NASA In-Space Propulsion Systems Roadmap
TA02 Low Thrust Panel

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Key Overarching Messages for NASA In-Space Propulsion

- Continuous funding over a range of TRLs is required
  - Ensures a stream of technologies being matured for new mission insertion opportunities
  - Avoids perpetual start/stop and increased cost due to agency and program level priority changes
  - Balances near term evolutionary development with longer term revolutionary high payoff research
  - Review of relevance and progress of technology development programs at regular intervals ensures ongoing applicability
- Mission level requirements are critical when determining what technology to fund
  - Just because it is higher performance doesn't mean it makes sense to develop
  - There must be a mission level benefit to the user community
    - Decreased overall/life-cycle cost (taking into account NRE and infrastructure investments)
    - Mission enabling/enhancing

Key Overarching Messages for NASA In-Space (cont'd)

- Particularly for low thrust in-space propulsion, the user community includes NASA, DoD, and commercial
  - Thrusters are often used similarly by each community
  - Increased coordination between NASA and industry is required to minimize cost and increase program advocacy (common reqmts)
- Funding through qualification is becoming increasingly required unless there is a clear common cost benefit or mission level need
  - Many recent in-space propulsion technology programs have been "stalled out" at TRL 6 due to lack of cost/mission benefit
  - Primes do not want to increase risk in propulsion subsystems
- Even within NASA, technology infusion needs to be tightly coupled to mission needs and cost constraints
  - Avoid inevitable cost/schedule overruns due to development programs targeted either too early or inappropriately for insertion
  - Coupling by nature is not as tight for lower TRL efforts

Notice that all major points above include "cost" and "mission"

In-Space Propulsion Systems: Mission Enablers

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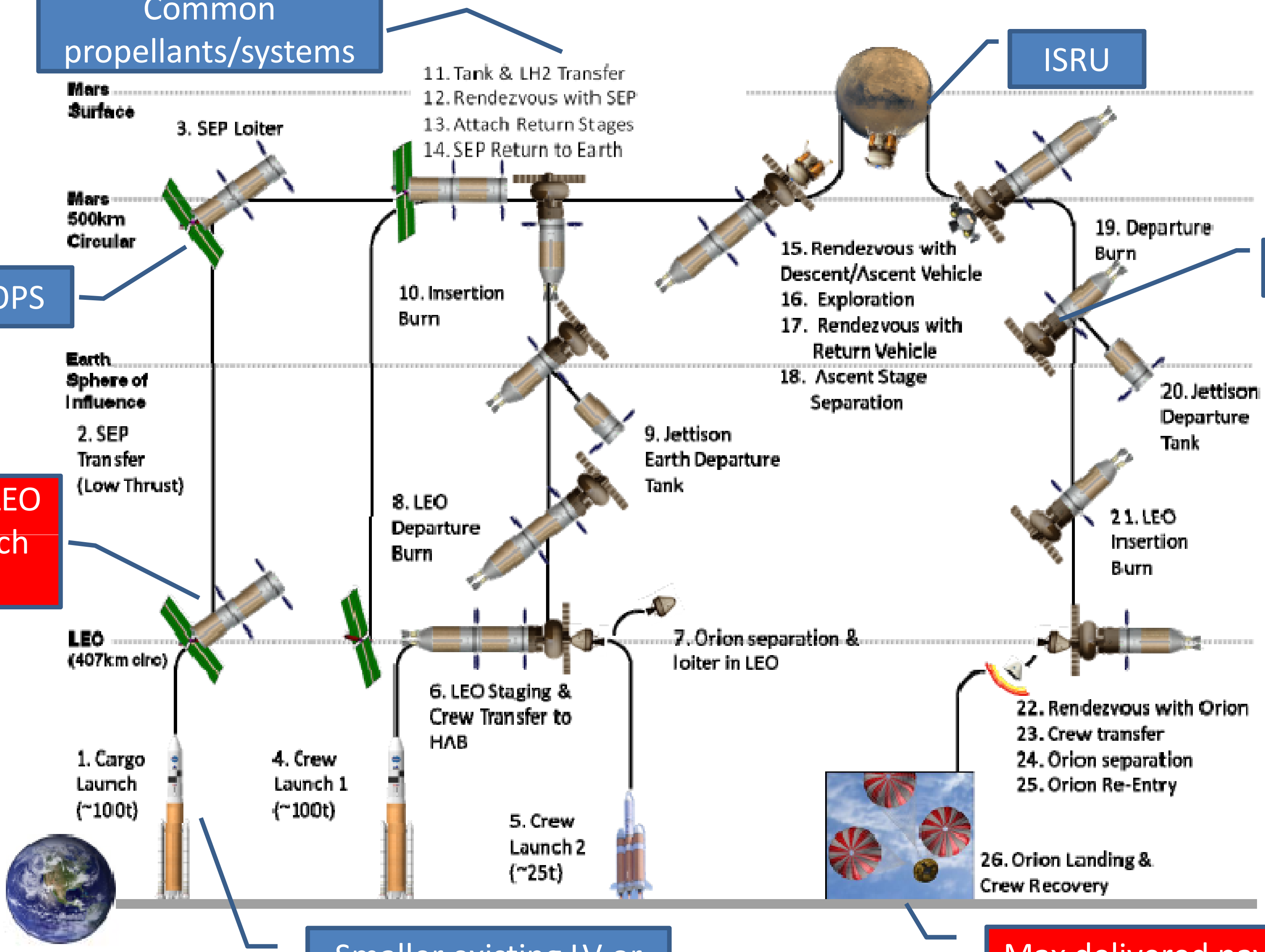


