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Abstract

At the National Aeronautics and Space Administration (NASA), foresight is a coordinated, iterative, and continual process for making informed decisions. NASA faces diverse and relatively unique challenges and opportunities as the leading U.S. agency for aeronautics development, cutting-edge scientific discovery, and human space exploration. To address these challenges and leverage opportunities, NASA uses foresight to strategically plan technology development across four mission directorates: Aeronautics Research Mission Directorate, Space Technology Mission Directorate, Science Mission Directorate, and Human Exploration and Operations Mission Directorate (recently separated into the new Exploration Systems Development Mission Directorate and Space Operations Mission Directorate). The mission directorates leverage a broad community of experts and partners to incorporate technology foresight into mission and program planning. Through this process NASA realizes tangible benefits to the agency's science, technology, and exploration programs.

As an independent office, NASA's Office of Technology, Policy, and Strategy (OTPS) provides strategic advice, supported by independent assessments and rigorous analysis, to inform NASA senior leadership on key areas to align mission and agency-level activities. OTPS serves as a trusted authority to inform technology strategy at the agency to enable future missions. Specifically, OTPS coordinates and uses inputs from a broad community of experts, both internal and external to NASA, to inform decision making for technology plans, investments, and partnerships. OTPS develops and maintains the NASA Technology Taxonomy to standardize communication across the agency's diverse technology portfolio and the related Strategic Technology Investment Plan that integrates priorities and informs technology investment. Through these efforts, OTPS has refined elements of foresight-informed strategic planning that may be applicable to other technology-driven industries where foresight is essential for resilience.

This chapter describes the processes of foresight for technology development at NASA and provides insight into the value the agency derives from these processes. The chapter further describes the role of OTPS as an independent advisory office that supports NASA's efforts to capitalize on foresight and strategic technology planning. We present these examples with consideration for how organizations in defense, security, and other technology-driven industries can operationalize foresight in their own strategic technology development.

Introduction

This chapter describes how the National Aeronautics and Space Administration (NASA) strategically plans technology development decades in advance of its intended use. We suggest that professionals, scholars, and policy makers can use elements of NASA's approach when advising decision makers on strategic planning and development of technology in defense, security, and other technology-driven industries where foresight is essential for resilience. Specifically, we see value in an independent office that can witness technology development across an organization and help apply foresight to increase the potential for mission success.

Developing technology is an essential and enabling activity at NASA. Representing approximately 10 percent of NASA's budget,[1] technology development involves the development of any "solution that arises from applying the discipline of engineering science to synthesize a device, process, or subsystem, to enable a specific capability."[2] In pursuit of its vision to "explore the secrets of the universe for the benefit of all,"[3] NASA develops technologies within its four mission directorates, each with its own purpose and plan for technology development.

This chapter reviews NASA's approach to technology development through the lens of NASA's mission directorates and the coordinating role of the Office of Technology, Policy, and Strategy (OTPS). Recently, NASA's organizational structure has changed, with the Human Exploration and Operations Mission Directorate restructured into the operations-focused Space Operations Mission Directorate and the development-focused Exploration Systems Development Mission Directorate. In addition, OTPS was formed in November 2021 through the integration of the Office of the Chief Technologist (OCT) and the Office of Strategic Engagement and Assessments (OSEA). The technology coordinating body role described in this paper was initially within OCT's mission and now is one of several focuses for the new Office of Technology, Policy, and Strategy. However, the technology development approaches published by the previous four mission directorates and OCT's coordinating role remains relevant. Therefore, this chapter reviews the technology development approaches published by the previous four mission directorates as of early 2021:

- The **Aeronautics Research Mission Directorate (ARMD)** designs, develops, and tests technologies to improve aircraft and air transportation systems for the benefit of the American aviation industry, the passengers and businesses who rely on aviation, and the local and global environment affected by air transportation.[4]
- The **Space Technology Mission Directorate (STMD)** leads space technology research and development throughout the agency and with agency partners to enable exploration missions, such as missions planned for the Moon and Mars, and to enable technology transfer back into the U.S. economy.[5]
- The **Science Mission Directorate (SMD)** uses space-based observatories and robotic missions to answer science questions related to five disciplines—Earth Science, Planetary Science, Heliophysics, Astrophysics, and Biological and Physical Sciences—to fulfill national and international priorities for scientific discovery; inform future robotic and human space expeditions; and inspire science, technology, engineering, and mathematics (STEM) education nationwide.[6]
- The **Human Exploration and Operations Mission Directorate (HEOMD)** manages current space operations in low-Earth orbit and beyond, including activities on the International Space Station (ISS), launch services, commercial space transportation, human spaceflight capabilities, systems for human exploration in space and on planetary

bodies, and transportation and communication for both human and robotic exploration programs.[7]

