

NASA'S LAUNCH PROPULSION SYSTEMS TECHNOLOGY ROADMAP

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ABSTRACT

Safe, reliable, and affordable access to low-Earth (LEO) orbit is necessary for all of the United States' (US) space endeavors. In 2010, NASA's Office of the Chief Technologist commissioned 14 teams to develop technology roadmaps that could be used to guide the Agency's and US technology investment decisions for the next few decades. The Launch Propulsion Systems Technology Area (LPSTA) team was tasked to address the propulsion technology challenges for access to LEO. The developed LPSTA roadmap addresses technologies that enhance existing solid or liquid propulsion technologies and their related ancillary systems or significantly advance the technology readiness level (TRL) of less mature systems like air-breathing, unconventional, and other launch technologies. In developing this roadmap, the LPSTA team consulted previous NASA, military, and industry studies as well as subject matter experts to develop their assessment of this field, which has fundamental technological and strategic impacts for US space capabilities.

This paper provides a brief overview of the roadmap released through the NASA Office of Chief Technologist [1] and reviewed by the National Research Council (NRC).

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. 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, the military, and other organizations over the past 15 years (a total of 17 major technology databases); 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 kg (\$/kg) to LEO; other metrics considered in many of the joint NASA planning activities with military agencies addressed "operationally responsive space," including 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 figures of merit:

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

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., the military Reusable Booster System (RBS). Similar benefits could result from launch assist or air-drop systems. Additional cost reductions and performance gains should come from either air-breathing or nonconventional 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.

This assessment resulted in the key mission milestones and representative launch manifest seen in the schedule bars of Figures 2 through 6. 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 CH₄ 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. The military Reusable Booster System (RBS) was also included in the manifest and is planned as the replacement for the current evolved expandable launch vehicle (EELV) fleet. 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 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

The phased planning strategy considered the following “architecture” development in chronological order:

- 1) Propulsion technologies would be developed for a Super Heavy Launch vehicle, and this vehicle would consist of either expendable solid or hydrocarbon fueled boost capability either with or without an LH2 core stage, and may or may not include an upper stage (depending on the core configuration). This is

comparable to the NASA’s current Space Launch System, and emphasizes safety and affordability.

- 2) Concurrent to Super Heavy launch vehicle development, technologies for low-cost expendable propulsion technologies that support small, medium, and medium/heavy commercial propulsion requirements are also included. These include hydrocarbon and other boost and upper stage propellant configurations.
- 3) Development of reliable, reusable rocket-based booster and upper-stage technologies is considered to mature later, where cost considerations are driven by reuse and reliability as opposed to low-cost unit production costs.
- 4) Air-breathing technologies are expected to mature after reusable rocket propulsion systems, but a consistent and continuous investment in component and subscale system demonstrators is necessary for development of an operational system
- 5) A concurrent, low-level investment in high-risk, high-payoff technologies is appropriate to maintain assessment of a broad range of non-conventional propulsion technologies.

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 as shown in Table 1. 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.

2 DETAILED PORTFOLIA 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 1, 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 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. The technology area breakdown structure that focuses on these five areas can be seen in Figure 1.

Table 1. 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 Engine	3. SRM Green Propellant
4. Nontoxic RCS	4. Advanced Expander Cycle Rocket	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)		

2.2 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. This technology roadmap is summarized in Figure 2.

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. This technology roadmap is summarized in Figure 3.

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. This technology roadmap is summarized in Figure 4.

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. This technology roadmap is summarized in Figure 5.

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. This technology roadmap is summarized in Figure 6.

3 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.

4 National Research Council (NRC) Review and Prioritization of the LPSTA Roadmap

On February 1, 2012, the NRC delivered the final report entitled “NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES: Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space” [2]. This report prioritizes the technologies within each of the NASA’s 14 Technology Areas, and also prioritizes across all 14 roadmaps. Within this integrated list of technology prioritization, none of the LPSTA technologies made the list of 16 high-priority space technology investments.

Within the LPSTA’s technology plan, the review panel’s quality function deployment (QFD) scored the level 3 technologies. Two technologies were assessed to be high priority based on their QFD scores:

- Air Breathing Propulsion Systems: Rocket Based Combined Cycle (RBCC)
- Air Breathing Propulsion Systems: Turbine Based Combined Cycle (TBCC)

The panel identified 12 technologies in LPSTA as medium priority, and of these, RP/LOX and LH2/LOX ranked the highest due to their importance to the overall launch industry, and to the future of NASA programs and missions (both human and science). Launch abort systems were noted to be of significant importance to human flight, with the potential to improved system safety performance. Of the 18 low-priority technologies, two were deemed non-credible for launch propulsion applications (nuclear propulsion and tethers).