Common propellants/systems

ISRU

CONOPS

Staging

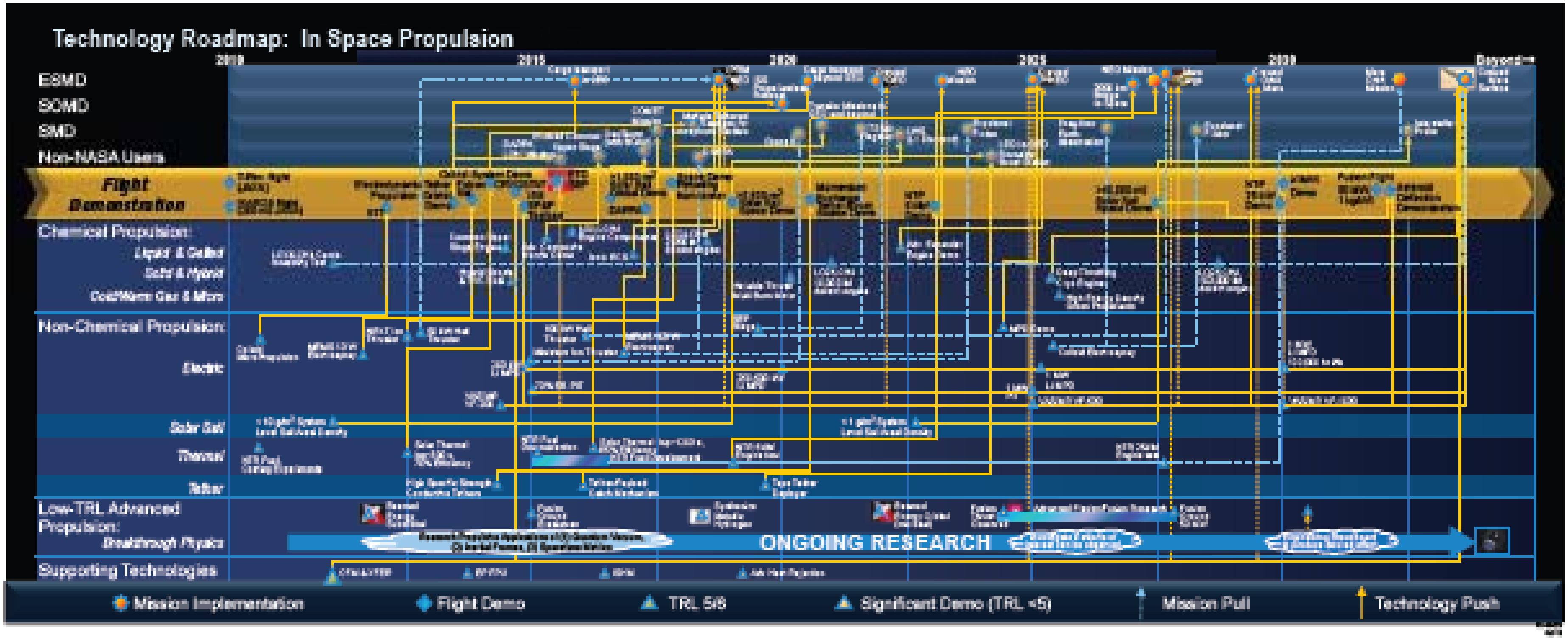
Min IMLEO or launch mass

Smaller existing LV or lighter weight new LV

Max delivered payload

NASA In-Space Propulsion Systems Roadmap

- Roadmap Comments
  - Can NASA really fund and complete all the applications and technologies identified? Do we need more prioritization and focus?



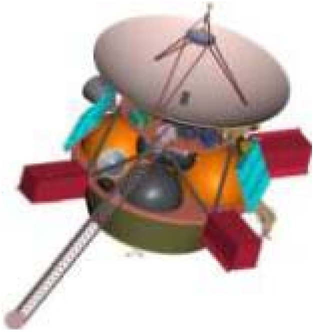
NASA In-Space Propulsion Systems Roadmap

- Every chemical propulsion technology category includes the $ designator indicating that improvements over the current SOA reduce cost/system complexity/improve system reliability
  - This is not true in every case (maybe any case) and should be revisited
  - Although the cost may be higher than the current SOA, it should still be minimized for technologies required to achieve NASA goals
- Focus should be on technologies that are (1) mission enabling/enhancing and (2) have use by industry for other applications
  - Is the technology a net positive at the mission level based on evaluation of cost, mass, performance, reliability? Ensure that realistic trades are performed, e.g. common propellant ACS.
  - Is there another use for the technology outside of NASA that can help control cost, risk, assured production
