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# Technology for Human & Robotic Exploration And Development of Space (THREADS) Strategic Research and Technology Road Maps Overview

by

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## ABSTRACT

A diverse family of technologies must be developed and demonstrated in order to enable the safe, affordable and effective human and robotic exploration and development of space. These technologies have the potential to enable a wide range of revolutionary new capabilities for space exploration and development. Opportunities include space resources development, space utilities and power, human habitation and bioastronautics, space assembly, inspection and maintenance, surface exploration and expeditions, and space transportation. In addition, the THREADS road maps provide for systems studies to guide these strategic research and technology investments, as well as technology flight demonstrations to validate the readiness (and likely cost) of emerging innovations in future applications.

A family of strategic research and technology road maps, outlining how these technologies might be advanced has been developed during 2000-2001. This paper outlines these road maps, emphasizing key needs in studies, research and technology, and technology flight demonstrations.

## INTRODUCTION

A wide-ranging family of technologies must be developed and demonstrated in order to enable the safe, affordable and effective human and robotic exploration and development of space. These technologies have the potential to enable a wide range of revolutionary new capabilities for space exploration and development. Opportunities include space resources development, space utilities and power, human habitation and bioastronautics, space assembly, inspection and maintenance, surface exploration and expeditions, and space transportation. In addition, the THREADS road maps provide for systems studies to guide these strategic research and technology investments, as well as technology flight demonstrations to validate the readiness (and likely cost) of emerging innovations in future applications.

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## BACKGROUND

Since the agency's creation, NASA has been a leader in efforts to pioneer the space frontier, working in collaboration with the international community to explore and develop space for the benefit of all humankind. These efforts have taken many forms. Within the Agency, it is the responsibility of the Human Exploration and development of Space (HEDS) Enterprise to define and implement future human space flight program opportunities. Similarly, it is the responsibility of NASA's Space Science Enterprise (SSE) to define and pursue future missions opportunities for robotic space exploration.

Collectively and collaboratively these organizations, their supporting NASA Field Centers and a host of industry, university and other participants frame and pursue US-sponsored space exploration (with the exception of Earth systems science studies).

## STEPPING STONES TO THE FUTURE

Current Agency planning does not revolve around a single exploration goal—as did the Apollo program of the 1960s. Instead, NASA aspires to send robots and humans safely and productively ever farther into our solar system, while enabling the commercial development of space. This vision may be characterized through a series of evolutionary scenarios—"stepping stones"—each of which entails progressively greater challenges, longer distances and duration, and greater discoveries and benefits.

Figure 1 summarizes this strategy (and some of the likely targets) for phased "stepping stones" for future robotic and human space exploration.

### Earth's Neighborhood

The first step is the Earth's Neighborhood (EN), which begins in low Earth orbit (LEO) and extends outwards to include GEO (geostationary Earth orbit), the Moon and the Earth-Moon Libration Points, and the nearby Sun-Earth Libration Points (at a distance of approximately 1,500,000 km). At present, this is the arena of greatest activity in space by far—including large-scale commercial activities, space science missions (e.g., the Hubble Space Telescope, HST) and human space flight programs (e.g., the Space Shuttle and the International Space Station, ISS).

During the next 5-10 years, NASA will continue to pursue privatization of Space Shuttle operations, while investing in upgrades and improvements to assure that the nation has safe and reliable human access to space until a replacement system is available. As the ISS becomes a reality, plans are under way to aggressively open the facility to commercial development. The Shuttle and the ISS will be the foundations for utilization and commercialization of Earth orbit. In addition, ever more ambitious space science missions will be deployed in the EN; these will likely include the Next Generation Space Telescope (NGST), and others.

Beyond the next 10 years, opportunities include possible "100 day class" mission activities on the Moon or at Earth-Moon and Sun-Earth Libration Points.[1] Libration Points (where gravitational forces balance) could be used as sites for planned post-NGST telescopes, or as launching points for voyages farther into space using infrastructures valuable to both exploration and commercial development. A return to the Moon, by robots and human explorers, would continue its exploration, enable unique science on and from its surface, and test technologies for later commercial development and continuing exploration. The new capabilities needed for these future exploration missions in the EN may enable the expansion of knowledge and to provide an experience base from which we can reduce the cost and risk of further explorations.

