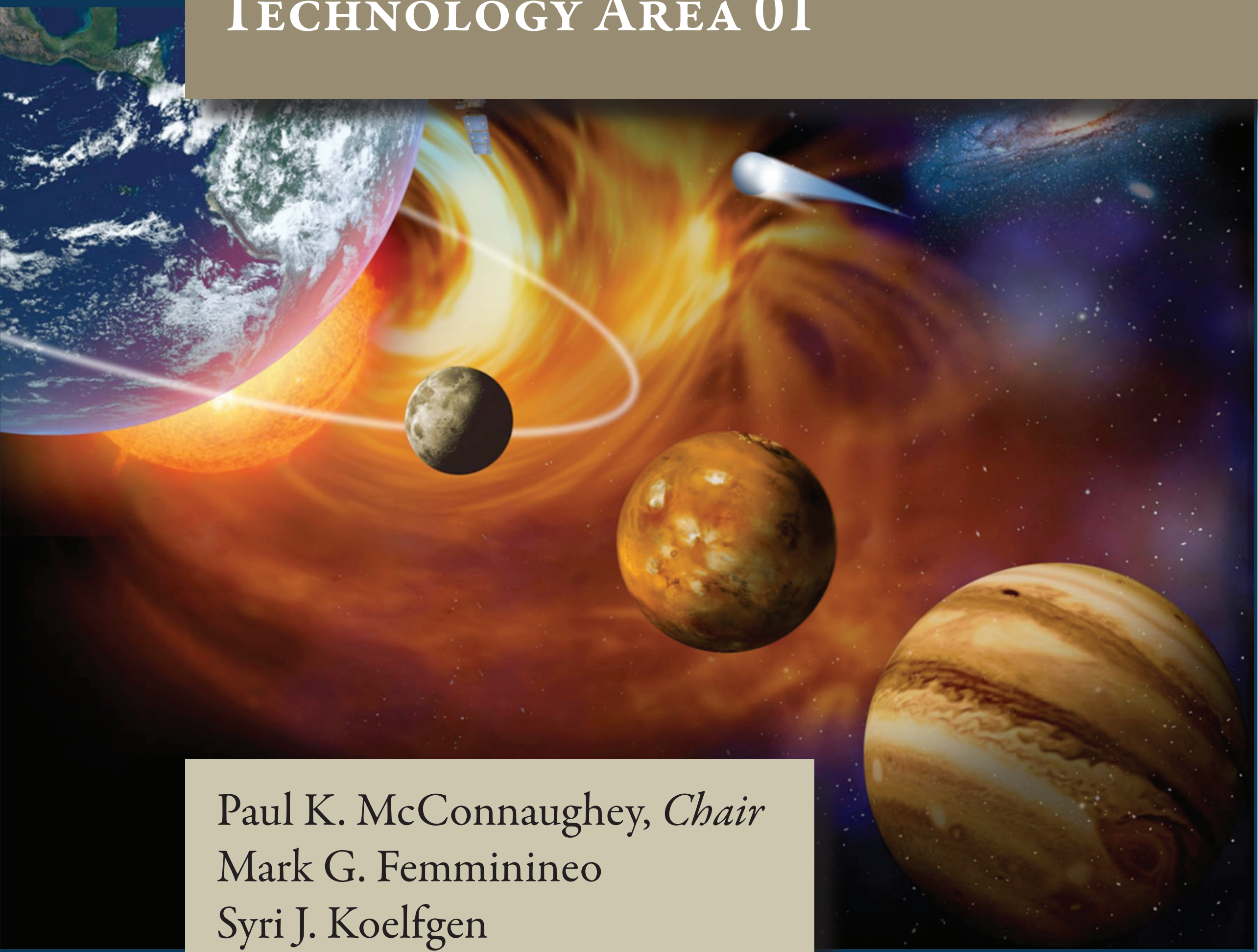
National Aeronautics and Space Administration

DRAFT Launch Propulsion Systems Roadmap

Technology Area 01



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 01 input: Launch Propulsion Systems. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

Safe, reliable, and affordable access to low-Earth (LEO) orbit is necessary for all of the nation's space endeavors. The Launch Propulsion Systems Technology Area (LPSTA) addresses technologies that enhance existing solid or liquid propulsion technologies or their related ancillary systems or significantly advance the technology readiness level (TRL) of newer systems like air-breathing, unconventional, and other launch technologies. The LPSTA consulted previous NASA, other government agencies, and industry studies and plans for necessary technology developments, as well as subject matter experts to validate our assessment of this field, which has fundamental technological and strategic impacts on the nation's space capabilities.

The LPSTA selected its most promising technologies based on critical figures of merit, including propulsion system production and operational costs, game-changing operational and performance capabilities, and national needs also identified by other government agencies and industry. The technologies reflect the future launch needs of the NASA mission directorates, other government agencies, and commercial industry, which include a wide range of payload classes, from small (<2 metric tons (t)) to >50 t.

The LPSTA identified a number of challenges across the range of possible launch propulsion technologies to be developed over the next 20 years. These technologies were prioritized based on an LPSTA team consensus for the identified needs and the expected return on investment for each technology area. In the near term, this includes tactical needs like high-strength oxygen-compatible materials for new hydrocarbon-based engines as well as more exotic technologies like launch assist approaches and fusion-powered nuclear thermal rockets (NTRs).

The LPSTA was organized around five primary technology areas: solid rocket propulsion systems; liquid rocket propulsion systems; air-breathing launch propulsion systems; ancillary propulsion systems, which include subsystems for existing systems, as well as smaller rocket systems like RCS and abort systems; and unconventional and other propulsion systems. Solid and liquid rocket propulsion systems have been used since the dawn of space flight, and naturally comprise fuel and oxidizers in solid or liquid form. These technologies are reaching the limits of theoretical efficiency and performance using conventional propellants. Air-breathing launch propulsion systems extract their oxidizer from the atmosphere and could be part of an integrated system that includes more conventional rockets to reach the vacuum of space. Hypersonic air-breathing systems, as demonstrated by X-43 and X-51, are still in the experimental stage. Improvements in ancillary propulsion systems would include the supporting subsystems for conventional propulsion systems, including controls and smaller rockets not directly responsible for lift to orbit. Unconventional launch technologies include systems that do not rely solely on onboard energy for launch or that use unique technologies or propellants to create rocket thrust. Included in this area are technologies that are at a very low TRL or that do not map into the other propulsion taxonomies.

Solid rocket motors (SRMs) have many advantages over liquid systems such as high-energy density and long-term stability and storability. However several disadvantages limit their applicability, which can be reduced or eliminated by advancing the technology base of SRMs to make them more attractive alternatives to liquid systems. Key disadvantages for SRMs today are lower performance (I_{sp}), lack of throttling on demand or ability to shut down on command, environmental concerns, and ground operations costs associated with safety issues in handling large solid segments. This roadmap proposes technology investments that address some of these disadvantages, as well as enhance the advantages mentioned above. Key areas for improvement include a green propellant alternative to current oxidizers, advancing the ability to assess damage tolerance limits and detect damage on composite cases, developing domestic sources for critical materials used in manufacturing of SRMs, formulating advanced hybrid fuels to get energy density equal to SRMs, and investing in the fundamental physics of SRM design including analysis and design tools.

Liquid rocket propulsion systems use propellants (fuels and oxidizers) that are kept in a liquid state prior to and during flight. The advantages of liquid rocket engines include generally higher I_{sp} and better thrust control (including throttling and restart capability) than solids. Liquid rocket propulsion systems are more operationally complex than solids and require some form of active flow control that introduces additional possibilities for failures. The liquid propulsion roadmap addresses the critical figures of merit by proposing technology investments in new liquid engine systems, propulsion materials research, high-density impulse and green propellants, and new subsystem modeling and design tools.

Air-breathing launch propulsion systems obtain the oxidizer for combustion from the Earth's atmosphere, which is combined with fuel brought on board. Air-breathing engines change modes as speed and altitude increases, and transition to pure rocket mode at high altitudes for the final ascent to space. This roadmap focuses on key technologies that would advance air-breathing launch propulsion systems during validation flight tests and would lead to the design of a staged air-breathing launch vehicle. These technology investments include the development of Mach 4+ turbines for turbine-based combined cycles, long-duration Mach 7+ scramjet operation, stable mode transitions of rocket-based and turbine-based combined cycle vehicles, an integrated air collection and enrichment system, and detonation wave engine operation.

Ancillary propulsion systems that support the main vehicle propulsion system or provide other key launch vehicle functions during ascent, are significant drivers in vehicle cost, complexity, and reliability. Development of new low-cost cryogenic and rocket propellant (RP) valves, lines and support components is essential to support less expensive new vehicle development and reinvigorate our nation's technology base in this area. Some capabilities that are within reach with up-front technology development include nontoxic reaction control systems, advanced sensors coupled with smart control systems providing robust integrated vehicle health management (IVHM), high-powered electromechanical actuators (EMAs) and their supporting power supply and distribution systems, large robust mechanical separation systems, and launch abort systems with high-thrust steerable motors tied to an adaptive flight control system. Once developed, these capabilities would have immediate positive impact on vehicle production and operational costs, overall vehicle reliability, and ground and flight safety.

Unconventional and other propulsion systems include near-, mid-, and far-term technology approaches primarily focused on reducing the cost of access to space. Ground-based, hypervelocity accelerators for low-cost delivery of large numbers of small, high-g tolerant payloads to LEO are a near-term technology that can provide significant payoff for a relatively small technology investment. Orbiting space tethers that can act as the final stage of a launch system and relieve the performance requirements for vehicle ascent, potentially enabling fully-reusable, suborbital vehicles with robust operating margins at current technology levels, are a promising technology of interest in the mid term. Mid- to far-term technologies that can provide breakthrough improvements in propulsion efficiency through the application of energy generated by means other than chemical combustion, such as power beaming, nuclear fusion, and high-energy density materials, are prime candidates for future investment.

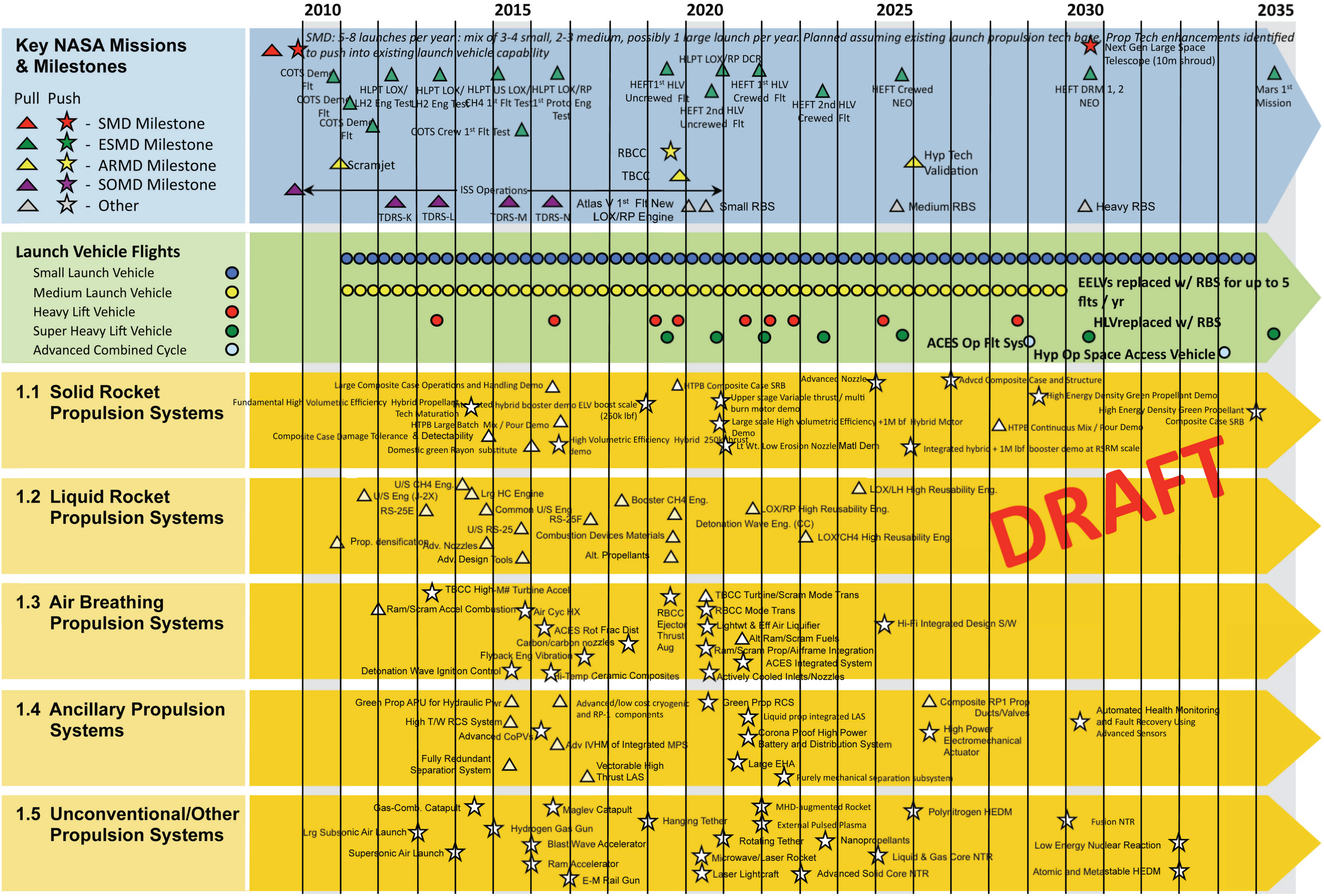
The LPSTA roadmap (Fig. 1) reflects a staged development of critical technologies that include both "pull" technologies that are driven by known short- or long-term agency mission milestones, as well as "push" technologies that generate new performance or mission capabilities over the next 20 to 25 years. While solid and liquid propulsion systems are reaching the theoretical limits of efficiency, they have known operational and cost challenges while continuing to meet critical national needs. Improvements in these launch propulsion systems and their ancillary systems will help maintain the nation's historic leadership role in space launch capability. Newer technologies like air-breathing launch propulsion, unconventional, and other propulsion technologies and systems, while low in TRL, can radically transform the nation's space operations and mission capabilities and can keep the nation's aerospace industrial base on the leading edge of launch technologies.