With a critical role in connecting technology development across all four mission directorates, NASA's OTPS coordinates and facilitates technology strategy and policy for the agency. As an office independent of the mission directorates, OTPS serves as a trusted authority to inform technology strategy at the agency to enable future missions. Led by NASA's Associate Administrator, Office of Technology, Policy, and Strategy—"who provides evidence-driven advice to NASA leadership on internal and external policy issues, strategic planning, and technology investments"[8]—OTPS coordinates internal and external inputs on strategic technology development from a broad community of experts, including chief technologists from each NASA field center who form the Center Technology Council. OTPS then facilitates and advises on the planning of technology development throughout the agency, ensuring that technology development aligns with agency and community needs while also accounting for both anticipated and unanticipated challenges and opportunities that arise with new discoveries. That is, as an independent office that coordinates, facilitates, and advises on technology strategy and policy, OTPS ensures that NASA's approach to technology development operationalizes foresight.

The following sections detail how NASA ensures the use of foresight in its technology development. First, we define foresight at NASA, providing examples of how scientific and technological discoveries both account for and uncover challenges and opportunities for conducting future discoveries. Next, we discuss how NASA approaches strategic technology development, detailing the approach of each of the four mission directorates. Then, we describe how the prior OCT's three main activities—integration, partnership, and innovation—enable the use of foresight in technology development throughout NASA. Finally, we provide recommendations for organizations in defense, security, and other technology-driven industries who want to ingrain foresight in their own technology development programs.

Foresight Provides Tangible Benefits at NASA

This section defines foresight for technology development at NASA. Throughout this section, note that "developing" technology at NASA encompasses both in-house technology development by NASA programs and investment in technology development outside the agency. As part of its mission to spur innovation and support economic growth, NASA invests in the development of ideas and technologies by academic and commercial partners and then purchases products or services from the developers at a later date. Throughout this chapter, we return to the role of NASA's community partners in strategic technology development.

At NASA, foresight is a coordinated, iterative, and continual process for making informed decisions. Like many technology-driven organizations, NASA must anticipate challenges and opportunities in technology development. However, as the leading agency in aeronautics development, cutting-edge scientific discovery, and human space exploration, NASA faces diverse and relatively unique challenges and opportunities for technology development. As these challenges and opportunities are often influenced by other missions and discoveries, NASA must coordinate information from throughout a broad community of scientific and technical expertise to inform strategic decisions. It is through these processes that NASA enables foresight in technology development.

In one example, NASA required an intensely coordinated effort for its 2018 InSight and MarCO missions, which combined technology demonstration with planetary science. The Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission involved landing a robotic lander on Mars to expand our knowledge about rocky planet interiors. Specifically, InSight is the first mission with the instrumentation to measure deep tremors on Mars, termed marsquakes.[9] However, implementing foresight, NASA used the flight for the InSight lander to also demonstrate the new application of CubeSats in deep space. Building on the success of hundreds of CubeSats in Earth orbit, the Mars Cube One, or MarCO, showed that miniaturized deep space communication equipment can relay data from a planetary lander to Earth.[10] In fact, for the first time, the two MarCO CubeSats relayed telemetry data near-continuously as InSight successfully completed its entry, descent, and landing. The success of MarCO has since led to new opportunities for scientific discovery using constellations of CubeSats as in the case of the Sun Radio Interferometer Space Experiment (SunRISE). The new SunRISE mission—in which a constellation of CubeSats work together as an aggregated aperture for a 10 km-baseline radio telescope to measure powerful eruptions from the Sun's atmosphere—is the result of an opportunity made possible with the use of foresight.[11]

NASA also uses foresight when planning in response to new discoveries, such as discoveries about the presence of water on the Moon. In 2008, with data from NASA's Moon Mineralogy Mapper (M3) aboard India's Chandrayaan-1, NASA first confirmed the presence of ice in the permanently shadowed craters near the Moon's poles.[12] This discovery affected plans for future human exploration of the Moon, including developing technologies to extract water from the ice in the shadowed craters, where the temperature is near -250 degrees Fahrenheit. This discovery also inspired new uses for other NASA science missions, like the first use of the Stratospheric Observatory for Infrared Astronomy (SOFIA) to investigate the surface of the Moon. In 2020, SOFIA confirmed the presence of water molecules in sunlit areas of the Moon. In response to this better understanding of the presence of water on the Moon, human exploration architectures evolved again, considering different technologies for water extraction and different destinations for human settlement on the lunar surface, a NASA goal for the next 10 to 30 years. In addition, this discovery prompted more scientific inquiries, including new questions about how water is created and how it can persist in a harsh, airless environment.[13] These inquiries thereby prompt new areas of research for upcoming science missions, like the Volatiles Investigating Polar Exploration Rover (VIPER) planned for 2024.[14] To make decisions now when planning activities decades away, NASA must continually coordinate known information with efforts to anticipate and validate new discoveries.