The NRC panel also identified two top technical challenges for launch propulsion, with the recommendation that NASA focus its LPTSA activities in the following areas:

- Reduce the total cost of access to space while increasing reliability and safety.
- Develop technologies to enable lower cost, high performance upper stage engines suitable for space access and in-space applications.

In general, the NRC considered conventional and current chemical launch propulsion technologies to be fairly mature, and that progress in reducing costs or improving reliability would be small and incremental relative to current capabilities (as opposed to significant or game-changing results). The NRC noted that industry and government have worked for decades to identify breakthrough technologies or concepts that would lower launch costs, but none appeared to be viable within the near-term horizon. They noted that greater potential for lowering launch costs may be in other (non-propulsion) technologies.

5 Concluding Comments

NASA’s Launch Propulsion Systems Technology Roadmap is a comprehensive and integrated plan that addresses a range of launch propulsion technologies. These range from upgrades on conventional chemical systems to advanced air-breathing and unconventional systems. Technologies were derived from

a range of launch architectures and capabilities that covered NASA’s needs (including science and human space flight missions), and have synergy with US national security needs.

Technologies were evaluated relative to propulsion system production costs, operational costs, game-changing systems or subsystems, and national needs. The NRC evaluated this technology plan, and prioritized air-breathing RBCC and TBCC systems as high, and also highlighted the need for upper stage/in-space propulsion and technologies that reduce cost.

The team developing the LPSTA plan agrees that investment should occur these areas of air-breathing propulsion, but also advocates a base-line investment in upgrades of conventional systems. Many advances have made the Space Shuttle Main Engine more reliable and reusable over the years (e.g. Si-nitride bearings and damping seals), and other technologies have resulted in lower-cost expendable engines due to lower part count and advanced materials and manufacturing techniques (e.g. blisks and ablative nozzles and combustion chambers). Incremental progress in propulsion system and subsystem technologies combine with progress in other vehicle subsystem areas (e.g. lightweight structures, low-cost manufacturing designs and techniques) will ultimately lead to lower launch costs at the vehicle system level.

REFERENCES

1. NASA’s Draft Launch Propulsion Systems Roadmap – Technology Area 01. Paul K. McConnaughey, Mark G. Femminineo, Syri J. Koelfgen, Roger A. Lepsch, Richard M. Ryan, and Steven A. Taylor. November 2010, 28 pages.
2. NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES, Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space, National Research Council, The National Academies Press, 2012, Washington, DC