1. INTRODUCTION

1.1. Technical Approach

Reliable and cost-effective access to space is a fundamental capability required for all of NASA's in-space missions. In light of this, NASA's Office of the Chief Technologist (OCT) has identified the Launch Propulsion Systems Technology Area (LPSTA) to highlight current and potential technology investments by the Agency. In this planning, Earth-to-orbit (ETO) transportation was considered, as other OCT technology areas (TAs) addressed beyond-low-Earth orbit (LEO) transportation. Also, the domain of this planning activity was limited to ETO propulsion systems; other technologies, which could apply to a launch vehicle, e.g., materials, structures, thermal, and ground systems, were addressed by other TA teams. This LPSTA was then subdivided into five areas of emphasis, which included (1) solid rocket propulsion systems, (2) liquid rocket propulsion systems, (3) air-breathing launch propulsion systems, (4) ancillary propulsion systems, and (5) unconventional or other propulsion systems.

Figure 1: *Launch Propulsion Systems Technology Area Strategic Roadmap (TASR).*



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These five areas of emphasis highlight both the current and future challenges for launch propulsion technology. Much of the work performed in the last 50 years has been through solid and liquid rocket propulsion technologies, which although nearing the theoretical limits of chemical combustion performance and efficiency, are still not as cost effective as desired. Technology developments in these areas tend toward enhancing existing capabilities. Other methods of reaching LEO are still at a low technology readiness level (TRL), with some being to the point of being quite theoretical in nature and concept. Therefore, the technologies needed to enable these new approaches are more diverse and fundamental. Targeted areas for improvement (lowering costs of current systems and maturing low TRL approaches) could benefit significantly from a prudent and balanced technology investment strategy.

To adequately survey the landscape of necessary technologies, the LPSTA team reviewed technology assessments and roadmaps developed by NASA, and other organizations over the past 15 years (a total of 16 major technology databases as seen in Table 1); consulted with experts in the fields of solid, liquid, air-breathing, ancillary, and unconventional launch propulsion technologies; and conducted fact-finding discussions with eight aerospace companies to get their inputs on industry needs and plans. Because there has been no significant investment or broad-based planning by NASA in launch propulsion technologies over the last 7 years, the LPSTA roadmap presents significant updates to planning launch propulsion technologies over a wide range of TRLs and approaches.

1.2. Benefits

The overall goals of LPSTA investments within NASA are to make access to space (LEO) more reliable, routine, and cost effective. The most common metric used to assess the latter is dollars per kilogram ($/kg) to LEO; other metrics considered in many of the joint NASA planning activities with other governmental agencies addressed short call-up time, launch vehicle turn-around time, sortie rate, and reduced weather constraints. Due to NASA's need for lower costs as opposed to the operationally responsive requirements, the LPSTA identified technologies with the following characteristics that could significantly lower dollars per kilogram to LEO based on the following

Propulsion system production costs
Propulsion system operational costs
Game-changing system & operational concepts
Game-changing propulsion system / subsystem efficiency and capability
National needs supported by input from other government agencies and industry

Table 1. *Databases Consulted by LPSTA.*

- Space Launch Initiative (SLI) Technology Data
- National Aerospace Initiative (NAI) Roadmaps
- Next-Generation Launch Technology (NGLT) Plan
- Advanced Planning and Integration Office (APIO) In-Space Transportation Roadmap
- Integrated High-Payoff Rocket Propulsion Technology (IHPRPT) Plan
- Capability, Requirements, Analysis, and Integration (CRAI) Database
- Alternate Horizontal Launch Space Access Technology Roadmap
- Boeing National Institute of Aerospace (NIA) Hypersonics Report
- NASA Fundamental Aeronautics Program Hypersonics Project 6-Month and 12-Month Reviews (with roadmaps)
- "USA Fundamental Hypersonics" presentation to 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference
- National Aeronautics Research and Development Plan
- Report to Congress: Roadmap for the High-Speed and Hypersonic Programs
- National Hypersonics Plan: Access to Space Team Roadmap
- Gryphon Integrated Product Team (IPT) Kickoff Meeting and Roadmap
- NASA Hypersonics Project Planning Meeting
- National Research Council (NRC) Decadal Survey of Civil Aeronautics

figures of merit:

The overall goal of these technologies would be to reduce launch costs by 25–50 percent over the next 20 years, with a higher reduction (>50%) expected for non-conventional and innovative concepts. It is expected that the most feasible path to achieve this goal is to develop launch systems with reusable elements that reduce operational and recurring hardware costs. This reduction could be achieved with significant incremental improvements in current systems or approaches, e.g., a reusable booster system. Similar benefits could result from launch assist or air-drop systems. Additional cost reductions and performance gains should come from either air-breathing or non-conventional approaches that would carry fuel on board and use ambient air as the oxidizer. These systems, using existing aviation infrastructure such as airports, runways, and jet engines, could produce much higher flight rates over a broader azimuth capability than rocket-based systems. Higher flight rates measured in hours instead of days, weeks, or months make missions requiring multiple launches or payloads much more feasible. To achieve these "airline like" operations, design teams have typically looked at applications of advanced air-breathing systems, with a focus on the hypersonic flight regime.

The challenge for all launch propulsion systems is that the performance requirements dictated by the physics of escaping Earth's gravity leave very little margin in the systems to find existing technology solutions that reduce cost, enhance reliability, or improve operability. Whether based on conventional liquid or solid based designs, or on a hypersonic boost approach, systems to date have not exhibited the performance, design, and life margins that lead to operational robustness. A true breakthrough in space access will require concepts that produce significant increases in system margins while still providing a high level of performance.

However, at present solid and liquid rocket-based propulsion systems remain the primary means for the U.S. to launch payloads to LEO. Given the nation's near-term dependence on space-based assets in LEO and other orbits, it is vital that the nation maintains its industrial capability to design, build, test, and fly updated and new solid and liquid rockets. National-level investments in technologies to support these systems will remain wise investments for the foreseeable future. This is consistent with a major finding from the LPSTA industry discussions, where the team identified the need to improve the United States' leadership in aerospace technology, independence from foreign sources of technology or materials, and the need to maintain a basic and consistent investment in launch propulsion system technologies and capabilities.

1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, DRAs

To develop a responsive set of technology goals and applicable mission manifest, as well as identify both "push" and "pull" technologies, the LPSTA team reviewed the National Space Policy, the NASA Draft Strategic Goals, and the draft Agency Mission Planning Manifest for 2011. The team also assessed the technology and implementation plans of NASA's mission directorates, including the Science Mission Directorate (SMD), Space Operations Mission Directorate (SOMD), the Exploration Systems Mission Directorate (ESMD, and the Aeronautics Research Mission Directorate (ARMD). In addition to these plans and goals, the team utilized the findings of the Human Exploration Framework Team (HEFT), which generated design reference missions (DRMs) in response to the proposed 2011 President's budget for NASA, and the results of the Agency Study Teams, which formulated initial responses to the Office of Management and Budget (OMB) budget guidance for 2011. The latter includes the Heavy-Lift Propulsion Technology (HLPT) plan and the Commercial Crew Development (CCDev) plan.

Results of this assessment are seen in the mission manifest depicted in the integrated LPSTA roadmap in Figure 1 of the Executive Summary. For the SMD missions, launch vehicle requirements result in a steady tempo of launches, comprising 5–8 payload launch requirements per year. The payload class ranges of these requirements include 3 to 4 small (<2 t) payloads per year, 2 to 3 medium (2–20 t) payloads per year, and a heavy (20–50 t) payload requirement every few years. As a customer of launch services, SMD depends on national capabilities and does not invest in launch propulsion system technologies; it is primarily interested in low-cost and reliable launch services. ESMD has a significant proposed investment in LPSTA; this can be seen in the HLPT plan and its emphasis on selected engine technologies, e.g., RP and methane (CH_4) prototype engines. It is also reflected in the HEFT planning to support a near-Earth object (NEO) mission (the requirement for a crewed super-heavy (>50 t) launch vehicle in the 2020 time frame), and in the funding of CCDev for low-cost, conventional launch propulsion technologies by 2015. ARMD planning includes regular efforts in hypersonic tests and technologies. These tests are critical for developing efficient hypersonic capabilities that support access to space for small- and medium-class payloads, as these hypersonic air-breathing vehicles could be used as a first-stage booster for an upper-stage and payload. OCT's investment in LPSTA is still to be determined, and this LPSTA roadmap provides an initial plan with options and candidates for future NASA technology funding.

Reflecting the mission requirements and the technology plans of the Agency, the LPSTA team developed a representative launch vehicle manifest (seen in the second row of Fig. 1), with launch vehicles categorized as:

🔵	Small: 0–2 t payloads
🟡	Medium: 2–20 t payloads
🔴	Heavy: 20–50 t payloads
🟢	Super Heavy: > 50 t payloads

These vehicle classes were used to generate representative vehicle systems that supported mission requirements. Launch propulsion technologies were then mapped to these vehicle systems. An additional category was included for flight tests of new launch vehicles, i.e.,○ air-breathing launch propulsion.

1.4. Top Technical Challenges

LPSTA identified major technical challenges for three time horizons, which reflect the needs and expected successes in the near (present to 2016), mid- (2017–2022), and long-term (2023–2028) time frames. These technologies were prioritized within each phase based on an LPSTA team consensus for both the identified needs and the expected ROI for each technology area. This resulted in a balance of challenges that address problems with operation and cost of current systems while establishing research in the non-conventional systems. Each of the technology challenges seen in Table 2 will be discussed in more detail in Section 2 of this roadmap report.