Given the nature of NASA's cutting-edge missions, NASA must use foresight to develop technology that accounts for anticipated and unanticipated challenges and opportunities over decades. NASA plans missions that have timelines 10 to more than 30 years into the future. Many of these missions rely on technical and scientific discoveries that have yet to be realized. With few organizations committed to decades of research about, for example, in-space transportation and lunar habitation, NASA is largely responsible for ensuring these technical and scientific discoveries happen. Therefore, NASA uses foresight to identify and then advance high-priority technology areas, while also conducting the experiments and demonstrations that inform the development of those technologies over time.

For example, NASA anticipates cryogenic fluid management (CFM) technologies are necessary for surface missions to the Moon in the 2020s and Mars in the 2030s. CFM technologies enhance system performance for key elements of human exploration architectures, including in-space propulsion, landers, and ascent vehicles. Anticipating this critical function, NASA has been developing CFM technologies since the 1960s.

The planned applications of CFM technologies have changed along with changes in mission architectures over time, but the technology has progressed throughout 60 years of development. In 2019, NASA demonstrated on the ISS a gauge for cryogenic storage and will further demonstrate its capability on a future lunar surface mission.[15] Additionally, NASA has begun developing prototype components for cryogenic liquefaction on planetary surfaces.[16] As system components mature, NASA accounts for the new opportunities, and documents future technology maturation assumptions, in planning mission architectures over decades.

In another example, NASA builds on over 70 years of supersonic flight research to demonstrate quiet supersonic flight over land in the 2020s. As the following section will describe, innovation in commercial supersonic aircraft is one of the "strategic thrusts" of ARMD. In pursuit of efficient, cost-effective, and environmentally compatible supersonic flight, NASA enhances technology that has been developed and in use for different applications for decades.[17] Beginning in 2024, NASA plans to fly the X-59 aircraft above U.S. communities to measure public response to the supersonic plane's quieter sonic boom. Data on the public response will be presented as regulatory officials consider lifting the 1973 ban on supersonic flight over land and define new allowable sonic boom levels with the international standards community.[18, 19] Foresight enables NASA to continually chart a course among the opportunities and challenges revealed over decades of research and development.

NASA is in the business of making new discoveries, and these new discoveries will always uncover new challenges and opportunities for agency missions. Therefore, in addition to planning technology development decades in advance of its use, NASA must also adapt technology development plans in response to anticipated and unanticipated discoveries. These discoveries happen in both scientific and technical developments, affecting other scientific and technical objectives.

Some scientific discoveries reveal new challenges for exploration, and some reveal new opportunities. The previous discussion of detecting water on the Moon, first as ice in permanently shadowed craters and then as molecules in sunlit areas, showed how scientific discoveries reveal new opportunities for both science missions and human exploration. In another example, the first one-year crew mission on ISS and NASA's Twins Study revealed additional challenges of long-duration human spaceflight as preparation for future multi-year Mars missions. Although some risks to human health have been mitigated by solutions developed using the ISS, these findings reveal additional effects as missions are extended. The needs for technology innovations and countermeasure strategies that address integrated human health and performance on longer missions reveal the interplay between human systems and architectures as they relate to mission risk.[20] NASA will continue to make new scientific discoveries that impact future missions, so using foresight means developing plans that are robust to new discoveries.

Likewise, new technological developments change how NASA plans missions. For example, the introduction of cost-efficient "rideshare" launches has opened new opportunities for science missions with CubeSats, like the previously mentioned SunRISE. The increase in the number of CubeSats has also created a challenge for accurate identification and tracking of the standardized miniature satellites, affecting technology development plans in that area.[21] In another example, a material used for computer chips, monocrystal silicon, has the potential to reduce the mass of X-ray telescopes. These new optics may provide an opportunity for a lightweight telescope with two orders-of-magnitude greater sensitivity than the state-of-the-art and at a lower cost.[22] The potential of this new technological development affects science missions involving observations of exploded stars and black holes. Both anticipated and unanticipated technology developments affect missions that might have already been decades in the making, thereby also affecting the technologies planned to enable those missions.