- Suggest adding columns to the evaluation table identifying (1) mission enabling/enhancing characteristics, including list of applicable missions, and (2) other industry applications

NASA In-Space Propulsion Systems Roadmap Missions

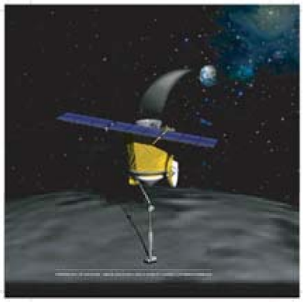
- MAX-C ($3.5B)/Mars Sample Return ($3.0B) – Planetary Decadal Survey Flagship
  - MAX-C cost to NASA needs to be $2.5B => cost reduction, partnering
  - Atlas V 531 launch vehicle required => launch mass limited
  - MAX-C and MSL cruise and descent propulsion – monopropellant N2H4
  - MAV baseline propulsion - solids for ascent with monopropellant ACS
    - Technical challenges: low payload fraction, landing survival, cold long-term environment
    - Early development required, MAV propulsion will be enabling (large benefit for increasing payload fraction)

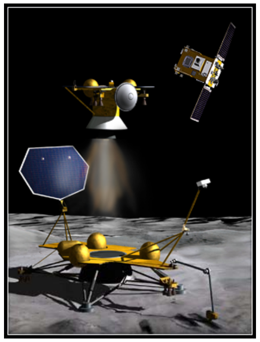
- Jupiter Europa Orbiter ($4.7B) – Planetary Decadal Survey Flagship
  - Affordability issue
  - Atlas V 531 launch vehicle required => launch mass limited
  - Orbiter propellant mass 2681 kg => JOI key driver for DM prop system
  - Large benefit for propellant mass savings (~40 kg of instruments already descoped) – cost vs. mass trade