Table 2. *Top Technical Challenges by Time Frame.*

Present – 2016	2016 – 2022	2023 – 2028
1. High-Strength Oxygen-Compatible Materials	1. Large ORSC Engine	1. Hypersonic Technology Validation Flight
2. Integrated Ramjet/Scramjet Flight to Mach 7+	2. ACES Integrated Flight System	2. High Energy Density Propellants
3. SRM Composite Case Damage Tolerance and Detectability	3. RBCC/TBCC Mode Transition	3. SRM Green Propellant
4. Nontoxic RCS	4. Advanced Expander Cycle Engine	4. Advanced Alt. Liquid Fuels
5. Advanced RP and Cryogenic MPS Components	5. MHD-Augmented Rocket	5. Nuclear Fusion NTR
6. TBCC Mach 4+ Turbine Acceleration	6. Large Scale, High Volumetric Efficiency Hybrid (1Mlbf Thrust.)	
7. Hypervelocity Accelerators	7. Power Beaming Technologies and Propulsion Systems	
8. Carbon-Carbon Nozzle (Domestic Source)		

2. DETAILED PORTFOLIO DISCUSSION

2.1. Portfolio Summary and Work Breakdown Structure

The LPSTA team assembled a work breakdown structure, referred to here as the Technology Area Breakdown Structure (TABS) to organize the technologies described in this section. This TABS, shown in Figure 2, concentrates on engines, motors, and other technologies capable of lifting payloads from the Earth's surface to LEO, as well as their associated propulsion-supporting subsystems. The top-level content represents a taxonomy based on the primary characteristics of propulsion systems, and they differ in their range of technical and operational maturity. Chemical solid and liquid rocket propulsion systems have been used since the dawn of space flight, and as their names suggest, consist of fuel and oxidizers in solid or liquid form. These technologies (as currently used on the Space Shuttle and other vehicles) are reaching the limits of theoretical efficiency and performance using conventional propellants. Air-breathing launch propulsion systems extract their oxidizer from the atmosphere and could be part of an integrated system that includes more conventional rockets to reach the vacuum of space. Hypersonic air-breathing systems, as demonstrated by X-43 and X-51, are still in the experimental stage. Improvements in ancillary propulsion systems would include the supporting subsystems for conventional propulsion systems, including controls and smaller rockets not directly responsible for lift to orbit. Unconventional launch technologies include systems that do not rely solely on on-board energy for launch or that use unique tech-

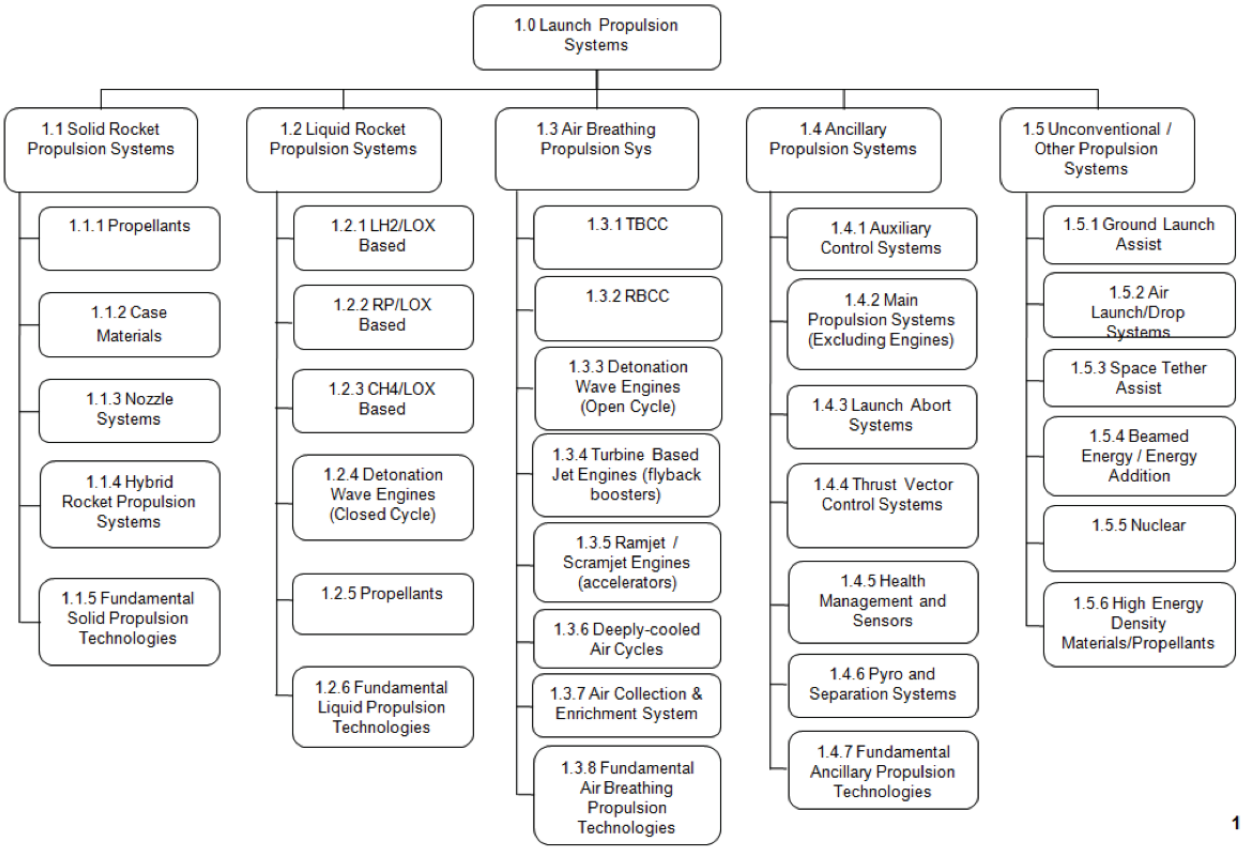

Figure 2. *Technology Area Breakdown Structure technology areas for launch propulsion.*

nologies or propellants to create rocket thrust. Included in this area are technologies that are at a very low TRL or that do not map into the other propulsion taxonomies. The technology area breakdown structure that focuses on these five areas can be seen in Figure 2.

2.2. Technology Description and Development Details

2.2.1. Solid Rocket Propulsion Systems (TABS 1.1)

Solid rocket motors (SRMs) have many advantages over liquid systems such as high-energy density and long-term stability and storability. However several disadvantages that limit their applicability can be reduced or eliminated by advancing the technology base of SRMs to make them more attractive alternatives to liquid systems. Key disadvantages for SRMs today are lower performance (I_{sp}), lack of throttling on demand or ability to shut down on command, environmental concerns, and ground operations costs associated with safety issues in handling large solid segments. This roadmap proposes technology investments that address some of these disadvantages, as well as enhance the advantages mentioned above. Key areas for improvement include a green propellant alternative to current oxidizers, advancing the ability to assess damage tolerance limits and detect damage on composite cases; developing domestic sources for critical materials used in manufacturing of SRMs, formulating advanced hybrid fuels to get energy density equal to SRMs, and investing in the fundamental physics of SRM design including analysis and design tools.

2.2.2. Liquid Rocket Propulsion Systems (TABS 1.2)

Liquid rocket propulsion systems use propellants (fuels and oxidizers) that are kept in a liquid state prior to and during flight. The advantages of liquid rocket engines include generally higher I_{sp} and better thrust control (including throttling and restart capability) than solids. Liquid rocket propulsion systems are more operationally complex than solids and require some form of active flow control that introduces additional possibilities for failures. The liquid propulsion roadmap addresses the critical figures of merit by proposing technology investments in new liquid engine systems, propulsion materials research, high-density impulse and green propellants, and new subsystem modeling and design tools.

2.2.3. Air-Breathing Propulsion Systems (TABS 1.3)

Air-breathing launch propulsion systems obtain the oxidizer for combustion from the Earth's atmosphere, which is combined with fuel brought on board. Air-breathing engines change modes as speed and altitude increases, and transition to pure rocket mode at high altitudes for the final ascent to space. This roadmap focuses on key technologies that would advance air-breathing launch propulsion systems during validation flight tests and would lead to the design of a staged air-breathing launch vehicle. These technology investments include the development of Mach 4+ turbines for turbine-based combined cycles, long-duration Mach 7+ scramjet operation, stable mode transitions of rocket-based and turbine-based combined cycle vehicles, an integrated air collection and enrichment system, and detonation wave engine operation.

2.2.4. Ancillary Propulsion Systems (TABS 1.4)

Ancillary propulsion systems that support the main vehicle propulsion system or provide other key launch vehicle functions during ascent, are significant drivers in vehicle cost, complexity, and reliability. Development of new low-cost cryogenic and rocket propulsion (RP) valves, lines, and support components is essential to support less expensive new vehicle development and reinvigorate our nation's technology base in this area. Some capabilities that are within reach with up-front technology development include nontoxic reaction control systems, advanced sensors coupled with smart control systems providing robust integrated vehicle health management (IVHM), high-powered electromechanical actuators (EMAs) and their supporting power supply and distribution systems, large robust mechanical separation systems, and launch abort systems with high thrust steerable motors tied to an adaptive flight control system. These capabilities, once developed, would have immediate positive impact on vehicle production and operational costs, overall vehicle reliability, and ground and flight safety.

2.2.5. Unconventional/Other Propulsion Systems (TABS 1.5)

Unconventional and other propulsion systems include near, mid, and far-term technology approaches primarily focused on reducing the cost of access to space. Ground-based, hypervelocity accelerators for low-cost delivery of large numbers of small, high-g tolerant payloads to LEO are a near-term technology that can provide significant payoff for a relatively small technology investment. Orbiting space tethers that can act as the final stage of a launch system and relieve the performance requirements for vehicle ascent, potentially enabling fully-reusable, suborbital vehicles with robust operating margins at current technology levels, are a promising technology of interest in the mid-term. In the mid to far term, technologies that can provide breakthrough improvements in propulsion efficiency through the application of energy generated by means other than chemical combustion, such as power beaming, nuclear fusion, and high-energy density materials, are prime candidates for future investment.

2.2.6. Technology Area Roadmaps and Table Descriptions

The LPSTA technology tables identify figures of merit and payload launch classes addressed.

Production cost improvements would include reducing vehicle manufacturing costs. Opera-

	Propulsion system production costs		Small: 0–2 t payloads
	Propulsion system operational costs		Medium: 2–20 t payloads
	Game-changing system and operational concepts		Heavy: 20–50 t payloads
	Game-changing propulsion system/ sub-system efficiency and capability		Super Heavy: > 50 t payloads
	National needs supported by input from other government agencies and industry		Flight tests of new launch vehicles, e.g., air-breathing launch propulsion

tional cost improvements would include reducing personnel or infrastructure costs. Game-changing system and operational concepts broadly expand space activities via higher mass or flight frequency. Game-changing efficiency and capability advances include improving individual vehicle or subsystem performance for more robust operations. National needs supported by input from other government agencies and industry help multiple government or industry partners.

2.2.6.1. Solid Rocket Propulsion Systems

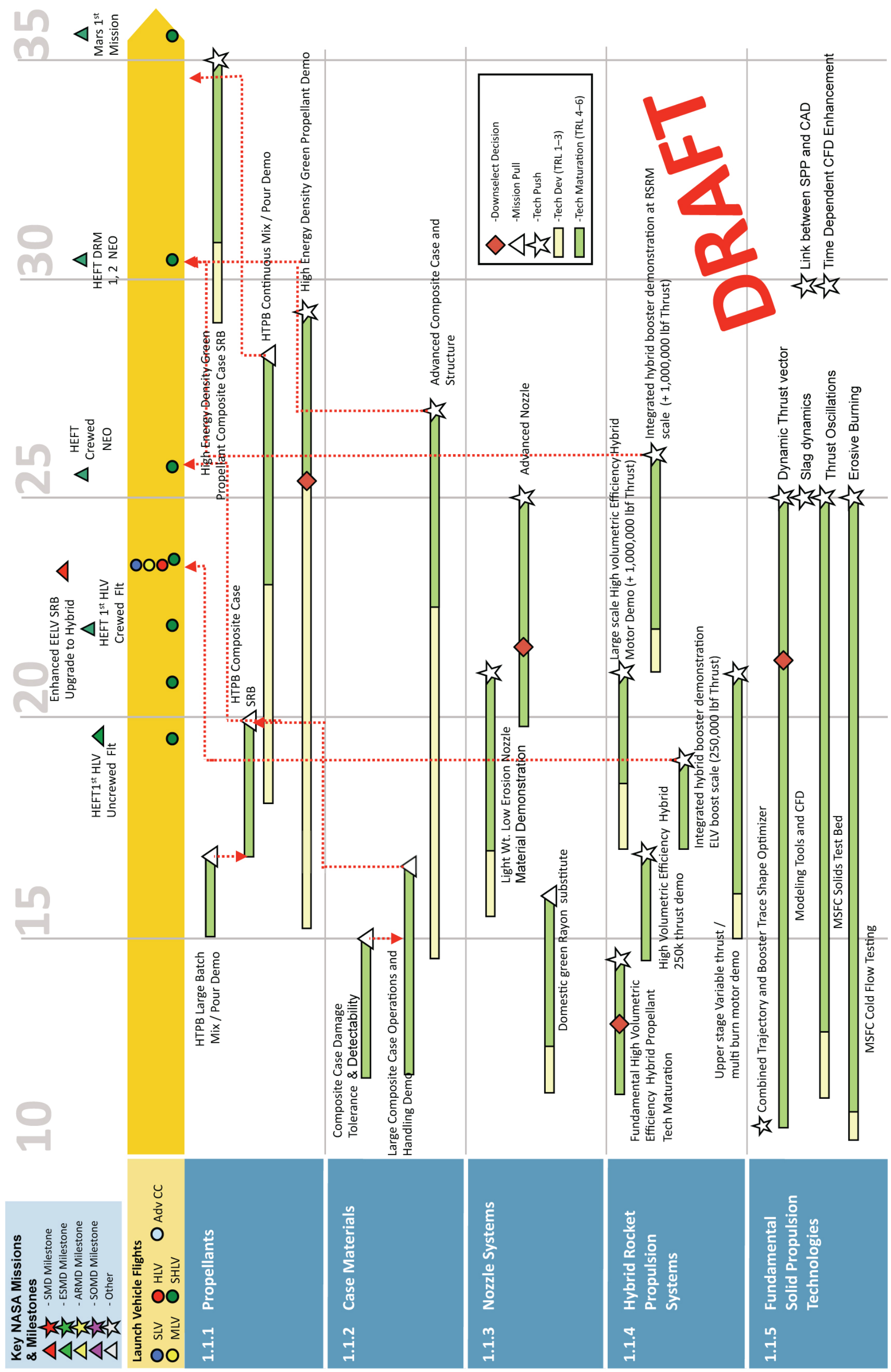

Figure 3. Solid Rocket Propulsion Systems Technology Roadmap.

