Earth Return

In-Space Transportation

Cross-cutting Technologies

Return

Earth

ETO
Office of the Space Architect

Work Breakdown Structure

1.0 Management & Integration
- Policy & Governance
- Systems Engineering
- Integrated Space Plan
- Annual SA Program Formulation
- Architecture Study Direction
- Integrated Reference Architectures
- New Initiative Evaluations
- Current Program Evaluations
- SA Board Recommendations
- Communications Strategy

2.0 Architecture Studies
- Management Integration & Administration
- Architecture Options
- Reference Missions
- Capability/needs Identification
- Leveraged Studies
- ISP Support
- CRAI Support
- System Support

3.0 Transportation
- Management Integration & Administration
- ISTP
- ISP Support
- CRAI Support
- Architecture Support
- Special Studies
- Leveraged Studies

4.0 CRAI
- Management Integration & Administration
- Integrated Roadmaps
- Capability/need Identification
- Capability/need analysis & Assessment
- Gap Analysis
- Investment Strategies
- ISP Support
- Architecture Support
- System Support
- Leveraged programs

5.0 Special Studies and Leveraging
- Management Integration & Administration
- Leveraged Studies

Space Architect
Integrated Space Transportation Architecture Inputs to the Space Architecture Work Breakdown Structure Format

1.0 Space Architect - Gary Martin, Headquarters

2.0 Integrated Space Transportation Architecture (ISTA)

3.0 MSFC POC/Bob Sackheim

3.1 ETO/ISTP
- 3.1.1 Shuttle (SSP)
  - RTF
  - Sustained Operations
  - SLEP
- 3.1.2 NGLT
  - ORSC Engine
  - Green RCS/OMS
  - Advanced Avionics
  - Thermal Protect Systm
  - Structure
  - Tanks
  - Upgraded Liquid Oxygen
  - Liquid Hydrogen (Cobra Type)
  - (LH₂ TCA)
  - IVHM
  - Hypersonics/NAI, CCEs
- 3.1.3 OSP
  - Capsule
  - Winged/Aero
  - Lifted Body/Aero
  - 3.1.4 ELVs
    - Small Launchers (SELV’s)
    - Existing ELV’s
    - HLLVs

3.2 Baseline Enabling Research
- 3.2.1 Applied Research
  - Better Nozzles, etc.
- 3.2.2 Fundamental Research
  - Antimatter
  - Advanced Nuclear, etc.

3.3 In-space Propulsion
- 3.3.1 Conventional Functions
  - 3.3.1.1 Orbit Transfer
  - 3.3.1.2 AVCS
  - 3.3.1.3 Pointing
  - 3.3.1.4 NSSK
  - 3.3.1.5 EWSK
  - 3.3.1.6 Orbit Adjust
  - 3.3.1.7 Drag Make-up
- 3.3.2 Non-conventional Approach
  - 3.3.2.1 Sails
  - 3.3.2.2 Tethers
  - 3.3.2.3 Aero Assist Tech
- 3.3.3 Orbiter Vehicle In-space Control Functions
  - 3.3.3.1 OMS & RCS
- 3.3.4 Nuclear Propulsion
  - MMRPS/RTG/RPS
  - REP
  - NEP
  - Nuclear Power
    - EP/EP/NTR/Converter Technology

3.4 Planetary Operations
- 3.4.1 Aero Assist
  - Aero Braking
  - Aero Capture
- 3.4.2 Entry Descent & Landing (EDL)
- 3.4.3 Ascent Vehicles

3.5 In-space Infrastructure
- 3.5.1 ISRU
- 3.5.2 Fluid/Propellant Depots
- 3.5.3 In-space Fluid Transfer Systems

3.6 Special Studies
- 3.6.1 Special Architecture Studies
- 3.6.2 Special Study Support
- 3.6.3 Humans Beyond ISS
- 3.6.4 Stations at Lagrange L-1/L-2 Moon/Sun
- 3.6.5 Studies/Analysis tools, e.g. ISEAP

Inputs to/from CRAI Team
Energy Comparison for Various Distances
Single Burn Delta V From LEO, ETO $\Delta V = 9.3 \text{ km/s}$