Figure 1: Technology Area Breakdown Structure for Launch Propulsion

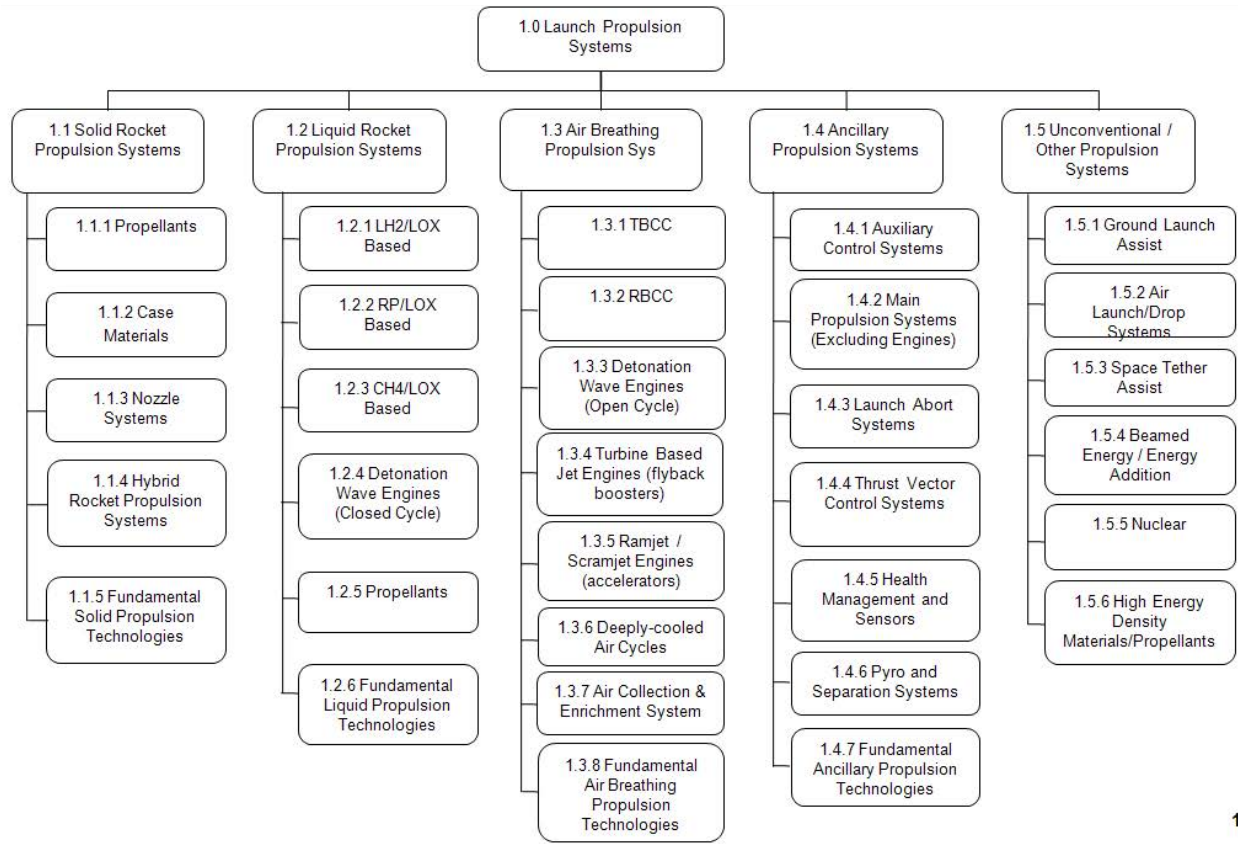


Figure 2: Solid Rocket Propulsion