2.2.6.2. Liquid Rocket Propulsion Systems

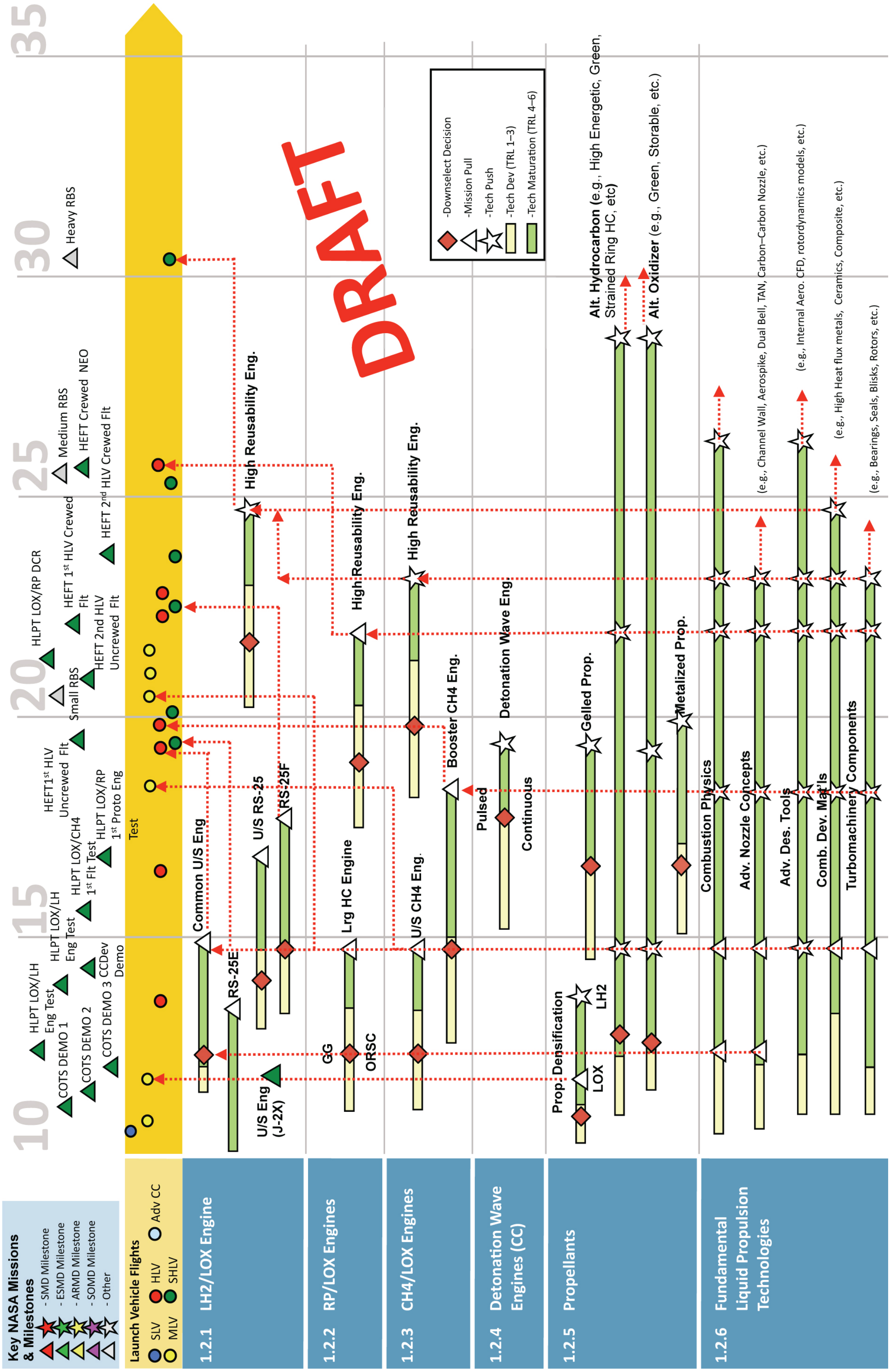

Figure 4. *Liquid Rocket Propulsion Systems Technology Roadmap.*

2.2.6.3. Air-Breathing Launch Propulsion Systems

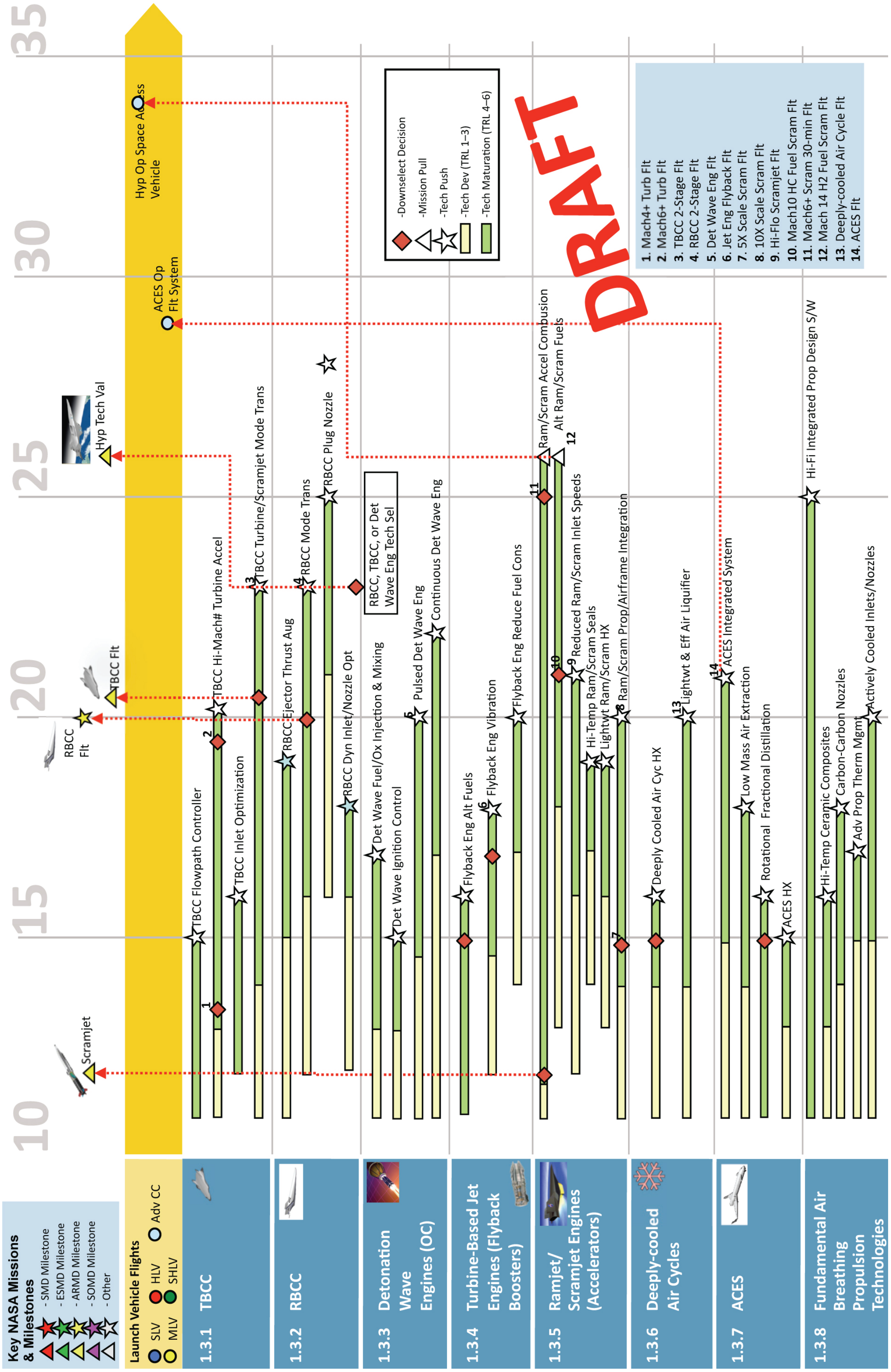

Figure 5. *Air-Breathing Propulsion Systems Technology Roadmap.*

2.2.6.4. Ancillary Propulsion Systems

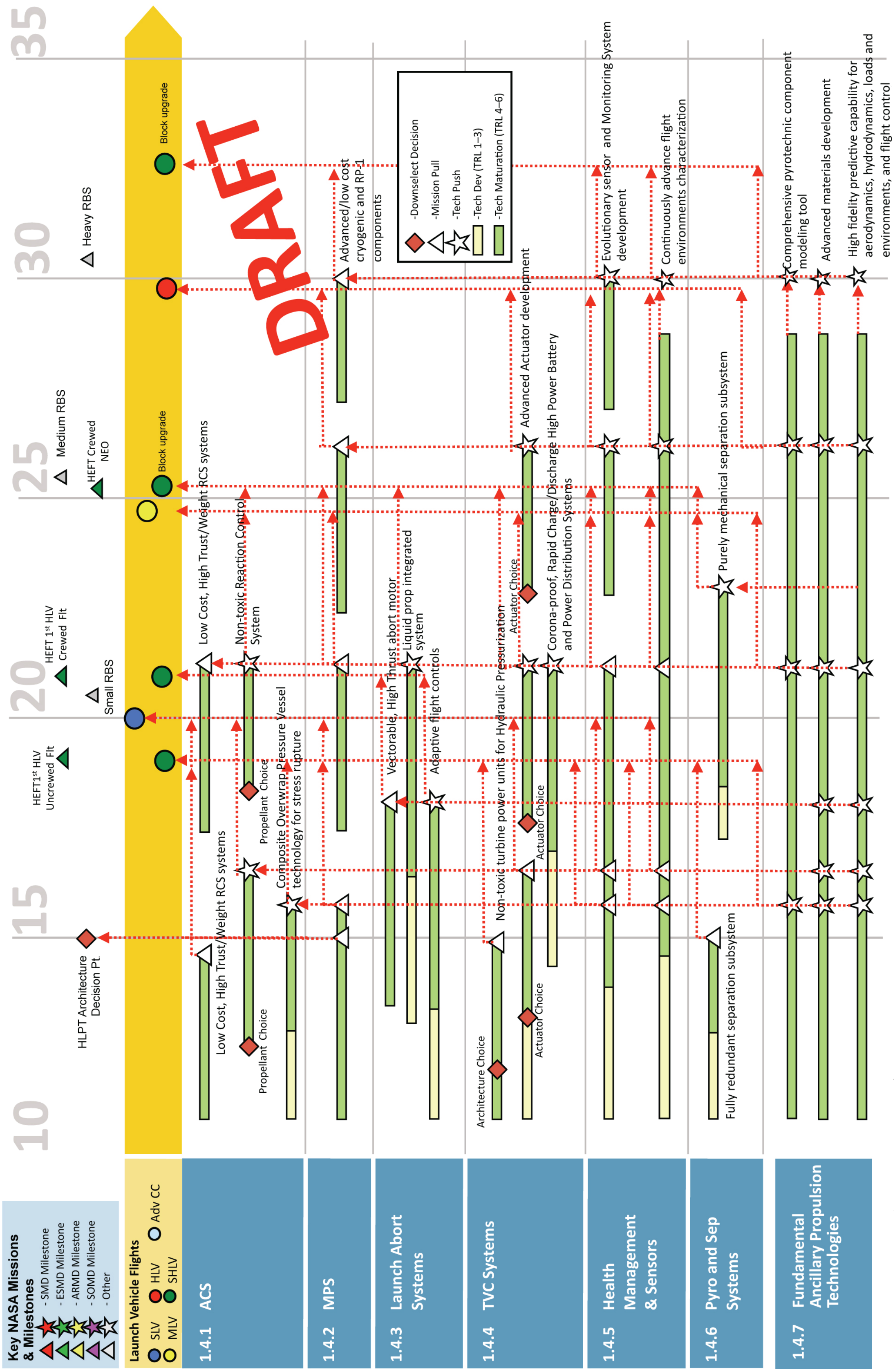

Figure 6. *Ancillary Propulsion System Roadmap.*

2.2.6.5. Unconventional/Other Propulsion Systems

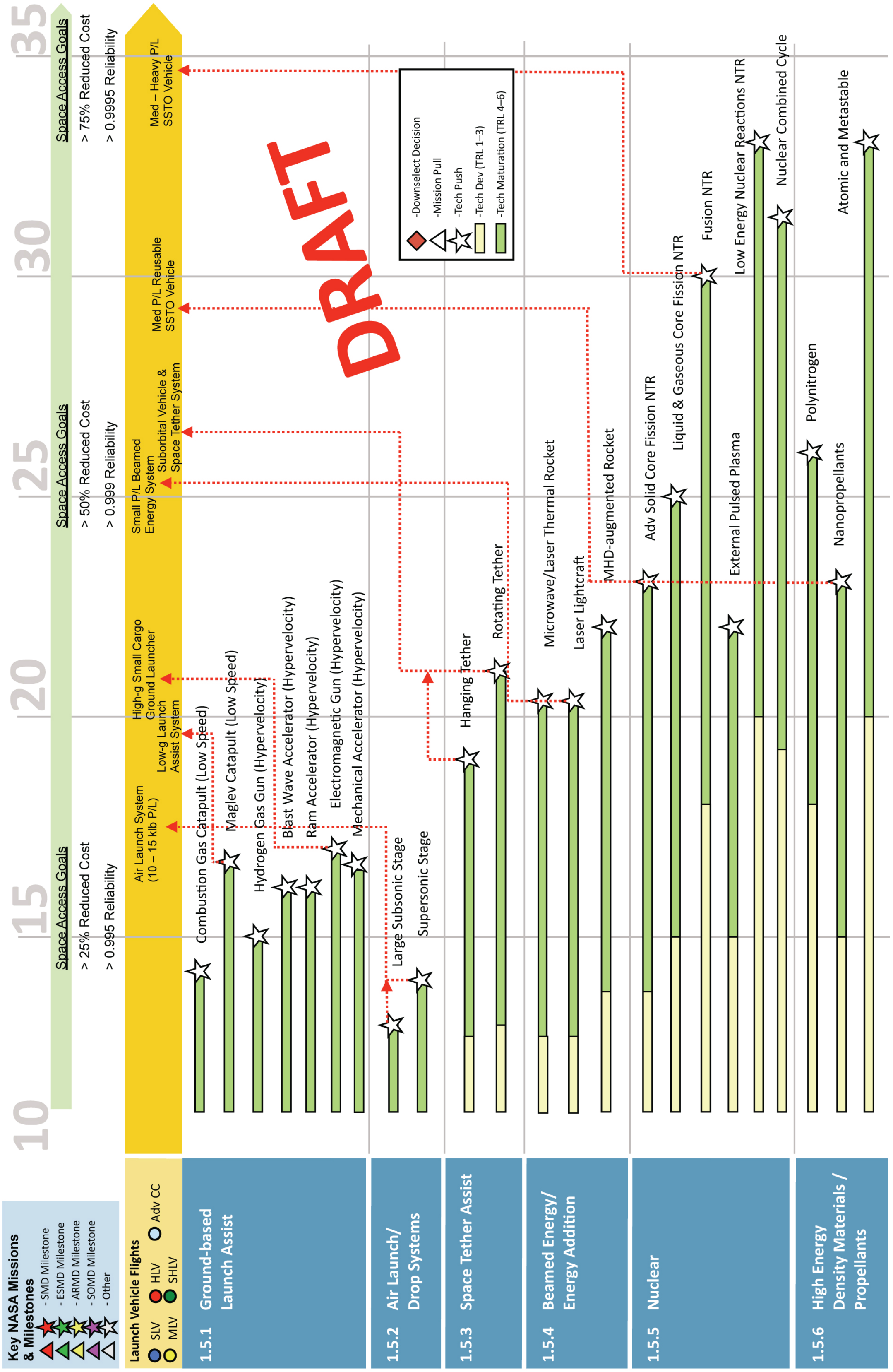

Figure 7. *Unconventional/Other Launch Technology Roadmap.*

2.2.7. Technology Area Tables

2.2.7.1. Solid Rocket Propulsion Systems

Table 3. *Solid Rocket Propulsion System Technology Investments.*

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
1.1.1 Propellants – New formulations for improved performance, environmental impact, and manufacturing processing				
HTPB Large Batch Mix/ Pour Demo	Scale up HTPB production to a 1,800-gal propellant mix to pour into a full-scale load test motor steel case 4-segment demonstrator.	4	Developing prebatch techniques that allow a full segment to be cast (approx. 13–15 mixes per segment).	Develop mix cycles at smaller scales, adapt a shorter mix cycle to a 1,800-gallon mixer, make several demonstration mixes using shorter mix cycle, evaluate data from test articles, and demonstrate effectiveness in full-scale motor firing.
HTPB Continuous Mix/ Pour Demo	Scale up to continuous mix with full-scale 4-segment steel case load test motor steel case demonstrator. Demonstrate quality assurance for new process to apply to human rated systems.	3	Need large-scale continuous mix facility, need mix process.	Demonstrate continuous mix process on smaller scale, build large-scale mix facility, cast smaller motor using large continuous mix process, evaluate data from test articles, demonstrate in full-scale motor firing.
AP Replacement Research	Fundamental research into alternative high-energy solid propellants that can replace the current AP used in today's motors.	2–3	Find replacement for ammonium perchlorate (AP) that has adequate energy, density, & stability.	Literature search, lab work, subscale testing, large-scale testing.
High-Energy Density Green Propellant Demo	Develop subscale demonstrations of promising candidates.	1–2	Need AP replacement (see above) and high-energy density ingredients.	Develop propellant using AP replacement (see above) and high-energy density ingredients, demonstrate in full-scale motor firing.
1.1.2 Case Materials – Advanced case materials development, damage detection and repair techniques, handling process development to mitigate damage to large composite cases				
Composite Case Damage Tolerance & Detectability	Develop damage tolerance limits and methods for detecting damage in large composite motor cases.	3	Detecting structural damage in the fiber structure of composite cases.	Evaluate alternative damage tolerance detection methods and assess against representative damage samples, test against full-scale hardware, qualify processes for flight application.
Large Composite Case Operations and Handling Demo	Develop and demonstrate technology for handling and operations processing of large composite cases.	3	Moving and handling large composite structures without damaging the composite structure.	Assess risks in handling operations for large composite cases, evaluate solutions for minimizing/eliminating risks, demonstrate solutions in full=scale hardware demonstration.
1.1.3 Nozzle Systems – Advanced lightweight ablative materials, alternative nozzle designs				
Lightweight, Low-Erosion Nozzle Material Demonstration	Develop and demonstrate new advanced lightweight ablative nozzle materials for solid motors.	2–3	Formulation of new lightweight materials.	Research alternative materials. Evaluate candidates in subscale test rig. Select most likely candidates for testing in large-scale demonstration.
1.1.4 Hybrid Rocket Propulsion Systems – High Propellant density material development with improved burn rate, combustion stability characterization/ design parameter understanding, upper stage multiburn motor				
High Volumetric Hybrid Propellant Technology Maturation (fuel/ oxidizer/additives web design work)	Hybrid motors do not have the desired volumetric efficiency of solid motors. Develop and demonstrate advanced propellant formulations and packaging concepts to improve hybrid volumetric efficiency.	2–3	Fuel regression rates are typically ~10 times less for hybrids compared to solids, with baseline HTPB fuels. Need to examine burn rate additives or paraffin or different oxidizer flows or multiport multilayer configurations.	Evaluate alternatives, test candidate subscale, test most promising alternatives in large scale, develop scaling parameters, demonstrate at 250,000 lbf and 1 Mlbf thrust size motors.
Upper-Stage Variable Thrust/Multiburn Motor	Hybrids can be used for upper-stage variable thrust/multiple-burn applications. Currently selected for use on Sierra Nevada's Dream Chaser vehicle.	3	Multiple-use components will be a large issue; getting sustained programmable impulse out of the motor is another large issue.	For representative missions/applications/ requirements, perform system studies and develop candidate component solutions that can be used and then reused multiple times, test at subscale and full scale as an integrated system.