The Physics Problem

**Total $\Delta V$ From Earth’s Surface (km/s)**

- LEO:
- Moon:
- Asteroids:
- Mars:
- Jupiter:
- Saturn:
- Uranus, Neptune, Pluto, Kuiper Belt:

**Distance (A.U.)**

- In 20 years

---

*Total $\Delta V$ for Elliptical Heliocentric Missions*

*Total $\Delta V$ for Hyperbolic Heliocentric Missions*
New Propulsion Technologies are Needed to Meet NASA’s Most Ambitious Goals

Vehicle Acceleration or T/W Ratio (g’s)

Specific Impulse (secs)

Unproven Technology (TRL 1–3)  Demonstrated Technology (TRL 4–6)  Operational Systems (TRL 7–9)

Expand the Frontier (>2023)

Develop the Frontier (2010 - 2023)

SAILS

Deep Space

10^2 10^3

Power Density (kW/kg) = 10^4

SPECULATIVE MOTIVE PHYSICS

10^{-2} 10^{-1} 1 10 10^2

ANTIMATTER

CONTINUOUS FUSION

PULSED FUSION

PULSED FISSION

THERMAL FISSION

CHEMICAL RBCC

CHEMICAL ROCKETS

ELECTRO-STATIC ROCKETS

ELECTRO-MAGNETIC ROCKETS

ELECTRO-THERMAL ROCKETS

LASER/SOLAR THERMAL ROCKETS

NONCHEM RBCC

LAUNCH

Launch

Deep Space

Omniplanetary

Expand the Frontier (>2023)

Develop the Frontier (2010 - 2023)
NASA’s New Integrated Space Transportation Plan (ISTP)

**Space Shuttle Life Extension Upgrades**

**Orbital Space Plane (OSP)**
- ISS Crew Rescue by 2010
- ISS Crew Transfer by 2012

**Next Generation Launch Technology (NGLT)**
- Enabling Future National Launch Capabilities
Enabling Near and Long Term Improvements in U.S. Launch

Near Term Options
- Shuttle Upgrades / Derived System
- New Rocket RLV
- Heavy Lift Expendable Launch

Longer Term Options
- New Rocket RLV
- Hypersonic RLV
- Very Heavy Lift Launch
Imagine the Possibilities....

- Significant Expansion in Robotic Probes Going Throughout the Solar System and Beyond
- Humans Exploring Space Beyond Low Earth Orbit
- Space Solar Power Systems Supplying Cheap Electricity Around the Globe
- Daily Tours To and From Space
- Industrial Space Platforms Developing New Materials and Medicines

A Primary Limitation is
Safe, Reliable and Affordable Space Launch
High Leverage, Cross-Cutting Technologies for Any Future Launch System

- Lightweight, Durable Airframes and Tanks
- Boost and 2nd Stage Engines
- Intelligent, Self Diagnosing & Correcting Systems
- "All Electric" Subsystems
- All-Weather, Durable Thermal Protection Systems
- Rapid Checkout and Launch Systems
- Non-Toxic Auxiliary Propulsion
- Space-Based Range Tracking System
- Crew Safety
- Shuttle Life Extension
- ELV Upgrades
- New Reusable Launch Vehicles
- Exploration
Cutting Edge Hypersonics Technologies for Future, Aircraft–like Operations

- Long Life, High Temperature Structures and Materials
- Mach 4 Turbine Engines
- Integrated Rockets
- Ram / Scramjets
- Highly Integrated Airframe Systems
- Combined Cycle Propulsion Systems
- Ultra High-Temp Leading Edges
DARPA/USAF Small Launcher Initiative

- DARPA and the Air Force have established a joint program
- DARPA has overall program management primacy
- The program is called FALCON (Force Application Launch from CONUS)
- FALCON RFP released on July 29, 2003
- The FALCON SLV initiative has some similarities to MSFC’s original Bantam Project
Many respondents to FALCON RFI (1/30/2003)
Why Will It Work This Time?