Systems Technology Roadmap

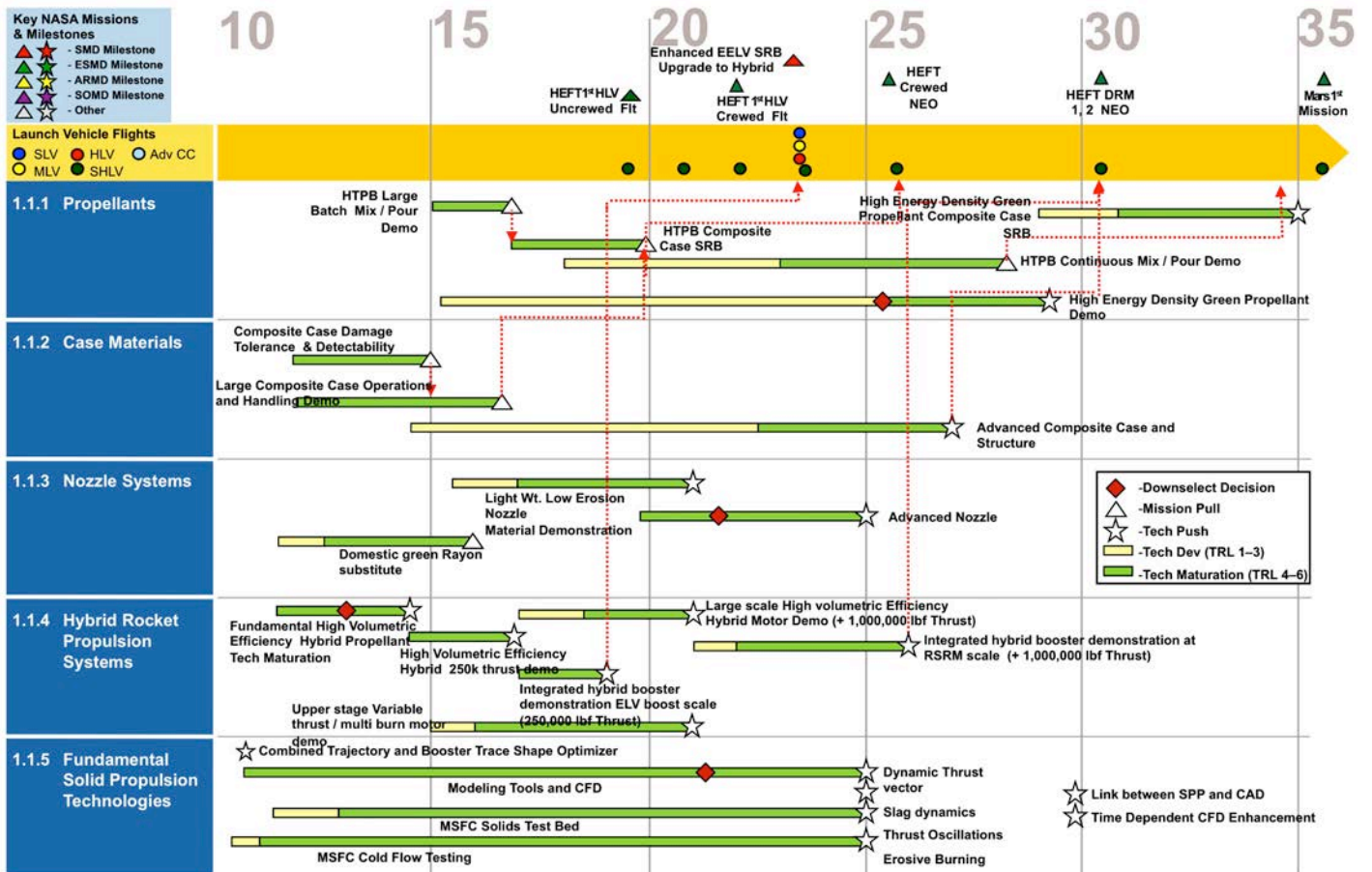


Figure 3: Liquid Rocket Propulsion Systems Technology Roadmap