1.1.5 Fundamental Solid Propulsion Technologies – Advanced design analysis tool development, validation through subscale solid test bed and cold flow testing				
Physics Based Modeling Development and Research	A combination of computational fluid dynamics (CFD) and analytical computation tools must continually be improved to advance the state of the art in designing and analyzing solid rocket motors. Validating these tools requires a robust cold flow and small-scale solids test program.	N/A	A consistent level of funding over multiple years is required to develop and execute the test plans necessary to more fully understand the subtle physics underlying SRM performance.	Validating key physical models will lead to improved prediction and analysis capability. For example erosive burning, which is currently treated as a liability, could be used to increase the performance of an SRM. Time scales of when the models will be brought online are hard to predict, but if nothing is done, the models will not improve on their own.

2.2.7.2. Liquid Rocket Propulsion Systems

Table 4. *Liquid Rocket Propulsion System Technology Investments.*

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
1.2.1 LH_2/LOX Engines – High I_{sp}, liquid hydrogen/liquid oxygen based engines for first or upper-stage propulsion				
J-2X	Upper stage engine for Constellation Program	5	Nozzle extension materials and manufacturing	Development testing (to begin early 2011)
SSME (RS-25) Derivatives	Expendable derivative (RS-25E) Upper stage for heavy-lift vehicle Expendable derivative (RS-25F)	5 3 4	Manufacturing processes and materials Integrated system interactions Manufacturing processes and materials	Full-scale development testing of new components
Common Upper Stage Engine	Common upper-stage expander cycle engine for EELV.	4	Manufacturing processes Materials	Subscale demonstrators, full-scale development
High Reusability Engine	Low-cost, high-reliability engine	3–4	Manufacturing processes Materials	Modeling of systems, subscale demonstrators, full-scale development
1.2.2 RP/LOX Engines – High energy density kerosene-based engines for first stage lift				
Large Hydrocarbon Engine	High-thrust booster engine	3–4	Manufacturing Processes Materials Combustion instability	Modeling of systems, subscale demonstrators, full-scale development
High Reusability Engine	Low-cost, high-reliability engine	2–3	Manufacturing Processes Materials	Modeling of systems, subscale demonstrators, full-scale development
1.2.3 CH_4 Engines – Alternative hydrocarbon engines with high energy density and I_{sp}				
Methane Upper-Stage Engine	Development of technologies to support high-altitude start and operation of LOX/CH_4 engine	3	Ignition Manufacturing processes Materials	Subscale demonstrator, full-scale demonstrators
Methane Booster Engine	Development of technologies to support operation of LOX/CH_4 engine.	3	Ignition Manufacturing Processes Materials	Subscale demonstrators, full-scale demonstrators
1.2.4 Detonation Wave Engines (Closed Cycle) – produce thrust by igniting fuel and oxidizer through a series of controlled detonation waves				
Closed Cycle Detonation Wave Engine	Detonation wave engines produce thrust by igniting fuel and oxidizer through a series of controlled detonation waves. In a closed cycle oxidizer is supplied by the vehicle.	3	Ignition Manufacturing processes Materials Cooling	Modeling of systems, subscale demonstrators, full-scale demonstrators
1.2.5 Propellants – Propellant research involves application of nontoxic green propellants, high-energy combinations of fuels and oxidizers				
Propellant Densification	Propellant densification delivers enhanced vehicle mass fraction performance	5 LOX 4–5 LH_2	Ground Support Equipment & Processes	LOX demonstration on Taurus II, LH_2 demonstrated in test only
Alternate Hydrocarbon Fuels	Demonstration of fuels for rocket applications and green propellants	3–5	Performance characterization	Subscale demonstrators, full-scale demonstrators
Alternate Oxidizers	Demonstration of alternate oxidizers	3–5	Performance characterization	Subscale demonstrators, full-scale demonstrators
Strained Ring Hydrocarbons	Isomers of existing hydrocarbons with novel arrangements of the atoms and increased bond energies, resulting in an expected I_{sp} increase	3	Low-cost, high-yield production.	Production R&D, combustion tests, subscale demonstrators, full-scale demonstrators
Gelled Propellants	Gelled propellants provide comparable density impulse to solid propellant systems while delivering the mission flexibility of a liquid system while demonstrating greater operational safety.	2–4	Performance characterization	Modeling of systems, subscale demonstrators, full-scale demonstrators
Metalized Propellants	Fuels with suspended metal powders or nano particles	2–4	Performance characterization	Modeling of systems, subscale demonstrators, full-scale demonstrators