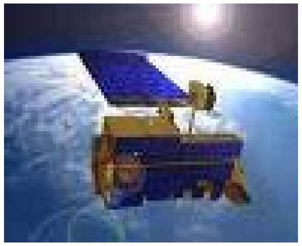


- Uranus Orbiter Probe ($2.7B) – Planetary Decadal Survey Flagship
  - Atlas V 531 launch vehicle required => launch mass limited
  - $150M SEP stage enabling for mission – 828 kg Xe at 4000 sec Isp (NEXT), Hall lower cost option
  - Orbiter propellant mass 1180 kg => UOI key driver, AMBR baselined (large benefit for propellant mass savings – cost vs. mass trade)

NASA In-Space Propulsion Systems Roadmap Missions







- Comet Sample Return ($800M) – Planetary Decadal Survey New Frontiers
  - Atlas V 521 launch vehicle required => launch mass limited
  - S/C propellant mass 468 kg with NEXT, possible with chemical on larger launch vehicle (Atlas V 551) (cost/risk trade)
- Lunar Polar Sample Return ($800M) – Planetary Decadal Survey New Frontiers
  - Atlas V 531 launch vehicle required => launch mass limited
  - Chemical propulsion baselined, return payload can be increased with higher Isp for increased cost
- Various Earth Observation ($200M-$650M) – Earth Science Decadal Survey
  - CLARREO, SMAP, DESTdynl, HyspIRI, SWOT, GRACE II, 3D Winds
  - Typical Delta II/Minotaur 4/Taurus II launch vehicle class
  - Chemical propulsion (hydrazine) baselined, payload can be increased with higher Isp for increased cost
  - Similar scenarios with Sun-Earth Connection spacecraft

NASA In-Space Propulsion Systems Roadmap Missions

- Human LEO/GEO/L1 (Human Exploration Framework Team - HEFT)
  - MPCV (Orion), monopropellant and storable bipropellant propulsion
  - Potential initial cryogenic propulsion stage
- Human Lunar Flyby/Landing (HEFT)
  - Cryogenic propulsion stage required, throttling for descent
  - SEP stage for cargo reduces launch vehicle size from 130t to 70t
- Human Near-Earth Asteroid (HEFT)
  - Cryogenic propulsion stage required
  - SEP stage for cargo reduces launch vehicle size from 130t to 70t
- Human Phobos/Mars (HEFT)
  - Cryogenic propulsion required, throttling for descent
  - Use of CH4 could tie to ISRU
  - SEP stage for cargo reduces launch vehicle size from 130t to 70t

NASA In-Space Propulsion Systems Roadmap Mission Summary

- Key themes
  - Cost reduction
  - Minimizing launch mass/maximizing payload mass
- Mission enablers
  - SEP stage for planetary flagship and human exploration
  - In-space cryogenic bipropellants for human exploration
    - Propellant management
    - Delta-V engines
    - Throttleability for ascent/descent
- Mission enhancers
  - NEXT/Hall thrusters for small body sample return
  - Higher performance storable biprop delta-V for planetary missions
  - Advanced monopropellant ACS for robotic and potentially human missions
  - Cryogenic ACS for human exploration
  - Space storable solids for planetary ascent
  - Nuclear thermal for human exploration

NASA In-Space Propulsion Systems Roadmap

- Technology Ranking – Group 1

Rank	Technology	Mission Applicability	Commercial/ Other Applicability	Comments
1	Medium-high power electric propulsion (NEXT, Hall)	• Uranus Orbiter Probe, Comet Sample Return (20kW) • Human Lunar, NEO, Phobos/Mars (300-600kW)	• Earth orbit transfer stage (20-30kW) • Common planetary transfer stage (20kW)	• 20-30kW demo becomes directly applicable to earth orbit and planetary transfer stage, scalable to higher power for human exploration • Enabling for outer planet orbiter/descent probe missions • Huge CONOPS IMLEO payoff for human NEO/ Phobos/Mars missions
2	In-space cryogenic propellant management	• All human missions beyond earth orbit (LOX, CH4, H2)	• Potential commercial tug or crew vehicle	• Common to low and high thrust propulsion
3	In-space cryogenic bipropellant delta-V engines	• All human missions beyond earth orbit (LOX, CH4, H2)	• Potential commercial tug or crew vehicle	• Throttleability for ascent/descent missions • Trade of H2/CH4 required (performance vs. mass/volume, ISRU)