Beyond Earth's Neighborhood

NASA continues to undertake an ambitious portfolio of robotic space science missions beyond the Earth's Neighborhood (EN). In the near-term, these include planetary programs such as the ongoing Mars Exploration Program (MEP), the Cassini probe to Saturn, and many others. The MEP is particularly challenging and should result within the decade in the return of samples from Earth's sister planet.

In the far term, there is an even more exciting range of exciting mission opportunities beyond the EN. These include orbiters and landers to study at close range Europa, a moon of Jupiter, or Titan, a moon of Saturn, an many others.

Through space science mission payloads, Agency mission designers are currently learning about the surface of Mars robotically in preparation for integrated human/robotic missions early in the next century. Resolving fundamental questions about the history of Mars and the possible presence of past or present life elsewhere in our solar system may be compelling reasons for such future missions.

Also in the far-term, NASA envisions 500-to-1000 day class missions that could extend Mars exploration to include human explorers or sorties. These missions would expand human presence across the inner solar system and better investigate the possibility of extraterrestrial life, while making possible visionary new commercial space opportunities.

Moreover, the region of space between Earth and Jupiter, there are many tens of thousands of asteroids - some composed of valuable minerals, others of materials that could be used to make propellants, in space construction or commercial ventures. Advancing capabilities could make possible future human/robotic sortie missions to these challenging and scientifically-interesting targets.

Sustained Campaigns of Exploration

Within the inner solar system—and at targets beyond—the long-term goals of robotic or human exploration are the same: where feasible, make possible affordable sustained campaigns of exploration. Only through the long-term, high-quality studies that continuing presence offers can we resolve the most profound and challenging of scientific questions.

Hence, options include robotic outposts on Mars, or in orbit around the outer planets. Also, as technology advances, even human space flight in the outer solar system—such as to Ganymede, a moon of Jupiter, or Titan, a moon of Saturn that has an atmosphere reminiscent of that of ancient Earth—might become possible later in this century. And, although unlikely in the coming decades, during this century technology may open the way for major robotic probes beyond the very edges of our solar system.

[1] Libration Points are locations in space where the gravitational forces of two bodies, such as the Sun and Earth, along with the acceleration (due to motion) of smaller bodies, such as space vehicles, are in balance.

## TECHNOLOGY FOR HUMAN/ROBOTIC EXPLORATION AND DEVELOPMENT OF SPACE

By examining in greater detail the stepping stone strategy characterized in the previous section, systems analysis studies yield a series of strategic research and technology (R&T) challenges: technical metrics (or measures) that allow progress in competing areas of R&D to be evaluated and compared. Figure 2 captures just a few of these technical metrics—"strategic technology chellanges"—stated in terms of the various stepping stones discussed above.

Attempting to catalog the resulting array of technologies is a daunting undertaking. In order to pursue this objective, a systematical, hierarchical work breakdown structure (WBS) has been formulated for THREADS. At the highest level, this WBS embraces three areas: Sysetms integration, analysis, concepts and modeling; enabling advanced research and technology; and technology flight demonstrations. Figure 3 illustrates this high-level WBS. Within each of these areas, a further array of individual programmatic themes and elements has been defined.

The following paragraphs summarize the goals and objectives of the several advanced research and technology (R&T) themes that comprise THREADS.

### Systems Studies, Concepts and Modeling

Pursuing systems studies, advanced concepts, modeling, etc., is intended to make possible the optimization of the investments made in technology for human/robotic exploration and development of space. In addition, these efforts should also identify and refine advanced system and architecture concepts that can dramatically increase the safety and reliability -- and reduce the cost -- of ambitious future human exploration missions and campaigns beyond Earth orbit. Finally, by pursuing these strategic studies in collaborations involving diverse NASA and non-NASA innovators, they should help to establish a foundation of relationships with the science community and potential commercial or international partners for future exploration activities. Specific objectives are to:

- Conduct advanced concepts studies to create and/or identify innovative new approaches to human exploration and the development of space;
- Identify and mature new, highly promising modeling tools for use in system and architecture and mission studies;
- Conduct detailed, end-to-end mission architecture studies incorporating the most promising new systems and infrastructure concepts;
- Identify and examine opportunities / issues associated with the future commercial development of space; and,
- Define and refine strategic research and technology road maps to provide ongoing guidance to technology development efforts.

Figure 4 provides a summary of the hierarchy of challenges that must be addressed in the area of systems analysis, integration and modeling. Some of the most important of these challenges include: advanced concepts definition, systems analysis, modeling and mission architecture studies.