- Simplicity of Design
  - Some simple designs are inherently more reliable and lower cost than others
    - See RLS papers for last 20 years
    - NASA and DOD have really shown zero interest in inherently low costs
- Trade Design Margin Against Performance and Weight
  - Nontraditional aerospace design philosophy
  - Greater design margins enhance reliability
  - Very high Thrust-to-Weight is not that critical for low cost, vertical launch
  - Lower Thrust-to-Weight is more reliable (but vehicle T/W >1.1 @ liftoff)
- Trade Design Margin Against Redundant Systems
  - Redundancy adds complexity and cost
- Use Rack and Stack Design Approach to Achieve Component Commonality
  - Commonality enables simplicity and lowers cost
  - Commonality enhances reliability
  - Provides evolutionary design approach for heavy lift using flight-proven building blocks
- Use Commercial (non-aerospace) Processes and Components As Much as Possible
  - Leverage commercial industry’s production rate
  - Commercial components are inherently higher margin; not optimized for performance
  - Commercial hardware is dramatically lower cost than comparable aerospace hardware
Notional Evolutionary Development Path

Shuttle depicted for size comparisons only.

One Of Many Possible Paths

<table>
<thead>
<tr>
<th>Stage 1 Engine</th>
<th>FALCON</th>
<th>Spiral 1</th>
<th>Spiral 2</th>
<th>Spiral 3</th>
<th>Spiral 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 Engine</td>
<td>New RP</td>
<td>2 SSME</td>
<td>New LH Engine (4)</td>
<td>Same as Spiral 2</td>
<td>Same as Spiral 2</td>
</tr>
<tr>
<td>Stage 2 Engine</td>
<td>New RP</td>
<td>FALCON Stage 2</td>
<td>Spiral 1 Stage 1</td>
<td>Same as Stage 1</td>
<td>EELV Core</td>
</tr>
<tr>
<td>Stage 3 Engine</td>
<td>New RP</td>
<td>FALCON Stage 3</td>
<td>--</td>
<td>--</td>
<td>EELV US</td>
</tr>
</tbody>
</table>

Notional Evolutionary Development Path
Technology Application to Shuttle Upgrades *(Initial NGLT Assessment)*

**External Tank**
- Self Reacting Friction Stir Welding
- Advanced Cryoinsulation

**Booster**
- LOx/RP liquid booster replacement (1+Mlb Prototype Engine)

**Airframe Structure**
- Ceramic Matrix Composite Control Surfaces
- Structural Health Monitoring Sensors

**Thermal Protection Systems**
- Light Weight, Intelligent Micrometeoroid Resistant Ceramic TPS
- Durable, Conformal Reusable Insulation
- Long Life, Durable Thermal Seals
- Rapid Waterproofing

**Ground Operations**
- Space Based Telemetry and Range Safety
- Silent Sentry/Passive Coherent Location (Advanced Range Technology)
- Range Architecture Development
- Advanced Umbilical Development
- Improved Propellant Management
- Densified Propellants
- Advanced Checkout Control and Maintenance System
- Launch Acoustic Environment Prediction

**RCS/OMS**
- LOx/Ethanol Dual-Thrust Level RCS Thrusters

**IVHM System Integration**
- Advanced Systems/Subsystems Diagnostic Algorithms
- IVHM/Flight Operations Integration

**Subsystems**
- High Horsepower, Electrically Driven Actuators
- PEM Fuel Cells
- Nontoxic Turbine Power Unit

**Aero & GN&C Tools**
- Separation and Abort Scenarios
- Reentry Heating Environments
- Localized Heating
- Integrated Development and Operations System
- Integrated Aerothermal/TPS Sizing

**Aft Compartment**
- Oxygen and Hydrogen Leak Detectors

**SSME**
- IPD Channel Wall Nozzle
- Advanced Turbomachinery
- GRCop-84 Main Combustion Chamber Liner
- Advanced Engine Health Management
Technology Application to Expendable Launch Upgrades (Initial NGLT Assessment)

Tanks
• Self Reacting Friction Stir Welding
• Advanced Cryoinsulation

Structures
• Structural Health Monitoring Sensors
• Lightweight metal matrix and polymer matrix composite structures

Ground Operations
• Space Based Telemetry and Range Safety
• Silent Sentry/Passive Coherent Location (Advanced Range Technology)
• Range Architecture Development
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IVHM System Integration
• Advanced Systems/Subsystems Diagnostic Algorithms
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Aft Compartment
• Oxygen and Hydrogen Leak Detectors

Replacement RP Engine
• LOx/RP liquid booster replacement (1+Mlb Prototype Engine)