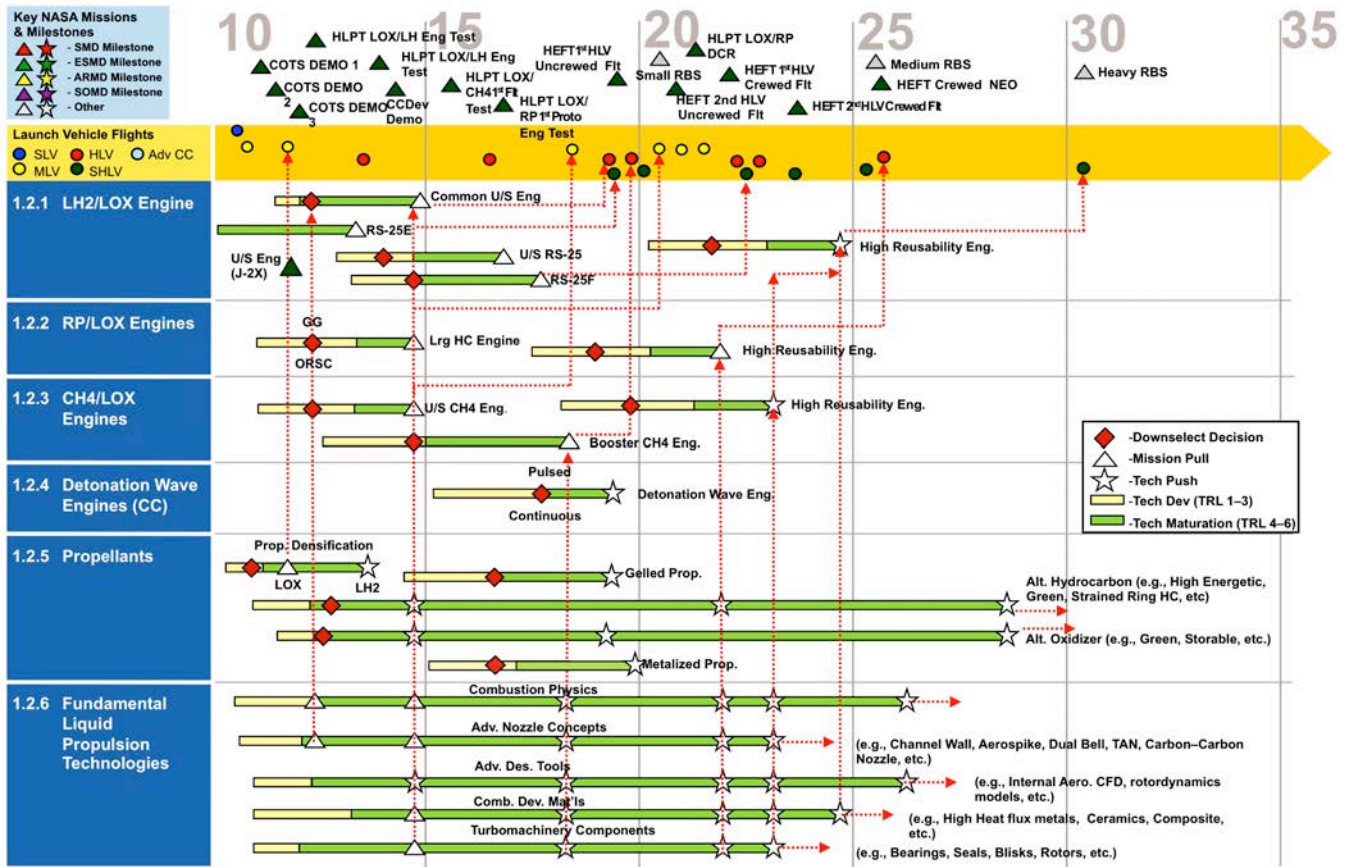


Figure 4: Air-Breathing Propulsion Systems Technology Roadmap

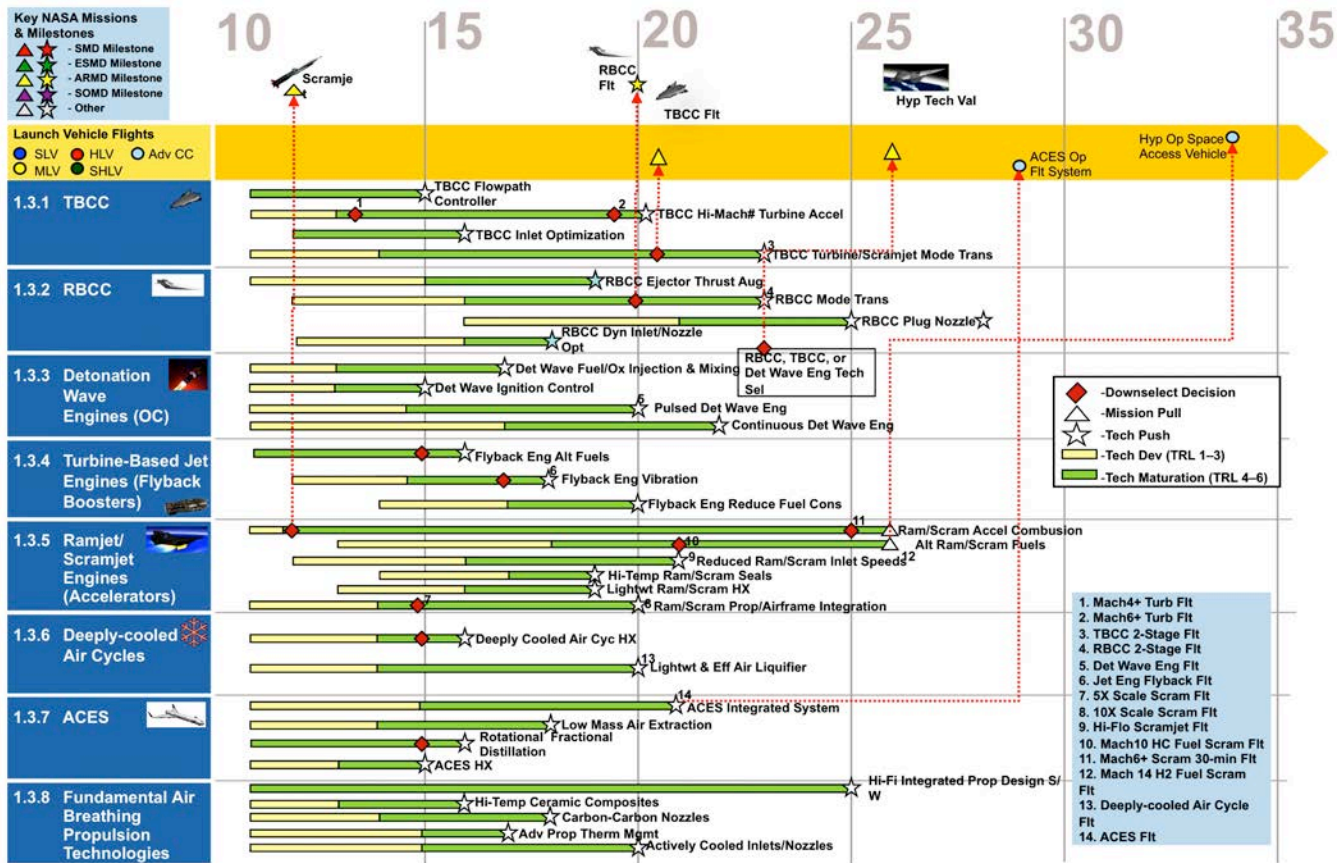