### Space Resources Development

The basic purpose for the space resources development (SRD) theme is learning how to be self-sufficient in space. This involves advancing the goals of:

- Driving down the cost of human/robotic exploration missions and campaigns;
- Supporting improved health/safety for human explorers beyond Earth orbit; and
- Work collaboratively with the space science community to test concepts and technologies

Pursuing these goals, entails progress in a number of specific objectives, such as to:

- Develop and validate the technology to utilize local resources, such as Regolith /

Minerals, Ices and Atmosphere -- in order to

- Produce, process and deliver consumables, such as Propellants -- storable and cryogenic; Life Support and other gases; Water;
- Fabricate key physical structural systems/elements from local materials, including Radiation shielding; Structural elements (e.g., trusses, panels, etc.), and Mechanical spares for mission system elements;
- Enable local fabrication of selected "finished products" and/or "end-items", such as Photo-voltaic cells and solar arrays, Wires, tubes, connectors, etc., and pressurized volumes; and,

And to...

- Test key technologies and demonstrate innovative new systems concepts in space; and,
- Establish a foundation for profitable commercial development of solar system resources in the mid- to far-term.

Figure 5 summarizes the various challenges that must be addressed in the area of space resources development. Some of the most important of these challenges include: in situ resource excavation and separation; resource processing and refining; and in situ manufacturing.

Space Utilities and Power

The vision of the Space Utilities and Power (SUP) theme within the THREADS road maps is the assure that abundant, affordable energy is available for future explorations... wherever (and whenever) needed. In support of this vision, goals for the theme include: working with appropriate NASA and external organizations to identify and establish robust sources for abundant power for in-space, surface and transportation systems for human/robotic exploration and development of space, while driving down the cost of human/robotic exploration missions and campaigns. Specific SUP theme objectives are to:

- Develop and validate technology for a range of power levels/requirements, such as
  - Platforms
  - Space Transportation
  - Mobile Surface Systems
  - Various other systems (e.g., Habitats, EVA Systems, etc.)
- including ...
  - Solar Power Systems
  - Nuclear Power Systems -- for surface and in-space power applications
  - Wireless Power Transmission Systems
  - Energy Storage Systems

And to...

- Test key technologies and demonstrate innovative new systems concepts in space
- Establish a foundation for commercial space power systems and/or applications in the longer-term

Figure 6 provides a summary of the hierarchy of challenges that must be addressed in the area of space utilities and power. Some of the most important of these challenges include: solar power generation, nuclear power generation, wireless power transmission and cryogenic propellant depots.

Habitation and Bioastronautics

The vision of the Habitation and Bioastronautics (HAB) theme is to learn how to live and work in deep space safely and affordable, and for extended periods of time. One of the goals that emerges from pursuing this vision is that of assuring robust and reliable capabilities to support health and safety of human explorers during long-duration space missions and operations. Another is to drive down the cost of human exploration missions and campaigns beyond Earth orbit, while developing and demonstrating critically-needed capabilities for human activities in space. Specific objectives for the HAB themes are to:

- Develop innovative new approaches and technologies to

- Determine and mitigate the risks to human explorers of the radiation environment beyond Earth orbit;
- Determine and mitigate the risks to human explorers of long-duration exposure to partial-/micro- gravity;
- Enable long-term, regenerative life support systems -- addressing toxicity, bio-hazards, and environmental monitoring and control; and
- Enable innovative, affordable and highly operable new technologies for extra-vehicular activity (EVA) systems and advanced space habitation systems.

And to:

- Test key technologies and demonstrate innovative new systems concepts in space;
- Establish a foundation for commercial space human systems/applications.

Moreover, the development of the strategic road maps of the HAB themes helps promote the close coordination among researchers (e.g,, with the Office of Biological and Physical Research (OBPR)), technologists and systems developers/operators.

Figure 7 indicates the several challenges that must be addressed in the area of habitation and bioastronautics. Some of the most important of these challenges include: partial/low gravity adaptation and countermeasures; radiation biological risk prediction and mitigation, advanced habitation systems and extravehicular activity systems.