LH₂ Engine Upgrades
• IPD Channel Wall Nozzle
• Advanced Turbomachinery
• GRCop-84 Main Combustion Chamber Liner
• Advanced Engine Health Management

RLS0011
Enabling “Firsts” in Space Launch Technology

**Booster Engine Prototype**
- Highly reliable hydrocarbon fueled rocket booster engine
- High reliability, long life hydrogen rocket engines

**Auxiliary Propulsion**
- Non-toxic propellants for orbital propulsion

**Vehicle Research and Technology**
- Airframes capable of containing cryogenic propellants and reentering the Earth’s atmosphere
- Durable high temperature thermal protection systems
- An intelligent, autonomous “all electric” launch system

**Propulsion Research & Technology**
- Long life, lightweight high temperature materials, seals and components

**X-43A and C**
- 1st controlled flight of a vehicle powered by a scramjet from Mach 5 - 7 and 10

**Revolutionary Turbine Accelerator**
- Lightweight, long life jet engines capable of flight at Mach 4
Think of What We Have Accomplished in the 100 years Since the Wright Brothers 1st Flight …

…… Imagine What We Will Do On the New “Ocean of Space”
In-Space Focused Scope

Orbital Transfer Vehicles

Interplanetary Transfer Stages

Planetary Capture

Ascent/Descent Stages

Reusable Upperstage

Solar Electric

Aerocapture

Sample return

In-Situ Prop/Ascent Chem Prop Stage
In-Space Propulsion

Enabling New Scientific Discoveries

Solar System Exploration

- Planetary Exploration Examples:
  - Orbiters
  - Landers
  - Sample Return

Sun Earth Connection

- Solar Science Examples (inc. Solar Sails):
  - LaGrange Missions
  - Orbiters
  - Pole Sitters
In-Space Propulsion Systems

Space Propulsion Systems for Space Access/Transportation

Earth to Orbit

In-Space

ISP Applic. Range

Expansible
- Small Indep. Upper stage (eg. Centaur, IUS)
- Dumb US (eg. ASUS)
- S/C IPS

Micro-spacecraft
- Formation Flying

Reusable
- Space-Based
- Earth-Based

High-Value Manned Asset Ctrl

- ISS
- Planetary Return/Ascent (w/people)
- Shuttle/RLV OMS and RCS
- Space Tourism

Spacecraft Ctrl (Robotic/Unmanned)

- Drag Makeup
- Station Keeping
- Pointing and ACS
- Controlled Reentry/Disposal
- Interstellar Flight

Chemical
- Liquid Rockets
  - Pump Fed
  - Expander Gas Generator
  - Staged Combustion
  - Enhanced Cycles
  - Pressure Fed

- Solid Rockets
  - see solid propellant options

Thermal
- Solar
  - Fission
  - Fusion

- Antimatter

Electric Propulsion
- Electro Thermal
  - Electrostatic
  - Electromagnetic

- Stored Electric Energy Conversion (eg. Super Flywheels)

Propellantless Propulsion
- Tethers
- Sails
- Solar Plasma
- Gravity Assist Aerocapture

Beamed Energy
- Laser
  - Thermal
  - Electric

- Microwave

Breakthrough Propulsion Physics
- Black Hole Assist
- Space Warps
- Gravo Magnetic Enhanced Weak Forces

Propellants & Propellant Systems

In-Situ Production
- Low G Fluid Management
- Storage
- Liquid Slush
- Solids
- Conventional (1.1 to 1.3)
- High Energy Liquids

- Bipropellants
- Monopropellants
- Gels
- Metallized Gels
- Endothermic
- High Energy Density Mtls
- LO2/HC
- All Cryogenic
- Green/non-toxic
- Tanks, Fuel lines, Valves and Controls
- Hybrids

Liquid Rockets

Solid Rockets

Liquid Hybrids

Pressure Fed Liquid Hybrids

Hybrids

Propellants & Propellant Systems

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- High Energy Density Mtls
- LO2/HC
- All Cryogenic
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- Hybrids
Missions Often Characterized by “Delta V”