Figure 5: Ancillary Propulsion Systems Technology Roadmap

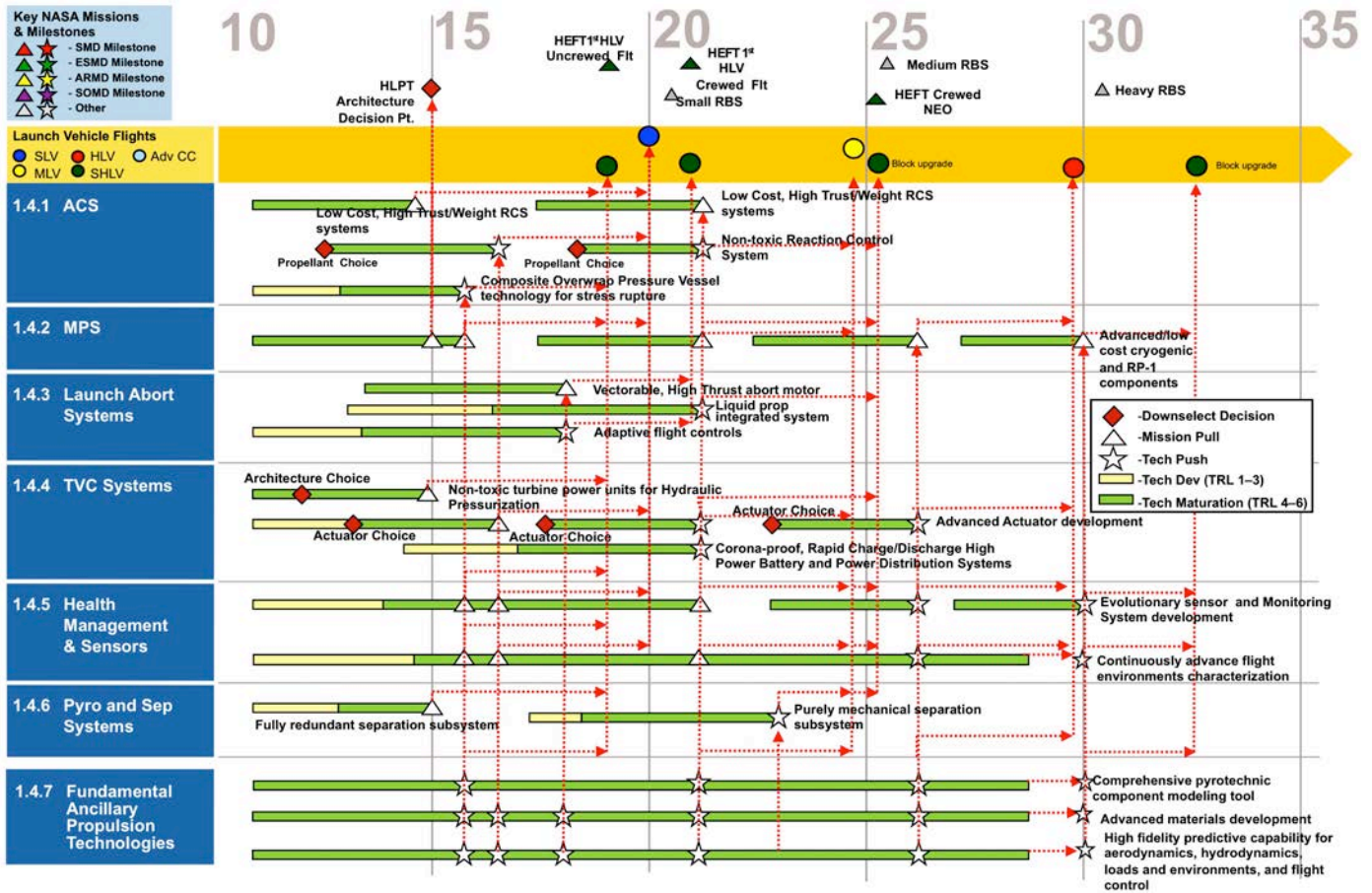


Figure 6: Unconventional/Other Propulsion Systems Roadmap