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
1.2.6 Fundamental Liquid Propulsion Technologies – Technologies enabling advances in liquid rocket engine launch propulsion including advanced engine design and modeling tools, advanced materials, new nozzle technologies, combustion physics research, and advanced turbomachinery components				
Combustion Physics	Fundamental physics modeling of combustion processes	N/A	Obtaining sufficient test data to anchor developed models and codes.	Modeling of systems, subscale demonstrators
Advanced Nozzle Concepts	Design, modeling, and demonstration of advanced nozzle concepts	N/A	Manufacturing processes Materials	Modeling of systems, subscale demonstrators
Advanced Design Tools	Development and validation of advanced design and modeling tools	N/A	Obtaining sufficient test data to anchor predictive analysis models and codes.	Modeling of systems, subscale demonstrators
Propulsion Materials	Modeling and demonstration of advanced materials	N/A	Manufacturing processes Materials	Modeling of systems, subscale demonstrators
Advanced Turbomachinery Components	Modeling and demonstration of advanced turbomachinery components	N/A	Manufacturing processes Materials	Modeling of systems, subscale demonstrators

2.2.7.3. Air-Breathing Launch Propulsion Systems

Table 5. *Air-Breathing Propulsion System Technology Investments.*

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
1.3.1 Turbine-Based Combined Cycle (TBCC) – Multiple propulsion modes starting with a turbine-based engine, transitioning with increases in speed to ramjet mode, scramjet mode, and finally to rocket mode				
TBCC Flow Path Controller	Ensure stable operation of propulsion system flow paths while maximizing vehicle I_{sp} and thrust	4	Controlling proper fuel/air mixture; control mass and speeds of inlet air to multiple inlets	Conduct tests on flow path-induced thrust fluctuations
TBCC High-Mach # Turbine Acceleration	Operate turbine engines to Mach 4 and pursue Mach 6 turbine acceleration	3	Need compressor, combustor, and turbine designs and materials that withstand high temperatures; thrust augmenter designs	Test high-temperature engine component designs and materials, test Mach 4+ augmenter performance, perform Mach 4 turbine ground and flight tests, investigate cooling to achieve Mach 6 turbine acceleration
TBCC Inlet Optimization	Initiate stable flow in multiple-speed inlets (for turbine, ram/scramjets and rockets)	4	Proximity of inlet systems leads to flow coupling effects	Test simultaneous inlet functioning, test thermal choking and positioning of the flow shock structures, test inlet geometries
TBCC Turbine/Scramjet Mode Transition	Maintain vehicle propulsive thrust during sequence of turbine engine shutdown and initiation of ramjet/scramjet combustion	3	Transitioning operation from one propulsion mode to another while maintaining thrust	Verify stable turbine flow path operation leading to stable ramjet/scramjet ignition, test stable turbine shutdown methods, determine safe thermal environment
1.3.2 Rocket-Based Combined Cycle (RBCC) – Multiple propulsion modes starting with a ducted engine (an ejector ramjet) to augment the airflow until the vehicle reaches suitable speeds at which point it transitions to ramjet mode, scramjet mode, and finally to rocket mode				
RBCC Ejector Thrust Augmentation	Supply increased mass flow to allow engine to operate at low supersonic speeds	3-4	Providing sufficient entrainment and mixing of air with rocket plume for increased low-speed RBCC performance	Test ejector geometries and map flow field
RBCC Mode Transition	Maintain vehicle propulsive thrust during sequence of ejector mode shutdown and initiation of ramjet combustion	3	Transitioning operation from one mode to another while maintaining thrust	Verify ejector flow path operation leading to stable ramjet /scramjet ignition, determine safe thermal environment
RBCC Plug Nozzle	Maintain efficiency at a wide range of altitudes	3	Plug nozzle shape and characterizing interaction of plug with flow path	Perform research to determine optimum plug nozzle shapes and map flow properties around nozzle
RBCC Dynamic Inlet/Nozzle Optimization	Initiate stable flow in multiple-speed inlets and nozzles (for ejector, ram/scramjets and rockets)	3-4	Proximity of inlet systems leads to flow coupling effects; nozzle sizing	Test simultaneous inlet functioning, test thermal choking and positioning of the flow shock structures, test inlet and nozzle geometries
1.3.3 Detonation Wave Engines (Open Cycle) – Acceleration achieved by igniting fuel and oxidizer through a series of controlled detonation waves, employing an open cycle where oxidizer is obtained from the atmosphere				
Detonation Wave Engine Fuel/Oxidizer Injection and Mixing	Inject and mix fuel and oxidizer at optimum rates and amounts	3–4	Timing of propellant injection and mixing is critical for reactions to occur	Test injector architectures, test mixing methods

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
Detonation Wave Engine Ignition Control	Start detonation reaction in a controlled manner	3–4	Controlling ignition; reduce noise; dampen pulsed operation vibration	Test detonation ignition techniques, study noise levels and research methods for reducing noise, develop vibration dampening technologies
Pulsed Detonation Wave Engine	Use detonation waves (in pulsed-mode operation) to combust fuel and oxidizer	3–4	Timing injection, mixing and ignition pulses; reducing vibration and noise	Test timing sequencing, integrate propulsion/ airframe for low- and high-speed flight tests
Continuous Detonation Wave Engine	Use detonation waves (continuous operation) to combust fuel and oxidizer	2-3	Controlling ignition and wave propagation; cooling; reducing inlet flow speeds	Research and test inlet flow speed reduction methods, integrate propulsion/airframe for low and high-speed flight tests
1.3.4 Turbine Based Jet Engines (Flyback Boosters) – Turbine engines modified to handle the stresses of launch and reentry that are able to fly a launched vehicle back to the launch site				
Flyback Engine Alternative Fuels	Demonstrate alternative fuels for commonality with existing rocket propellants	4–5	Ability to provide high energy content; able to absorb heat; thermal stability	Flight test alternative fuels
Flyback Engine Vibration	Reduce potential engine damage during launch	3	Dampening vibration on engine during high-speed flyback	Develop and flight test vibration dampening technologies
Flyback Engine Reduced Fuel Consumption	Reduce amount of fuel needed to operate flyback engine	3-5	Finding fuels with increased energy content; increase efficiency of combustion.	Research, develop, and flight test methods to reduce flyback engine fuel consumption
1.3.5 Ramjet/Scramjet Engines (Accelerators) - Ramjets ingest atmospheric air at the engine inlet at high speeds and compresses it; air is then slowed to subsonic speeds, at which point it is combined with fuel for combustion. Scramjets compress and ignite air at supersonic speeds				
Ramjet/Scramjet Acceleration Combustion	Increase ramjet and scramjet combustion performance and achieve effective combustion over a wide speed range	3–4	Optimizing timing of injection, mixing, igniting, and burning; maintaining sustained operation with high-combustion temperatures	Data review of previous flight tests and continued flight tests of ramjet/scramjet combustion studies
Alternative Ramjet/ Scramjet Fuels	Research alternative fuels for ramjet and scramjet operation	2–3	High energy content; ability to achieve effective combustion over a wide speed range; ability to heat-sink; thermal stability	Flight test alternative fuels, certify fuels
Reduced Ramjet/ Scramjet Inlet Speeds	Allow ramjets and scramjets to begin operation at lower speeds	2–3	Profile inlet boundary layer and shock interactions; determine leading edge and inlet flow path shapes	Research and test inlet geometries allowing lower inlet speeds, study inlet flow-field physics
High-Temperature Ramjet/Scramjet Seals	Employ seals that survive under high temperatures	3	High-temperature tolerance	Research and test seal materials and mechanisms
Lightweight Ramjet/ Scramjet Heat Exchangers	Employ heat exchangers made from lightweight materials	3	Developing efficient and lightweight heat exchangers able to operate under ramjet/scramjet flight conditions	Research and test lightweight heat exchangers
Ramjet/Scramjet/ Propulsion/ Airframe Integration	Integrate the propulsion geometry with the vehicle airframe	3–4	Designing overall vehicle to combine optimal propulsion performance with most effective airframe size	Review past flight test data and refine propulsion/airframe geometry in continued flight tests
1.3.6 Deeply-Cooled Air Cycles – Cryogenic liquid hydrogen fuel is used to cool or liquefy incoming air from the engine inlet; air is then combusted with the liquid hydrogen to create thrust				
Deeply-Cooled Air Cycle Heat Exchangers	Increase efficiency of heat exchangers used during deeply-cooled air cycle process	3	Increase heat transfer coefficient; design compact, lightweight heat exchanger	Heat exchanger design, fabrication, verification and flight test
Lightweight and Efficient Air Liquefier	Liquefy air collected from the atmosphere to be used as oxidizer	3	Reduce weight of air liquefier system	Research and test lightweight materials for air liquefiers
1.3.7 Air Collection & Enrichment Systems (ACES) – Liquid oxygen (LOX) is generated by separating it from the atmospheric air, which allows vehicles to take off without LOX on board, minimizing takeoff weight				
Low-Mass Air Extraction	Extract air during high-altitude flight	3	Extract adequate amount of air for ACES operation in reasonable amount of time at high altitudes	Low-mass air extraction research, design, fabrication, verification, and flight test
Rotational Fractional Distillation	Generate LOX by the separation and distillation of high pressure air (at its dew point)	4	Efficient distillation operation under g-forces	Create ground demonstrator of rotational fractional distillation unit, flight test unit

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
ACES Heat Exchangers	Increase efficiency of heat exchangers used during air collection and enrichment process	3–4	Increase heat transfer coefficient; design compact lightweight heat exchanger	Heat exchanger design, fabrication, verification and flight test
ACES Integrated System	Combining ACES subsystems into an operational system	2–3	Maturing ACES subsystems; performing integrated system analysis	Complete ACES system integration and transient ACES operational analyses; produce integrated system and flight test
1.3.8 Fundamental Air-Breathing Propulsion Technologies – Technologies facilitating air-breathing launch propulsion system development				
High-Fidelity Integrated Propulsion Design Software	Develop high-fidelity models and design software for hypersonic propulsion systems	N/A	Increasing accuracy and speed of model computations; increasing fidelity of design software	Continued software research, development, test and validation with hardware systems
High-Temperature Ceramic Composites	Develop materials capable of withstanding high temperatures experienced in hypersonics	N/A	Advanced material synthesis; material interaction with extreme environments (e.g., temperature, corrosion); physical and structural property characterization	Research, develop, and test high-temperature ceramic composites
Carbon-Carbon Nozzles	Develop lightweight, high-temp carbon-carbon based nozzles	N/A	Increasing carbon-carbon strength under compression and shock	Research, develop and test carbon-carbon nozzles
Advanced Propulsion Thermal Management	Develop advanced propulsion thermal management systems capable of supporting vehicle operation under varied temperature ranges	N/A	Designing thermal management systems that can adapt to diverse temperature ranges	Evaluate and test integrated thermal management systems operating under transient and continuous heat and cooling loads
Actively Cooled Inlets/ Nozzles	Develop techniques for cooling propulsion components using the working fluid	N/A	Integrating materials and working fluid without adverse effects to materials, working fluid, or propulsion system	Evaluate and test active cooling inlet/ nozzle concepts