Typical Mission Examples

<table>
<thead>
<tr>
<th>Mission Description</th>
<th>ΔV Required KM/SEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Year GEO Stationkeeping</td>
<td>~0.5</td>
</tr>
<tr>
<td>LEO to GEO (0.3 days)</td>
<td>~4</td>
</tr>
<tr>
<td>LEO to GEO (250 days)</td>
<td>~6</td>
</tr>
<tr>
<td>Titan Orbiter (1way)</td>
<td>~11</td>
</tr>
<tr>
<td>Neptune SR (NEP)</td>
<td>~85</td>
</tr>
<tr>
<td>LEO to Alpha Centauri</td>
<td>30000.0</td>
</tr>
</tbody>
</table>

Far Away Places Truly Stress the Bounds of Propulsion
In-Space Transportation

Enabling New Scientific Discoveries

- Solar Electric Propulsion
- Nuclear Electric Propulsion
- Solar and Plasma Sails
- Chemical Propulsion
- Planetary Aeroassist
- Tethers
In-Space Propulsion Program Will Advance Mid-TRL Technologies to Support NASA Mission Applications

System Test, Launch & Operations

System/Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

TRL 9

TRL 8

TRL 7

TRL 6

TRL 5

TRL 4

TRL 3

TRL 2

TRL 1

NASA Implementation: (Deep Space One Ion Engine Example)

In-Space Propulsion Technologies

Aeroassist

Adv. Electric Propulsion

Solar Thermal

Adv. Chemical

Tethers

Solar Sails

Plasma Sails

Low-TRL Technologies For the Future

External Pulsed Plasma

Fusion & Antimatter

Beamed Energy
Electric Propulsion Overview
Three Classes of Concepts

**Electrothermal:**
Gas heated via resistance element or discharge and expanded through nozzle

**Electrostatic:**
Ions created and accelerated in an electrostatic field

**Electromagnetic:**
Plasma accelerated via interaction of current and magnetic field

**Examples -**
- Arcjets
- Resistojets
- Microwave

**Examples -**
- Ion Engines
- Hall Accelerators

**Examples -**
Pulsed Plasma
MPD/LFA
Pulsed Inductive
### Match the Power System to the Destination

<table>
<thead>
<tr>
<th>Main Asteroid Belt</th>
<th>Trojan Asteroids</th>
<th>Centaur Minor Planets</th>
<th>Trans-Neptunian Objects</th>
<th>Kuiper Belt Objects / Comets</th>
</tr>
</thead>
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**Inner Planets**

- **Solar Electric Confined to Inner Solar System**
  - Also limited reach to large outer planetary bodies with aerocapture (Jupiter, Saturn, Uranus, Neptune only)

<table>
<thead>
<tr>
<th>Inner Planets</th>
<th>Jupiter and Moons</th>
<th>Saturn and Moons</th>
<th>Uranus and Moons</th>
<th>Neptune and Moons</th>
<th>Pluto/Charon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jupiter</strong></td>
<td><strong>Saturn</strong></td>
<td><strong>Uranus</strong></td>
<td><strong>Neptune</strong></td>
<td><strong>Pluto/Charon</strong></td>
<td></td>
</tr>
</tbody>
</table>

- **Radioisotope Electric for New Frontiers Class Outer Solar System Missions**
  - Targets with low Mass
  - 500 W Class RTG
  - <50 kg payload
  - Delta II Launchers

- **Nuclear Electric for Large Flagship Missions to Outer Planets**
  - Large Targets
  - 100 kW Class Reactor
  - >500 kg Payloads
  - Delta IV Launch Vehicles

**RTG for Surface Lander**
Electric Propulsion and Power Source for Space Missions

Piloted
- Outer Planets
- Inner System Sample Returns
- Inner Planets, Comets, and Asteroids
- Earth Orbit

Solar
- Solar with AeroCap, & Chem

Nuclear
- Isotope

Solar at Earth with Aerocapture & Chemical at Target

Nuclear
- Isotope

Hall
- MPD, PIT, VASIMR
Projected high power handling capabilities at low specific mass make MPD and PIT thrusters candidates for high power NEP robotic and crewed interplanetary missions.
Project Prometheus

“Jupiter Icy Moons Orbiter”
Established Nuclear Energy Sources: Fission

Overcomes limitations of other candidate power sources
- Chemical: already near theoretical performance limits
- Radioisotopes: versatile and long-lived, but low power density and limited Pu-238 supply
- Natural sources (e.g., solar, EM tethers): highly dependent on location with respect to sun or planet
- Advanced concepts (e.g., beamed energy, fusion): too immature, may not work, and/or require substantial in-space infrastructure and investment