Ultimately, building resilience into technology development plans requires an approach with foresight—to plan for the anticipated challenges of future missions *and* the potential disruptions from discoveries by current missions or new technological developments. To benefit from foresight, effective processes and strategies to incorporate it are necessary throughout the technology and mission development.

NASA's Approach to Strategic Technology Development

This section describes how NASA uses foresight to strategically plan technology development throughout the agency (as of early 2021). First, however, we have two important notes about the approaches described below. As mentioned previously, the development of technology at NASA includes investments in commercially developed technologies. Therefore, the following descriptions of technology development strategies within NASA's four mission directorates also include these developments by commercial partners. Furthermore, the technologies developed under the purview of NASA's mission directorates are not necessarily intended for use in NASA missions exclusively. ARMD in particular develops technologies that are ultimately intended for use outside NASA, by America's aerospace industry.

All four mission directorates contribute to the agency's overarching objectives and each does so through directorate-specific guiding objectives. These guiding objectives (also called "missions" or "strategies") drive strategic decisions within each mission directorate, including decisions about technology development. Fulfilling each objective typically requires some level of technology development. Therefore, each mission directorate maintains its own strategic approach to technology development.

Aeronautics Research Mission Directorate (ARMD)

ARMD plans for the next 25 years by examining global trends in aviation needs. A biennial Strategic Implementation Plan (SIP) details how ARMD expects to "develop and advance technologies that meet the needs of the aviation community, the Nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation."[23] To meet these needs, ARMD begins with an analysis of global trends, or mega-drivers. Using a trend analysis by subject matter experts and senior stakeholders, ARMD identified three mega-drivers: 1) global growth in demand for high-speed mobility; 2) affordability, sustainability, and energy use; and 3) technology convergence.

In addition to the mega-drivers, ARMD's strategic approach to technology development incorporates community dialogue. This community includes domestic and international partners and experts from other government organizations, academia, and industry. ARMD also incorporates inputs from reviews of ongoing research by federal advisory committees and the National Research Council's Aeronautics Research and Technology Roundtable. Finally, ARMD partners with the National Academies of Science, Engineering, and Medicine (NASEM) to provide in-depth information on ARMD topics through detailed studies.

In response to the mega-drivers and this community dialogue, ARMD developed six "strategic thrusts." These strategic thrusts represent areas of prioritization for aeronautics objectives: 1) safe, efficient growth in global operations; 2) innovation in commercial supersonic aircraft; 3) ultra-efficient subsonic transports; 4) safe, quiet, and affordable vertical lift air vehicles; 5) in-time system-wide safety assurance; and 6) assured autonomy for aviation transformation. In the 2019 SIP, ARMD details how these strategic thrusts help focus activities to prepare for the potential futures envisioned by the mega-drivers.

Within each strategic thrust, ARMD determines measurable, community-level outcomes. These outcomes represent the envisioned capabilities made possible by ARMD's research, with contributions from key partners, phased across three periods: 2015 to 2025, 2025 to 2035, and beyond 2035. For example, under the second strategic thrust, innovation in commercial supersonic aircraft, ARMD envisions three phased outcomes: a supersonic overland certification standard in 2015 to 2025; affordable, low-boom, low-noise, and low-emission supersonic transport in 2025 to 2035; and increased utility and market growth of supersonic transport in 2035 and beyond. In each case, ARMD develops technologies with the expectation that partners will be able to continue innovation and incorporate the technologies into markets that have yet to emerge. The 2019 SIP further details specific metrics for the desired outcomes, to measure progress in achieving the outcomes over time.

Finally, ARMD articulates research themes for technologies that are necessary for achieving the outcomes. Each research theme represents a long-term area of research for the technologies necessary to achieve one or more of the outcomes. For example, representing the technology necessary to achieve three phased outcomes, the research themes under the second strategic thrust are elimination of environmental barriers to commercial supersonic aircraft; integrated design and efficiency; modeling, simulation, and test capability; and efficient supersonic flight operations. Using these research areas, ARMD prioritizes research activities across its portfolio.

ARMD has experienced success transitioning technologies with this approach to strategic technology development. As an example of operationalizing foresight, this approach balances forward-looking prioritization with not only the specificity necessary for portfolio planning but also the flexibility needed to adapt to anticipated and unanticipated challenges and opportunities as they arise. This approach suits ARMD in part because ARMD does not develop technologies for its own use. Elements of this approach are applicable to another mission directorate that develops technology for others.