2.2.7.4. Ancillary Propulsion Systems

Table 6. *Ancillary Propulsion System Technology Investments.*

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
1.4.1 Auxiliary Control Systems (ACS) – These systems provide roll control for single-engine first stage ascent, as well as full upper-stage attitude control during stage separation and coast using small thrusters for propulsive force to rotate the vehicle about the roll, pitch, and yaw axes.				
Low-Cost, High Thrust to Weight Ratio Reaction Control Systems (RCS)	Current RCS mono-prop or bi-prop systems are very costly. New materials and production techniques could reduce thruster cost, as well as reduce the weight of the support systems.	4	Low leakage for extended propellant exposure	Propellant exposure testing, demonstrate new production techniques
Non-Toxic RCS	Nontoxic RCS propellants can reduce ground infrastructure cost and complexity, improve ground safety and operational timelines, as well as potentially reduce flight vehicle system production costs and improve performance. Work has been done already for various bi-prop alternatives like LOX/methane, LOX/LH_2, LOX/ethanol, and GOX/methane. Hydroxl Ammonium Nitrate (HAN) and Ammonium Dinitramide (ADN) are promising monopropellant alternatives.	4–5	Propellant material compatibility Small/lightweight cryogenic lines and valves	Material compatibility testing, demonstrate repeatable, consistent ignition and combustion stability
Composite Overwrap Pressure Vessel (CoPV) advances to reduce stress rupture	Develop understanding of root cause of stress rupture and fine tune design without oversizing the tank. This would permit a reduced safety factor, resulting in lighter weight tanks. Advances in CoPV technology also could be applied to MPS applications.	2	Material properties understanding	Applied research into physical properties and initiation of stress rupture, develop lower weight designs based on this data

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
1.4.2 Main Propulsion Systems (MPS) – Subsystems that provide propellant conditioning and feed, tank pressurization, and purge supply to the engine use insulated lines and components for cryogenic applications				
Advanced, Low-Cost Cryogenic and RP Components	Evolutionary development of robust, low cost fill and drain, recirculation, and engine isolation valves, ducts, recirculation pumps and cryogenic helium regulators for expendable and reusable launch vehicles using materials advances and improved production methods would greatly reduce production costs and improve reliability for reusable applications.	4	Maintaining low mass Design simplification for production	Design for cost, reliability, and reusability, demonstrate production capability at reduced cost
1.4.3 Launch Abort Systems – Propulsive systems for pulling spacecraft away from the launch vehicle in the event of a launch failure				
Vectorable High-Thrust Abort Motor	High-thrust abort motor designs with vectorable thrust enable improved launch abort vehicle control through all flight regimes. High-thrust TVC also requires high slew rate, high slew angle, high thrust (50,000–150,000 lbf) solid propellant motors and associated systems.	4	Development of the high peak power batteries (i.e., thermal batteries that would be acceptable to NASA) for TVC use	Demonstrate integration of the TVC system with the motor cases
Adaptive Flight Control	Automated flight controls for launch abort vehicles (e.g., at a minimum as an outer loop around a more conventional flight controller) would address the uncertainty inherent in abort scenarios and improve abort system reliability over a wide range of operating and environmental conditions.	2	Lightweight, minimal volume for self contained LAS flight control system	Demonstrate capability of system sized to fit within available LAS constraints
Liquid Propellant Integrated Abort System	Liquid propulsion systems capable of providing both the high thrust required for vehicle abort and low thrust required for on-orbit maneuvering and attitude control from an integrated package.	1	Fast-response, high-pressure, mid-thrust (3,000–5,000 lbf) propulsion systems, with variable thrust/sec (throttleable or pulse modulated) development	Maturation of associated components including high-pressure tanks, regulators, bi-propellant valves, and the thruster itself are needed
1.4.4 Thrust Vector Control (TVC) Systems – Actuators that adjust the direction to the exhaust gas plume to provide vehicle steering				
Non Toxic Turbine Power Units for Hydraulic Pressurization	Develop replacement for hydrazine-driven hydraulic power units using either nontoxic propellant or a blow-down type system.	4	Integrated vehicle impacts	Initial development of options, demonstration tests
Advanced Actuator Development (EHA, EMA, IAP)	Advance state of the art of electro-hydrostatic and electromechanical actuators as well as an integrated actuator pack¬age for use on a wide range of launch vehicles especially RLVs for simpler, lower cost integrated TVC systems.	3	Fault tolerance Power draw	Demonstrate robust operation with fault tolerance
Corona-proof, Rapid Charge/Discharge High Power Battery & Power Distribution Systems	Advanced actuators will require greater electrical power from a high-voltage, rapid-discharge battery & distribution system. This system must be developed to avoid corona effects during ascent.	3	Lightweight shielding Robust battery	Provide sufficient environmental testing for shielding development
1.4.5 Health Management & Sensors – Propulsion system instrumentation and associated avionics architecture that monitor propulsion system health				
Evolutionary Diagnostic/ Prognostic Sensor and Monitoring System Development	Develop advanced sensors for all ancillary applications for use in ground processing and flight to improve hardware life as well as fault detection and isolation. Includes cryogenic & hypergolic liquid level sensors, flowmeters, leak detection sensors, extreme environment sensors, & rotating machinery sensors using advances in fiber optic, Piezo-electric, Microelectromechanical & nanosensor technology.	3	Extreme environments Signal processing bandwidth	Environmental testing, demonstrate integrated function with hardware development

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
Continuously Advance Flight Environments Characterization	Continue to develop, flight qualify, and implement add-on flight instrumentation (sensors to monitor strain, temperature, vibration, acoustics, etc., along with associated power, data acquisition, and wireless communication technologies for flight environments) that can provide the necessary environmental information to verify, and potentially optimize designs of launch vehicle propulsion systems.	2–3	Extreme environments Power restrictions	Environmental testing
1.4.6 Pyrotechnic and Separation Systems – Linear-shaped charges or frangible bolts are typically used for stage separation				
Fully Redundant Separation Subsystem	Demonstrate, first through ground testing and then later in flight, dual redundancy for stage separation whether the separation subsystem uses a linear shaped charge or a frangible type joint to increase safety.	2–3	Vehicle system interactions due to pyro shock loads	Model system, design prototype, ground test, update model and prototype
Purely mechanical separation subsystem	Develop minimal weight highly reliable mechanical stage separation system for medium and large launch vehicles. Eliminating pyrotechnic separation systems would eliminate pyro shock concerns for nearby flight hardware and simplify production and ground processing.	3–4	Minimizing weight penalty for purely mechanical system and scale-up to large systems	Load requirements, prototype system, lab test, flight test
1.4.7 Fundamental ancillary propulsion technologies basic technologies that would apply to the all the various ancillary systems				
Advanced Materials Development	Critical to advances for all ancillary systems. Material improvements advance the state of the art by reducing weight and/or cost.	N/A	Material Compatibility	Implement advances into component design
High-Fidelity Predictive Capabilities for Aerodynamics, Loads & Environments, & Flight Control	Improved models with predictive capability, anchored with appropriate test data, would greatly benefit MPS, ACS, TVC, and LAS development by providing a large reduction in model uncertainty as well as reductions in development time and cost.	N/A	Obtaining sufficient test data to anchor developed models and codes.	Develop and refine codes based on applicable test data
Comprehensive Pyrotechnic Component Modeling Tool	Develop comprehensive pyrotechnic component computer modeling tool, anchored with testing, to reduce the development cost and schedule impact of new pyrotechnic component designs.	N/A	Adequate characterization of component performance	Generate performance database, develop model, anchor with test

2.2.7.5. Unconventional/Other Propulsion Systems

Table 7. *Unconventional/Other Propulsion System Technology Investments.*

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
1.5.1 Ground-based Launch Assist – Applying a method of accelerating a vehicle horizontally or vertically to give it a higher initial velocity and to reduce the amount of propellant required to reach orbit				
Combustion Gas Catapult (Low Speed)	Combustion gas launch assist is a pneumatic hot gas system derived from mature aircraft carrier steam-catapult technology. Assist velocities would range from subsonic to transonic.	3–4	High-volume gas generation capabilities. High transient thermal and mechanical stresses. Low maintenance seals. Vehicle separation dynamics.	Tests to incrementally increase launcher length and velocities, vehicle separation tests
Maglev Catapult (Low Speed)	Magnetic levitation techniques are used to support and accelerate a vehicle for horizontal launch assist. Assist velocities would range from subsonic to transonic.	3–4	Scaling to large vehicle masses. Energy storage and power switching. Vehicle separation dynamics.	Energy storage and power switching R&D, subscale system demo, including sep testing
Hydrogen Gas Gun (Hypervelocity)	A large-bore gun that accelerates a payload/rocket stage along the barrel through the rapid expansion of hydrogen gas from a high-pressure reservoir.	3	Hydrogen pressurization. Projectile integrity.	Hydrogen pressurization system design and test, subscale system demo

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
Blast Wave Accelerator (Hypervelocity)	The blast wave accelerator uses rings of high explosives inside a long tube that are sequentially detonated to accelerate a payload/ rocket stage.	3	Projectile and launcher integrity. Timing of sequential detonation and detonation uniformity. In-bore stability.	Detonation testing, projectile acoustic tests, subscale system demo
Ram Accelerator (Hypervelocity)	The ram accelerator consists of a long, sealed tube filled with a mixture of fuel and oxidizer, such as hydrogen and oxygen. A projectile resembling the center body of a ramjet is shot into the tube, igniting the mixture and blasting the projectile down the tube, which acts like the outer cowling of a ramjet.	3	Erosion of the projectile and tube. Premature fuel detonation in front of the projectile. Greater than Mach 6 in-tube, supersonic combustion. Large, fast-acting valves.	Laboratory experiments at in-tube Mach of 6–10, and ultimately velocities of 6–8 km/s, subscale system demo
Electromagnetic Gun (Hypervelocity)	A railgun consists of a pair of copper rails, mounted in an insulating barrel, with the rails connected to a rapidly switched high current source. An armature on the projectile to be fired completes the circuit, resulting in a magnetic force that drives the projectile down the barrel.	3–4	Power requirements. Structural integrity of projectile and launcher. Rail erosion and life. Energy storage and power switching. Plasma armature performance.	Energy storage and power switching R&D, plasma armature R&D, rail erosion tests, subscale system demo
Mechanical Accelerator (Hypervelocity)	Typified by the Slingatron concept, it consists of a long tube arranged in a spiral pattern which accelerates a small payload to orbital velocity by gyrating the tube assembly in an oscillatory pattern. Acceleration of the payload is by centripetal forces.	3–4	Structural integrity of the system. Friction in the interior of the spiral tube. Projectile integrity.	Structural design, stress and vibration analysis. Testing of techniques to reduce tube friction. Subscale system demo.
1.5.2 Air Launch/Drop Systems – Space launch vehicles carried to the upper atmosphere by a carrier aircraft				
Large Subsonic Stage	Stage launch vehicle from top or bottom of very large (jumbo jet-class) subsonic carrier aircraft.	5	Increasing aircraft lift capabilities. Stage separation dynamics. Large, twin fuselage configuration.	High-lift device R&D, configuration R&D, separation simulations and subscale testing
Supersonic Stage	Stage launch vehicle from carrier aircraft at supersonic speeds.	5	Mated configuration drag. High-q stage separation.	Low-drag config. R&D, subscale sep tests
1.5.3 Space Tether Assist – Space-based tethers using momentum exchange to accelerate payloads from suborbital to orbital velocities, reducing requirements for launch vehicle ascent performance				
Hanging Tether	A gravity-gradient stabilized tether that reaches down to the upper atmosphere from orbit (e.g., Skyhook). Payloads are delivered to the bottom of the tether by a suborbital vehicle, then transported up along the tether and released into orbit.	2–3	Tether life in LEO environment. High-speed tether reel-in and reel-out. Flywheel energy storage. Rapid payload capture mechanism. Robust tether dynamics modeling.	High-speed reel demo, flywheel ground demo, orbital electrodynamic tether propulsion demo, subscale orbit demo, including P/L capture
Rotating Tether	A tether that rotates or spins in the plane of its orbital motion (e.g., Rotovator or Bolo). Payloads are delivered to the tether by a suborbital vehicle and are transferred into orbit by the rotation of the tether and an exchange of momentum.	2–3	Tether life in LEO environment. Reliable tether deployment. Flywheel energy storage. Rapid payload capture mechanism. Robust modeling of tether dynamics.	Flywheel ground demo, orbital electrodynamic tether propulsion demo, subscale orbit demo, including P/L capture
1.5.4 Beamed Energy / Energy Addition – Ground-based laser, microwave, or other focused electromagnetic radiation to heat air at the base of a vehicle, or the propellant carried onboard, to produce propulsion at high efficiencies				
Microwave/Laser Thermal Rocket	Microwaves or lasers beamed from a ground or space station are directed at a heat exchanger mounted on a vehicle to heat stored propellant and create thrust via a thermal rocket, achieving I_{sp} from 600 to 900 sec.	2–3	Very large power transmitters (GW-class), accurate tracking, efficient energy conversion, and thermal management.	Power beaming and tracking tests, heat exchanger R&D, small-scale flight demo
Laser Lightcraft	A pulsed laser from a ground station is used to heat atmospheric air, or onboard propellant, and rapidly expand it against a focused pusher plate on the vehicle, generating thrust.	2–3	Very large power transmitters (GW-class), accurate tracking, efficient energy conversion, and thermal management.	Power beaming and tracking tests, small-scale flight demo, all propulsive modes
MHD-augmented Rocket	Magnetohydrodynamic (MHD) effects can be used to further accelerate the exhaust products of a conventional chemical rocket engine to achieve significantly higher levels of thrust and Isp (1,000 – 2,500 sec).	2–3	Power requirements. Mass efficiency of system components. Thermal management.	Power systems R&D, low-mass component development and test, ground engine tests