Space Assembly, Inspection and Maintenance

The vision of the Space Assembly, Inspection and Maintenance (SAM) theme within THREADS is to enable a broad range of future design choices through robust and flexible operations. Hence, a primary goal for SAM is to enable a much more robust set of options for affordable implementation of ambitious new modular space systems and missions, while driving down the cost of exploration missions and campaigns beyond low Earth orbit. Specific objectives are to:

- Develop and validate technologies for the space assembly of large systems -- including both science mission systems (e.g., observatories) and human operational systems;
- Enable autonomous and/or tele-presence systems inspection;
- Advance remote or shared control of these capabilities in near-Earth and interplanetary space;
- Develop and validate the capability to extend the life and reduce the costs of a new generation of space systems through repair, refueling, upgrades and re-use of components from one system to another;
- Minimize the impact of space system failures by enabling easy access for repair -- thus reducing system-level functional redundancy (and associated costs);
- Enable a reduction in the total mass launched to orbit for given mission architectures;
- Test key technologies and demonstrate innovative new systems concepts in space; and,
- Establish a foundation for commercial space assembly, inspection and maintenance systems and services in the mid- to far- term.

Figure 8 provides a summary of the challenges that must be addressed in the area of space assembly, inspection and maintenance. Some of the most important of these challenges include: in-space assembly and construction; in-space system deployment; autonomous rendezvous and capture (and self-assembling systems); inspection and diagnostics; and servicing maintenance and repair.

Exploration and Expeditions

The vision of the Exploration and Expeditions (ExE) theme within THREADS is to make it possible for future space exploration to pursue profound science and share the experience. A principal goal is to promote collaboration among researchers and technologists in several organizations (such as the Space Science Enterprise, the Human

Space Flight Enterprise, and others) to enable future human and robotic exploration missions to effectively address -- and at a fundamental level -- the "grand" science challenges facing NASA. Other goals include driving down the expected costs of human/robotic exploration missions and campaigns beyond low Earth orbit, while sharing the experience of exploration with the public. Specific objectives are:

- Through partnership among HEDS, SSE and other organizations, develop and validate the capability to gain sub-surface knowledge and access -- both remotely and through sampling -- ranging down to 1000s of meters
- Enable safe and affordable human exploration of lunar, planetary and other surfaces -- locally as well as over global distances involving traverses of up to 1000s of kilometers
- Integrate and validate the technologies needed to revolutionize public engagement in "virtual exploration" -- ranging from higher rate communications, to the creation of virtual reality simulations, to innovative human-machine interfaces
- Test key technologies and demonstrate innovative new systems concepts in space
- Establish a foundation for commercial space exploration markets -- at a pace consistent with market place prospects

Figure 9 provides a summary of the hierarchy of challenges that must be addressed in the area of surface exploration and expeditions. Some of the most important of these challenges include: surface systems; subsurface access and knowledge; virtual exploration; and, control and communications.

<u>Space Transportation</u>

The overriding vision of the Space Transportation (STR) theme in THREADS is to enable future explorations to "get there and back--safely and affordably. The primary goal of this road map is to assure that decisions are made to pursue future space exploration and development goals, the transportation technology is available. This goal involves identifying and developing new space technologies that can significantly increase the safety and reliability of future human and/or robotic exploration missions and campaigns beyond Earth orbit, while reducing their costs. Specific objectives are to:

- Identify and refine human/robotic exploration and development of space requirements for new, highly promising options for very low-cost Earth to orbit (ETO) transportation;
- In partnership with NASA and non-NASA organizations, develop and demonstrate the technologies needed to assure that future human exploration in-space transportation systems are safe and "robustly" reliable;
- And ... develop and validate technologies for the affordable transportation to -- and from -- targets in space beyond LEO;
- Enable reliable and affordable transportation to all points of interest globally on the Moon or Mars; and,
- Establish a foundation of advanced transportation infrastructures needed to enable future commercial development of space in the mid- to far-term.

By framing these roadmaps, THREADS should make it possible for various organizations to work more effectively together, including NASA's Aero-Space Technology Enterprise, Space Science Enterprise, and Human Space Flight Enterprise.

Figure 10 provides a summary of the hierarchy of challenges that must be addressed in the area of space transportation—including ETO transportation, in-space transportation and excursion transportation. Some of the most important of these challenges include: ETO propulsion; in-space propulsion (including electric and chemical); vehicle airframe and structures; vehicle aero-maneuvering (aero-braking, aero-entry, etc.); and, vehicle subsystems (including avionics).

In addition, the THREADS road maps provide for technology flight demonstrations to validate the readiness (and likely cost) of emerging innovations in future applications.