Space Technology Mission Directorate (STMD)

Like ARMD, STMD is not its own customer; STMD takes a similar approach of working with a community of experts to identify trends that drive strategic technology development decisions. STMD conducted a trend analysis to determine "major axes [of] change that have shaped, are shaping, and will continue to shape the global civilian space industry and civil space research over the next several decades."[24] The trend analysis involved a review of industry research, a literature review, an analysis of current technologies and their forecasted impacts, and discussions with STMD customers in HEOMD, SMD, and other government and industry organizations.[25]

Working with this trend analysis and ongoing community dialogue, STMD arrived at a list of strategic thrusts. Again, the strategic thrusts identify areas of prioritization for technology development—areas that are envisioned to have major impacts on space missions through 2040 and beyond. As of 2021, STMD has four strategic thrusts: 1) *Go* with rapid, safe, and efficient space transportation; 2) *Land* with expanded access to diverse surface destinations; 3) *Live* with sustainable living and working farther from Earth; and 4) *Explore* with transformative missions and discoveries.[26] These themes of *Go, Land, Live, Explore* summarize the major lines of investment in STMD's portfolio.

STMD then develops outcomes for achieving the four strategic thrusts and includes an Envisioned Future that further describes possible futures enabled by achieving the outcome. For example, under the strategic thrust *Go*, STMD articulated three outcomes that result from development in this area: nuclear technologies for fast in-space transit; cryogenic storage, transport, and fluid management technologies for surface and in-space applications; and advanced propulsion technologies for future science and exploration missions.[27] These outcomes are not projected to be accomplished in one particular timeframe; rather, they are the results of ongoing developments pursued in parallel.

STMD then articulates the primary capabilities necessary to achieve these outcomes. For example, as of 2021, advanced propulsion and CFM are capabilities necessary to achieve the *Go* outcomes. Many of these capabilities are crosscutting, enabling outcomes for different thrusts. As mentioned earlier, advancements in CFM technologies also enable outcomes found in the *Land* and *Live* thrusts.

Finally, STMD uses these capabilities to identify and prioritize gaps in technology plans. These plans incorporate input from industry experts, specific capability needs for SMD and HEOMD missions, and insight from NASA's principal technologists and Systems Capability Leadership teams—in-house subject matter experts who specialize in a given technology area. Consequently, technology development decisions not only address the capability gaps of STMD's two main customers—SMD and HEOMD—but also ensure the general advancement of technology in different areas that are a priority for NASA and the larger community.

Like the ARMD approach, STMD's approach to strategic technology development operationalizes foresight. This approach is specific enough to guide investments and balance STMD's portfolio but flexible enough to adapt to changes arising from new discoveries or developments that may or may not be anticipated.

The differences between ARMD's and STMD's approaches show how the use of foresight in planning technology developments is not one-size-fits-all. For one, they have different customers with different needs, and their approaches reflect these differences. Whereas phased outcomes help ARMD plan technology developments to meet its customers' needs over time, STMD's concurrent outcomes reflect the crosscutting nature of the technologies that enable different elements of different missions over decades. Meanwhile, the remaining two mission directorates, SMD and HEOMD, are largely their own customers, and as a result, their approach to strategic technology development differs further.

Science Mission Directorate (SMD)

The Science Mission Directorate (SMD) uses the decadal survey process to define science priorities for more than 100 missions across five divisions. Developed by NASEM, the decadal surveys set high-level science priorities for specific disciplines, with guidance for achieving an envisioned 10-year program within the discipline. The results are broad strategic science goals, which due to their expansive nature, drive a different process for incorporating foresight. From these goals, SMD defines, develops, and forecasts technologies to realize these future science objectives.

With this approach, SMD incorporates the larger science community's recommendations for developing science-enabling technology programs and making competitive selections for small- and mid-scale missions. Within each of the five SMD divisions, the division director manages the division portfolio in accordance with guidance from the relevant decadal survey, with modifications as needed to reflect the current budget. The decadal surveys are then used again to assess the division's progress in achieving the stated science priorities, during NASEM's midterm reviews.[28]

The five most recent decadal surveys in each discipline guide each SMD division's plan for technology development:

- Astrophysics: *Astro2020: Decadal Survey on Astronomy and Astrophysics* (2020)
- Earth Science: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (2017)
- Heliophysics: *Solar and Space Physics: A Science for a Technological Society* (2013)
- Planetary Science: *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032* (2022)
- Biological and Physical Sciences: *Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era* (2011)

Each of these decadal surveys provide specific guidance on budgeting and prioritizing the technology development necessary to achieve their stated recommendations.