Greatly extends capability, sophistication and reach of future science missions
- Enables use of high-performance electric propulsion beyond inner solar system
- Provides long-duration, power-rich environments for sophisticated scientific investigations, high-data rate communications and complex spacecraft operations

Improves safety, capability and performance of future human planetary missions
- Power-rich spacecraft and surface operations
- Rapid transportation to reduce extended exposure to solar/cosmic radiation and zero-g

Fissioning 12 fl oz (341 ml) of Uranium yields 50 times the energy contained in a Shuttle External Tank
Energy Density: 82 billion joules per gram

\[= 50 \times\]
Mission Objectives

• This mission responds to the National Academy of Sciences’ recommendation that a Europa orbiter mission be the number one priority for a flagship mission in Solar System exploration.

• JIMO will search for evidence of global subsurface oceans on Jupiter’s three icy moons: Europa, Ganymede, and Callisto.

• JIMO will be the first flight mission to use nuclear power and propulsion technologies.

• This mission will set the stage for the next phase of exploring Jupiter and will open the rest of the outer Solar System to detailed exploration.
Nuclear Electric Propulsion

Nuclear Systems Initiative; Revolutionizing Space Exploration

- Faster Missions into Deep Space
- Power-rich Spacecraft for Sophisticated Investigations
- Ambitious Missions involving Multiple Planetary Destinations
- High-data Rate Communication
- Civil and Military Power Spinoffs

Broad Set of Concept Options with Common Technologies
**Fission Electric Power & Propulsion System**
**Diagram & Representative Technology Options**

**Reactor Power System**
- Reactor
- Shield
- Heat
- Power Conversion
- Power Mgmt & Distribution
- Heat Rejection

**Electric Propulsion System**
- Power Processing Unit (PPU)
- Electric Thrusters
- Propellant Feed System
- Propellant Tank

**Spacecraft Bus**
- Spacecraft Subsystems
  - C&DH
  - GN&C
  - RF
  - RCS
  - TCS
  - SW
- Science Payload

**Heat Rejection**
- 2-phase loops (capillary pumped loop, loop heat pipes)
- Heat pipes
- Pumped loops

**Power Management and Distribution**
- Depends upon power conversion:
  - AC
  - DC
  - Low/high input voltage

**Options for Reactors**
- Heat pipe cooled
- Liquid-metal cooled
- Gas cooled

**Power Conversion**
- Thermoelectric
- Segmented thermoelectric
- Stirling
- Brayton
- Thermo photovoltaic

**Electric Propulsion**
- Ion thruster
- Hall thruster
- MPD, PIT
Technical Challenges Required For NEP Systems Development
Potential Support to Human Space Exploration

- **Nuclear power and propulsion are key enablers of expanded human exploration**
  - Enables human exploration beyond earth orbit
  - Provides high power for human protection against charged solar particles
  - Provides abundant power at destination
  - Enables complex, long duration missions

- **Nuclear surface power is essential for extended reconnaissance of the Mars surface**
  - Long-range surface and sub-surface exploration
  - Human habitat and life support
  - *In-situ* manufacturing of consumables
  - *In-situ* propellant production
Development of Low-TRL Propulsion Technologies Can Take Decades

1903:
- LO2/LH2 Rocket
- The Rocket Equation
\[ \Delta V = I_{sp} \cdot \ln(M_{final}/M_{initial}) \]

"Earth is the cradle of humanity, but one cannot live in a cradle forever."