Low Thrust

NASA In-Space Propulsion Systems Roadmap

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- Technology Ranking – Group 2

Rank	Technology	Mission Applicability	Commercial/ Other Applicability	Comments
4 **Low Thrust**	Advanced storable bipropellant delta-V engines	• Uranus Orbiter Probe • Lunar Sample Return • Earth Observation Missions • Discovery Missions	• GEO apogee burn commercial • LEO drag maintenance/ maneuvering	• AMBR, higher pressure engines • Large marginal payload increase for 1.5-6% Isp increase for high delta-V missions
5 **Low Thrust**	Advanced monopropellant ACS (HAN, AF-M315E, ionic liquids)	• MAV ACS • Higher performance/ better packaging ACS for human exploration vehicles	• ACS for commercial and government spacecraft • Less toxic propulsion for MDA applications • Small spacecraft requiring low toxicity propulsion	• 40-50% density-Isp advantage over hydrazine plus lower freezing point • Lower toxicity for easier integration • Benefit for smallsats with minimal available volume • High temperature oxidation-resistant materials development required
6 **Low Thrust**	In-space cryogenic bipropellant ACS engines	• All human missions beyond earth orbit (LOX, CH4, H2)	• Potential commercial tug or crew vehicle	•Trade of H2/CH4 required (performance vs. mass/volume, ISRU) • Trade of cost/mass/ performance vs. storable monoprop/biprop required

Technology Ranking - Group 3

Rank	Technology	Mission Applicability	Commercial/ Other Applicability	Comments
7	Space storable solid propellant rockets	• MAV delta-V • Sample return delta-V		• Key issues are landing survivability and storage environment
8	Nuclear thermal propulsion	• Human missions to NEO, Phobos, Mars		• NTR for NEO provides minimum number of mission elements and IMLEO • Long history dating to 1950's • ~10 years development required
9	Low TRL (1-3), high payoff propulsion Low Thrust	• Potentially all NASA missions	• Numerous applications depending on technology performance and cost	• Required to enable a robust technology portfolio for future missions

NASA In-Space Propulsion Systems Roadmap

- In-space low thrust investment recommendations
  - SEP high power Hall and ion thruster systems (enabling/enhancing)
    - Logical extension to existing technology development programs (NEXT, HPPS, etc.)
    - Demo and system qualification for planetary flagship missions
    - Follow on scaled development for SEP cargo stated for human exploration
    - Power distribution/management and power processing units are challenging
    - Non-NASA applications in orbit raising and transfer stages
  - Advanced storable bipropellant delta-V engines (enhancing)
    - Large marginal gain in payload for 1-2% Isp increase for large delta-V missions such as outer planet orbiters and sample return
    - Logical extension to existing AMBR program (higher performing and lower cost than current SOA) and higher pressure technology roadmap
    - Non-NASA applications in GEO apogee engines, LEO delta-V engines
  - Advanced monopropellants for ACS (enhancing)
    - Potential higher performing, higher density, lower toxicity, lower temperature propellant than hydrazine
    - Multiple development paths – low/high pressure, HAN blends/AF-M315E/ionic liquids
    - High combustion temperature challenges for materials and catalyst
    - Non-NASA applications in spacecraft ACS, MDA, and DoD/DARPA/commercial smallsats

Summary

- In an environment of flat to decreasing budgets, life cycle cost reduction and mission enablement/enhancement are the key factors
- Ensure strong coupling to missions and mission level requirements
  - Resist the urge to fund “a little bit of everything”
  - But do fund a consistent level of low-TRL high payoff technologies
- Partner with industry where applicable for increased advocacy and reduced costs
- Key in-space propulsion technologies
  - High power electric propulsion
  - In-space cryogenic bipropellant propulsion
- Key in-space low thrust propulsion technologies
  - SEP high power Hall and ion thruster systems
  - Advanced storable bipropellant delta-V engines
  - Advanced monopropellants for ACS