For example, the decadal survey for Earth Science detailed recommendations for addressing, within the decade, the science community's highest priority concerns for Earth Science topics. The decadal survey described how the recommendations were primarily for NASA but also for the National Oceanic and Atmospheric Administration and the U.S. Geological Survey. The decadal survey's priorities came from a list of 35 key questions, derived from an initial list of 290 ideas from the science community, which a 20-member steering committee narrowed down with the help of five interdisciplinary panels. The committee then defined the objectives necessary to answer these 35 key questions, where "advances are most needed in both curiosity-driven and practically focused Earth science," and prioritized these objectives as "most important," "very important," and "important."[29] For example, the key question "How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?" is addressed by one of the "most important" objectives, such as "Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade."[30] Finally, the decadal survey included explicit recommendations for funding NASA programs to achieve these prioritized objectives, in a way that is "designed to be affordable, comprehensive, robust, and balanced."[30]30

Using the guidance from the decadal surveys, SMD ensures that its technology development decisions derive from foresight, in that they derive from a coordinated process for making informed decisions. This coordinated process includes analysis of past missions, as well as modeling and testing to develop strategic and implementation plans to minimize risk and increase likelihood of science mission success. This NASA process is leveraged to enable mission execution based on science prioritizations from NASEM, which collects and consolidates input from a national community of experts, while SMD leads technology development decisions to enable transformative science.

Ultimately, underpinning every strategic technology development decision at SMD is its mission statement: "Discover the secrets of the universe. Search for life elsewhere. Protect and improve life on Earth."[31] To do the science necessary to pursue these goals, SMD uses NASEM's recommendations to balance small, medium, and large missions across the directorate's five divisions.

Human Exploration and Operations Mission Directorate (HEOMD)

Finally, capability needs for human exploration architectures drive technology development at HEOMD. As of 2021, HEOMD develops technologies that enable capabilities for missions in the Moon-to-Mars architecture. This architecture includes the Gateway orbiting lunar outpost, Artemis missions returning humans to the lunar surface building to a sustained human presence on the Moon, and a roundtrip human mission to Mars.[32] Because these missions have crosscutting capability needs, HEOMD works with an internal community of experts to identify gaps in needed capability areas and the technologies needed to address those gaps.

HEOMD uses an annual capability data call and analysis to incorporate foresight in its strategic technology development approach. This data call goes to technical discipline experts from across NASA, including Systems Capability Leadership Team members, principal technologists from STMD, technology program executives from HEOMD, and technical fellows from NASA's Engineering and Safety Center. [33]

The data call invites these experts to identify known gaps in capability areas, at the level of vehicles, systems, and components. These experts are to describe capability gaps in quantitative terms instead of technological solutions. The data call also requests that the experts characterize capability gaps in terms of five possible closure pathways: new technology, development, engineering, acquisition of new knowledge, or architectural trade studies.

A Capability Integration Team (CIT) collects and analyzes the data call responses. At the beginning and again at the end of the data call process, the CIT works with HEOMD's human spaceflight architecture team, which defines requirements for human missions, to provide any additional capability gaps. Finally, the CIT maps the closure of capability gaps to the different architecture elements that then become possible. The 2020 data call found that 36 percent of the identified capability gaps required a technology development solution to achieve closure.[34]

Using the results of the data call and ensuing analysis, HEOMD can strategize for technology development that is resilient to uncertainty. While every mission directorate faces uncertainty, HEOMD in particular faces a "fundamental uncertainty due to the ever-evolving architectures for Moon and Mars exploration, along with the interconnectedness of elements within these architectures."[35] In addition to the evolving and interconnected nature of exploration architectures, HEOMD is uniquely challenged in the demonstration of technologies, which requires testing in a relevant environment and demonstrating sufficient reliability to enable humans to live in space for long durations with little or no resupply. Testing on Mars depends on a two-year cycle for orbital alignment, and as yet, the tested technology cannot return to Earth for a posttest analysis. Although technology demonstrated on the International Space Station (ISS) and Gateway can return to Earth, both platforms have limited volume available for testing technology in microgravity and the space environment. Furthermore, ISS, Gateway, and the Artemis missions provide different and complementary environments and crewed durations that are analogous to aspects of roundtrip human missions to Mars. Specifically, the ISS tends to be preferred for long-duration testing of capabilities needed for Mars transit, Artemis is preferred for testing Mars surface capabilities, and Gateway provides opportunities for furthering our autonomy and radiation protection technologies. Coordinating payload manifests and technology demonstration opportunities across these platforms is a complex challenge. With foresight, HEOMD not only coordinates expert input to inform technology development decisions, but also considers the breadth and depth with which a capability—as well as the technologies and technology demonstrations that enable it—is needed.