Year

Routine Human Access to Space

Solar Sails

Ion

Arcjet (NH3)

Hall (SPT)

MPD (Pulsed)

STS

Znamya

Cosmos

DS-1

ARGOS ESSEX

Express

SFU-1 (NASDA)
Propulsion Research

Unlocking the Potential of A Broad Spectrum of Revolutionary Concepts

Fission & Fusion Propulsion

Advanced Chemical Propulsion

Antimatter Propulsion

Breakthrough Physics

Electro-magnetic Propulsion
Rocket Engine Prototype (REP) Project Overview

♦ Objectives
  • Provide risk mitigation for large class, Oxygen Rich Stage Combustion Engine (ORSC)
  • Design and Test a high-fidelity prototype engine
  • Validate existing analytical tools
  • Develop and validate new analytical tools as required to develop the flight ORSC engine system

♦ Success Criteria
  • ORSC Engine System @ TRL 6 (demonstration in relevant environment)

♦ Goals
  • Improved Safety
  • Reduced Cost
  • Improved Operability and Responsiveness

♦ Current Activity limited to Prototype Engine Design and Technology Development
## ORSC Prototype Engine Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Prototype</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thrust</strong></td>
<td></td>
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<tr>
<td>Sea Level klb.</td>
<td>1064</td>
<td>1049</td>
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<tr>
<td>Vacuum klb.</td>
<td>1130</td>
<td>1160</td>
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<td><strong>Reliability</strong></td>
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<td>Failures Per Million Missions traceable</td>
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<td><strong>Operability</strong></td>
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<tr>
<td>Shift turn time</td>
<td>8</td>
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<td><strong>Specific Impulse</strong></td>
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<td>Sea level sec.</td>
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<td>301</td>
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<tr>
<td>Vacuum sec.</td>
<td>324</td>
<td>335</td>
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<tr>
<td><strong>Weight</strong></td>
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<tr>
<td>Dry lbm.</td>
<td>17,922</td>
<td>14,956</td>
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<td><strong>Life</strong></td>
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<tr>
<td>Missions</td>
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<td><strong>Dimensions</strong></td>
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<td>Length in.</td>
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<td>Diameter in.</td>
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<tr>
<td>Area Ratio</td>
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<td>36:1</td>
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</table>
Rocket Engine Prototype Project Overview

♦ Deliverables

• Oxygen Compatible Materials
• Manufacturing Technology Demonstrations
• Turbopump Inducer Waterflow Test
• Turbine Damping “Whirligig” Test
• Single Element Preburner and Main Injector Test
• 40K Multi-Element Preburner and MI
• Full-Scale “Battleship” Preburner
• Prototype Preburner Test Article
• Full-Scale Prototype TCA
• Turbopump Hot-Fire Test Article
• Prototype Engine
• Validated Analytical Models

On Current Contract
Full-Scale Preburner
- High fidelity simulation of internal flow geometry
- Injectors, Chamber, Splitter Ducts, and Turbine Simulators

Objectives
- Stability demonstration
- Flow uniformity at turbine inlets
- Materials usage

Turbine Simulator
NGLT & REP ORSC Future Space Launch Roadmap

Space Shuttle

Expendable Launch Vehicles

RLV Full Scale Development Decision

OSP Λ Crew Return

OSP Λ Crew Transfer

New Heavy DoD ELV

ORSC Technology Development Program

RS-84 Study Report

SDR PDR IDR CDR

Prototype Engine Test

ORSC Flight Engine Development

RS-84 Design

Authority To Proceed (ORSC Competitive Selection)

ORSC Technology Development, Prototype Engine Design & Fabrication

1st Flight Engine Delivery

ORSC Flight Engine Development

1st Flight

1st Flight

1st Flight
# Combustion Devices Roadmap

<table>
<thead>
<tr>
<th>FY02</th>
<th>FY03</th>
<th>FY04</th>
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<th>FY07</th>
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<tr>
<td>Single Element Test</td>
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<td>40K PB Test</td>
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<td>40K TCA Stage Test</td>
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<td>Full Scale Battleship Pre Burner Test</td>
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<td>Flight Engine Design &amp; Development</td>
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**Program Milestone**

**REP ORSC Combustion Devices Roadmap**
## REP ORSC Turbomachinery Roadmap

### Turbomachinery

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- **IPD Oxidizer Turbopump**
- **Turbine Damping Test (Whirligig)**
- **Water Flow Test (Inducers and Impellers)**
- **Turbine Air Flow Technology (TAFT)**
- **Analytical Model Development**
- **Fabricate 3 Turbopump Sets**
- **Pump Manufacturing Demo**
- **Damper Materials Test**
- **Seal Materials Test**
- **Turbopump Cold Flow Test**
- **Hot Fire Test**
- **Prototype Engine Test**
- **Flight Engine Design & Development**
- **Program Milestone**