Technology Investment	Description	TRL	Major Challenges	Path to TRL6
1.5.5 Nuclear - Using nuclear fission or fusion reactions for high propulsive performance.				
Advanced Solid Core Fission NTR	A nuclear thermal rocket (NTR) that uses an advanced solid-core nuclear fission reactor. The reactor employs fine alloy fibers arranged in a lattice for greatly improved heat transfer to the propellant and increased Isp (>1,000 sec) with reduced mass.	2	Lightweight, robust, high-temperature core with low pressure drop and high surface area. Radiation shielding. Accident hazard containment.	Core material and manufacturing R&D, rad shielding R&D, component tests, ground engine tests
Liquid & Gaseous Core Fission NTR	Thermal rockets that use liquid- or gaseous-core nuclear fission reactors. These would operate at very high temperatures, potentially enabling Isp of 3,000–5,000 sec.	2	Nuclear criticality, radiant heat transfer, and fuel containment. Radiation shielding. Accident hazard containment.	Analysis and lab testing, rad shielding R&D, component design and testing, sys grnd demo
Fusion NTR	A thermal rocket that uses a fusion reactor. Concepts for achieving clean aneutronic fusion include Inertial Electrostatic Confinement, Inertial Electrodynamic Fusion, and Dense Plasma Focus. Performance is generally similar to fission NTR.	2	Device size to achieve power break-even. Control of ion and electron feeds. Structure and cooling. Drive current/ voltage. Magnetic field drive (for IEF).	Scaled-up reactor tests, continuous reactor operations demo, component design and testing, sys grnd demo
External Pulsed Plasma	External pulses generated by successive detonations of nuclear material are used to generate propulsion by the action of plasma expanding against a pusher plate at the rear of the vehicle. (Isp of 5,000–10,000 sec).	2	Type of pulse unit, its degree of collimation, detonation position and fissile bum-up fraction. Pulse unit safety and loading. Pusher plate-plasma interaction.	Pulse unit R&D, detonation testing, plasma interaction tests, subscale flight demo
Low-Energy Nuclear Reactions NTR	A thermal rocket that uses a reactor that operates on Low Energy Nuclear Reactions (LENR), a form of "cold fusion." Performance would be similar to other NTR approaches, but without the radiation hazards.	1	Development and validation of underlying LENR predictive theory. Demonstration of controlled reactions.	LENR process research, experimentally initiate and control LENR, component design and testing, sys grnd demo
Nuclear-based Combined Cycle	The energy from nuclear reactions is applied in a combined cycle propulsion system with both air-breathing and rocket modes of operation. Specific impulse values in air-breathing mode are essentially infinite.	2	Challenges are similar to those of conventional TBCC and RBCC systems and advanced NTR, but include integration of a nuclear reactor into an air-breathing flow path.	Analysis and lab testing (including wind tunnel tests), rad shielding R&D, component design and testing, sys grnd demo, flight demo
1.5.6 High Energy Density Materials/Propellants – Propellants or materials that contain considerably higher stored energy per mass than conventional chemical propellants				
Polynitrogen	New liquid or solid compounds of nitrogen, such as N_4 or N_8, which release very high energy upon decomposition into N_2 molecules, potentially enabling I_{sp} of 350–500 sec.	2	Stability/shock sensitivity, production, and storage.	Formulation R&D, production R&D, stability tests, propulsion demos
Nanopropellants	Propellants with embedded nanoscale particles of combustible material (e.g. aluminum powder), providing greater reactive surface area and energy.	2	Controlled energy release. Consistently reproducible properties.	Production R&D, combustion/ stability tests, propulsion demos
Atomic and Metastable	Very high-energy propellants that contain atomic free-radicals or metastable forms of molecules, such as atomic hydrogen, metastable helium, and metallic hydrogen. Potential for I_{sp} > 2,000 sec.	2	Stability/shock sensitivity, production, and storage.	Production R&D, energy release and stability tests, propulsion demos

3. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

The launch vehicle propulsion technology area has many interdependencies and synergies with many of the other technology areas. (If a TA is not listed, no significant interdependency was identified.) Among them are:

In-Space Propulsion – Most of the fundamental tools, rocket propulsion, and nonrocket (tether) propulsion systems have direct synergy with the in-space propulsion area. This is particularly true for launches from planetary surfaces, including bodies with atmospheres, both for robotic sample return and for safe and assured return of humans. Many of the technology challenges facing launch vehicle propulsion systems are common to the ones facing this TA.

Space Power and Energy Storage Systems – There are several propulsion systems like beamed energy that use high-power electrical storage and distribution systems, which are synergistic with this TA. Nuclear propulsion systems are also considered synergistic with this TA in the area of power generation.

Robotics, Tele-Robotics, and Autonomous Systems – Fault detection, isolation, and recovery capabilities as well as prognostic/diagnostic capabilities in this TA are synergistic with IVHM technology.

Scientific Instruments, Observatories, and Sensor Systems – Sensor technologies related to cryogenic or high-temperature applications are highlighted in this TA and the LPSTA and are synergistic.

Entry, Descent, and Landing Systems – Technologies for reaction control systems and reentry propulsion are synergistic with this technical area.

Nanotechnology – Many areas of nanotechnology, including low-weight, high-strength and/or high-temperature materials, sensors, propellants, coatings, and insulation directly feed into launch vehicle propulsion applications. This is an interdependent technical area.

Modeling, Simulation, Information Technology, and Processing – We share interdependency with this TA, as fundamental design and analysis tools are needed for engine component and system development and test.

Materials, Structural and Mechanical Systems, and Manufacturing – Many areas of this TA, including low-weight, high-strength, and/or high-temperature materials, sensors, coatings, and insulation as well as manufacturing processes would directly feed into launch vehicle propulsion applications. This is an interdependent technical area.

Ground and Launch Systems Processing – There are both synergies and interdependencies between LPSTA and this TA. Sensor development for ground applications is synergistic with propulsion applications particularly for cryogenic systems. The LPSTA and this TA are interdependent regarding IVHM technology development.

Thermal Management Systems – In general, thermal management is a critical need for launch propulsion systems. While we do share synergy with this TA regarding cryogenic insulation technologies, propulsion systems could share interdependency with this TA if they broadened their scope to include propulsion-specific applications.

4. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

In addition to supporting NASA goals for space exploration and the achievement of routine, low cost access to space, the advancement of launch propulsion technologies supports national needs as a whole. These needs include those of other government agencies, such as the military, the national security community, and NOAA, which would benefit greatly from the reduced costs, improved reliability, and greater utility of new launch systems enabled through advanced propulsion technology. Similarly, the success and competitiveness of the commercial launch industry would be greatly enhanced through the creation of more efficient and cost effective launch propulsion systems. The President has tasked NASA with helping the nation sustain and expand its world leadership in aerospace technology, which in turn provides many spinoffs to other industries and a major opportunity to reinvigorate STEM education. The President's current budget proposal also emphasizes developing the commercial launch industry. This could lead to the establishment of new, emerging markets for an active and aggressive entrepreneurial launch industry.

Over the last decade and a half, the U.S. aerospace industry has been significantly impacted by the lack of investment in launch propulsion technologies. This has caused the U.S. to lose several key technology capabilities that enable access to space. Some critical aspects of our ability to access space rely on foreign suppliers, e.g., ORSC engines, which put restrictions on the use of their supplied technologies. These restrictions have a significant impact on national security and defense, and they can only be addressed by creating a national supply base for these critical components and technologies. Thus, any investment in propulsion technology will help to offset this loss, will help establish a basis on which to reinvigorate the fundamental LPSTA capability, and will re-grow technological "seed corn" for the future.

ACRONYMS

ACES Air Collection and Enrichment Systems
ACS Auxiliary Control System
Adv/Advcd Advanced
AIAA American Institute of Aeronautics and Astronautics
Alt. Alternative
AMPM Agency Mission Planning Manifest
ADN Ammonium Dinitramide
AP Ammonium Perchlorate
APIO Advanced Planning and Integration Office
ARC Ames Research Center
ARMD Aeronautics Research Mission Directorate
ATP Authority to Proceed
CAD Computer Aided Design
CC Closed Cycle
CCDev Commercial Crew Development
CFD Computational Fluid Dynamics
CH_4 Methane
CoPV Composite Overwrap Pressure Vessel
COTS Commercial Orbital Transportation Services
CRAI Capability, Requirements, Analysis, and Integration
Cyc Cycle
DCR Design Certification Review
Demo Demonstration
DGLR Deutschen Gesselleschaft für Luft- und Raumfahrt (German Scientific Society for Aeronautics)
DRA Design Reference Architecture
DLR Deutschen Zentrums für Luft- und Raumfahrt (German Aerospace Center)
DRM Design Reference Mission
Dyn Dynamic
ECLS Environmental Control and Life Support
EELV Evolved Expendable Launch Vehicle
Eff Efficient
EHA Electrohydrostatic Actuator
EHS Environmental Health System
ELV Expendable Launch Vehicle
EMA Electromechanical Actuator
Eng Engine
ESMD Exploration Systems Mission Directorate
ETO Earth to Orbit
Flt Flight
FOM Figure of Merit
GG Gas Generator
GOX Gaseous Oxygen
Grnd Ground
GW Gigawatt
HAN Hydroxyl Ammonium Nitrate
HC Hydrocarbon
HEDM High-Energy Density Material
HEFT Human Exploration Framework Team
HLPT Heavy Lift Propulsion Technology
HLV Heavy Lift Vehicle
HTPB Hydroxyl-Terminated Polybutadiene
HX Heat Exchanger
Hyp Hypersonic
IAP Integrated Actuator Package
IEC Inertial Electrostatic Confinement
IEF Inertial Electrodynamic Fusion
IHPRPT Integrated High Payoff Rocket Propulsion Technology
IPT Integrated Product Team
Isp Specific Impulse
ISS International Space Station
IVHM Integrated Vehicle Health Management
JSC Johnson Space Center
k Thousand
kg Kilogram
klbf Thousands of pounds of force
KSC Kennedy Space Center
LAS Launch Abort System
lbf Pounds of force
LCC Life Cycle Cost
LENR Low-Energy Nuclear Reactions
LEO Low-Earth Orbit
LH_2 Liquid Hydrogen
LOX Liquid Oxygen
LPSTA Launch Propulsion Systems Technology Area
LST Life Support Technologies
Lt. Wt. Light Weight
Mgmt Management
MHD Magnetohydrodynamics
Mlbf Millions of pounds of force
MPS Main Propulsion System
MSFC Marshall Spaceflight Center
N_2 Nitrogen
N/A Not Applicable
NAI National Aerospace Initiative
NEO Near Earth Object
NGLT Next Generation Launch Technology
NIA (Boeing) National Institute of Aerospace
NRC National Research Council
NTR Nuclear Thermal Rocket
OC Open Cycle
OCT Office of the Chief Technologist
OMB Office of Management and Budget
Op Operational
Opt Option
ORSC Oxygen Rich Staged Combustion
PBAN Polybutadiene Acrylonitrile
Prop Propellant
Proto Prototype
Pt. Point
Rad Radiation

RBCC	Rocket Based Combined Cycle
RBS	Reusable Booster System
RCS	Reaction Control System
R&D	Research and Development
RLV	Reusable Launch Vehicle
RP	Rocket Propellant (hydrocarbon-based)
RSRM	Reusable Solid Rocket Motor
sec.	Seconds
SHLV	Super Heavy Lift Vehicle
SLI	Space Launch Initiative
SMD	Science Mission Directorate
SOMD	Space Operations Mission Directorate
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
S/W	Software
Sys	System
T	Metric ton
TA	Technology Area
TABS	Technology Area Breakdown Schedule
TBCC	Turbine Based Combined Cycle
TDRS	Tracking and Data Relay Satellite
Tech Dev	Technology Development
Therm	Thermal
TRL	Technology Readiness Level
TVC	Thrust Vector Control
T/W	Thrust to Weight (ratio)
U.S.	United States
U/S	Upper Stage

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