Across all four mission directorates, NASA's approach to strategic technology development operationalizes foresight. For each mission directorate, recommendations from a broad community of expertise drive decision making for technology development over decades. This community comprises both internal expertise (such as the STMD principal technologists) and external expertise (such as the steering committee members for NASEM's decadal surveys). The inputs from this community of expertise ensure the quality of foresight in NASA's technology development decisions.

Furthermore, each mission directorate builds a degree of flexibility into its decades-long technology development strategies. By focusing these strategies on desired outcomes and capabilities rather than specific technical solutions, each mission directorate accounts for anticipated and unanticipated opportunities and challenges that might arise and impact technology developments.

Coordinating the many different inputs within each mission directorate is a challenge in itself. Coordinating the different technology development strategies throughout the agency is a separate challenge, for which NASA instituted an independent office, described in the next section.

OTPS Activities to Enhance Foresight in Strategic Technology Development

This section describes how OTPS performs three major activities to enable the use of foresight in strategic technology development across NASA, with an emphasis on integration, partnership, and innovation.

The coordination that enables the use of foresight in technology development at NASA is a massive and complex undertaking. As previously described, coordinating technology development within each mission directorate involves collecting and analyzing inputs from a community of experts and then using that analysis to inform carefully detailed strategies, ensure alignment with the mission directorate's objectives, identify and mitigate gaps, and balance the mission directorate's portfolio.

This coordination is connected through a larger scale effort to inform agency-wide policies and strategies for technology development. In addition to working with a broad community of experts, this agency-level effort involves working with U.S. Congress and the President's Administration, international partners, commercial partners, and the general public, to articulate technology development needs and ensure alignment with activities throughout the agency. Ultimately, this larger effort makes it possible for NASA to account for anticipated and unanticipated challenges and opportunities for technology development as they arise. To undertake this effort, NASA empowered OTPS as an agency-level office independent of any mission directorate.

The prior OCT led three activities in the implementation of NASA's overarching strategic technology development approach: strategic integration, science and technology (S&T) partnership, and innovation. These activities, described below, remain influential across NASA's mission directorates, and OTPS is currently in the process of incorporating them into a broader set of strategic priorities.

Within its strategic integration activity, OTPS coordinates input from NASA's four mission directorates to develop policy, requirements, and strategy for technology development. Through this integration, OTPS captures and shares best practices for guiding technology development, including among other government agencies. OTPS supports and augments these best practices through targeted studies. Two major outputs of the prior OCT's strategic integration activity are the Technology Taxonomy and the Strategic Technology Investment Plan (STIP).

NASA uses the Technology Taxonomy to standardize communication across the agency's diverse technology portfolio. To develop the 2020 version of the Technology Taxonomy, the prior OCT worked with NASA's Center Technology Council to coordinate input from internal experts, including technical fellows, Systems Capability Leaders, and principal technologists. A taxonomy draft was then circulated throughout the agency to collect feedback and then made available for public review and comment. The final version comprised 17 discipline-based technology areas, which were further broken down by subareas and then technology types within the subareas. The taxonomy is a foundational element of NASA's technology management process. NASA's mission directorates reference the taxonomy to solicit technology development proposals and to inform decisions on NASA's technology policy, prioritization, and strategic investments. [33] The Technology Taxonomy also provides the organizing structure for NASA's technology tracking database TechPort, which makes data on more than 12,000 technology projects searchable and available to the public.[36]

NASA uses the STIP to integrate priorities and inform technology investment across all four mission directorates. Using input from the National Research Council and from each mission directorate on technology requirements for the next 20 years, the STIP categorizes technology investment priorities for the agency-wide technology portfolio. The STIP also details NASA's four guiding principles for technology investment: 1) balance investments across all technology areas; 2) balance investments across all levels of technology readiness; 3) balance investments across the three investment categories—Critical, Enhancing, and Transformational; and 4) provide transparency to the public. In the prior OCT's assessments of NASA's technology portfolio, these guiding principles serve as a measure of how well the portfolio reflects appropriate technology investment.

Whereas the strategic integration activity represents OTPS efforts to inform and guide technology development internal to NASA, OTPS's science and technology (S&T) partnership activity represents external coordination among government agencies, by identifying capabilities and technologies of mutual interest. The main output of this activity is participation in the S&T Partnership Forum to identify technology solutions to joint challenges. Established in 2015, this forum is an interagency initiative to strategize synergistic technology development across space agencies. As an informal collaboration between NASA, the Department of Defense, and the Intelligence Community, the forum enables joint capability studies, sharing of technology roadmaps, and Technical Interchange Meetings focused on S&T topics of mutual interest,[37] such as in-space assembly technologies[38] and trusted autonomy.[39] Through its participation in the forum, OTPS helps NASA optimize its partnerships and technology investments, by facilitating the sharing of resources, reducing duplication in technology development, and coordinating expert inputs on technology development needs.[40]

Finally, OTPS coordinates and promotes innovation among NASA's own expert workforce. The prior OCT's innovation activity sought to stimulate progress in unanticipated areas of technology development. The goal of this activity was "to transform diverse ideas into value" among NASA's workforce.[41] To connect NASA's workforce to tools and strategies that may increase the pace of innovation, OCT used a five-part innovation framework: 1) *clarify the need* by defining challenges to increase the diversity of ideas; 2) *assess the ecosystem* by developing mechanisms to determine who and what can help address the challenges; 3) *define the future state* by expanding the vision to sustain innovation and establish the "why"; 4) *develop, communicate, and coordinate experiments* focused on learning; and 5) *share lessons learned* to ensure we fail smart. Using this framework, OCT activities produce such outputs as an agency-wide cloud-based innovation portal; risk leadership strategies to assess NASA's risk portfolio; co-opetition challenges, combining the best aspects of competition and collaboration; and innovation experiments, to promote the mindset among NASA's workforce that failure provides valuable knowledge and a tool for future success.

Across these three activities, OTPS enhances the use of foresight in technology development at NASA. OTPS coordinates and uses inputs from a broad community of experts, both internal and external to NASA, to inform decision making for technology plans, investments, and partnerships. OTPS advises and advocates for innovative technology development that pushes against the boundaries of unforeseen challenges, while also promoting the synergistic development of technologies to address known challenges. OTPS provides the agency-level view of what technology opportunities and challenges are possible now and in the anticipated and unanticipated future.

Conclusion

This chapter concludes with considerations for organizations in defense, security, and other technology-driven industries who want to operationalize foresight in their own strategic technology development.

We note that some elements of NASA's approach to foresight are unique to NASA's goals and challenges. For example, because NASA's goals are rooted in the advancement of science and exploration, foresight is embedded in every activity by default. NASA is positioned to consistently push the boundaries of the unknown, whether it is a new scientific discovery or a new milestone for humankind. Therefore, ensuring that technology development plans are resilient to the discovery of new opportunities or challenges is a necessary component of every strategic approach.

In a second and related example, NASA faces some technological challenges that are not a concern for other organizations. Much of NASA's technology development must account for the harsh effects of the space environment on both the technology itself and on the human body. Many NASA space missions also involve travelling and communicating over orders of magnitude longer distances than any activities conducted on Earth. Therefore, NASA's technology development plans are likely designed to address different unforeseen challenges than would concern other organizations.

Finally, NASA must communicate its use of foresight to a broad audience, from the Administration and Congress to the general public. Given NASA's role of making history with exploration and discovery, while also encouraging STEM interests among the general public, NASA's plans for technology development are consistently and widely under scrutiny. Therefore, NASA's ability to clearly articulate the use of foresight in its plans might not reflect a need among organizations with activities that are less public.

Despite these differences, we suggest that organizations in technology-driven industries can benefit from adopting elements of NASA's approach to using foresight. In particular, we recommend the institution of an independent office to ensure that technology development accounts for anticipated and unanticipated challenges and opportunities 10 to 30 years away. We recommend three actions while creating this office:

1. *Ensure the office functions independently of the entities who perform the technology development.* Part of the success of OTPS is its ability to objectively assess how the mission directorates align with agency guidance for technology investment and prioritization. The prior OCT also assessed the extent to which the agency-wide technology portfolio is evenly balanced and offered recommendations to address an imbalance within any mission directorate. We anticipate that other technology-driven industries can benefit from ensuring that this coordinating office remains neutral in its decisions and guidance.
2. *Empower the office with an advisory role.* As an independent office that coordinates inputs from a broad community of expertise, OTPS is in a position to give objective expert advice about technology development to entities both within and outside NASA. Other organizations can benefit from instituting a similarly central office for coordinating and providing expert advice on technology development.
3. *Direct the office to engage with communities of experts.* The breadth of the community involved will differ by different organization needs, but every organization requires some level of expert input to inform the decisions that ultimately enable a foresight-driven approach to technology development.

By instituting a similarly independent office to coordinate, facilitate, and advise in respect to technology development, other organizations can build resilience into their technology development plans, so that they might account for anticipated and unanticipated opportunities and challenges.

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