Technology Flight Demonstrations

The goal of technology flight demonstrations (TFDs) in THREADS is to validate critical candidate emerging technologies at a systems level to better inform management and policy-maker decisions concerning costs, schedules and uncertainties. Some potential TFDs that could be pursued during the coming years include:

- Infrastructure for the assembly /and/or construction of large space observatories, very large communications satellies, etc.;
- Revolutionary space solar power, enabling "beamed power" to locations of interest on the Moon, Mars, etc
- Affordable transportation in the Earth's; neighborhood and beyond;
- Mega-Communications Satellites;
- Integrated human/robotic terrestrial and lunar test beds to validate technologies for safe, long-term human/machine outposts capable of global explorations; and,
- Revolutionary in space infrastructures that can support affordable interplanetary transportation and space industrialization.

Figure 11 provides a summary of the challenges to be addressed in the area of technology flight demonstrations. These include nearer-term challenges, such as defining strong TFDs to be pursued and the integration (and flights) of smaller technology flight experiments. In addition, the WBS includes options for TFDs in support of each of the several phases of the "stepping stones" strategy—beginning with the Earth's Neighborhood.

## A ROAD MAP TO FUTURE SPACE EXPLORATION AND DEVELOPMENT

Effective long-range planning is impossible without some clear ideas about the time frames during which goals and objectives are to be pursued. The goals and objectives encompassed by THREADS are tremendously ambitious. As a result, the concept of recurring "cycles of innovation" is essential to the THREADS approach. These cycles—which parallel the "stepping stones" discussed earlier—propose successive opportunities for revolutionary new technologies to be drawn from the laboratory for testing in space or in ground test beds and prototypes. Figure 12 synthesizes these themes to frame a far-reaching strategic R&T road map for THREADS.

## CONCLUSIONS

NASA hopes to work with the international community to achieve truly profound goals in space exploration and development during the next several decades. In so doing, we can make possible startling discoveries in space science—and someday the permanent extension of human presence beyond the bounds of Earth and enable historic improvements in the quality of life and in our understanding of the solar system and the universe. These visionary goals will be enabled by achieving ambitious goals and objectives in advanced new technologies for the human and robotic exploration and development of space.

A key purpose of the THREADS strategic R&T road maps is to provide a needed framework for coordinating R&D activities across a wide variety of organizations. If this strategic road map is implemented, then during the next 25 years, we will:

- Pursue capability-focused technology R&D in government-industry partnerships—enabling exploration and commercial space goals to support one another through the development of important new systems and infrastructure that can meet the needs of both;
- Define breakthrough concepts for affordable exploration campaigns in the far term while robotic sortie missions lead the way in collecting data, demonstrating technologies and setting in place continuing operations at key sites;
- Address fundamental scientific questions in biology, in medicine, in materials, in engineering and other areas, and to facilitate solving the challenges of microgravity and radiation for long-duration human space flight;

- Utilize the International Space Station to validate new generations of space capabilities;
- Transform relationship with students, faculty, industry and the public by engaging them broadly in setting goals for the exploration and development of space; and,
- Make possible dramatic increases in discovery, scientific knowledge and human accomplishment through international partnerships in robotic and human exploration missions.

These road maps enable can us to advance ambitious concepts for the future robotic and human exploration and development of space. Through THREADS, NASA, the US, and international organizations can plan and make coordinated progress toward important long-term goals for civilian space programs.

## GLOSSARY OF ACRONYMS

| | |
|---|---|
| **ASTP** | Advanced Space Transportation Program |
| **AU** | Astronomical Units |
| **CPD** | Cryogenic Propellant Depot |
| **DRP** | Design Reference Point |
| **EN** | Earth's Neighborhood |
| **ESA** | European Space Agency |
| **ETO** | Earth-to-Orbit |
| **EVA** | Extravehicular Activity |
| **ExE** | Exploration and Expeditions |
| **GEO** | Geostationary Earth Orbit |
| **GRC** | (NASA) Glenn Research Center |
| **HAB** | (Human) Habitation and Bioastronautics |
| **HEDS** | Human Exploration And Development Of Space |
| **HLLV** | Heavy Lift Launch Vehicle |
| **HST** | Hubble Space Telescope |
| **Isp** | Specific Impulse |
| **ISS** | International Space Station |
| **LEO** | Low Earth Orbit |
| **L-Point** | Libration Point |
| **MEO** | Middle Earth Orbit |
| **MEP** | Mars Exploration Program |
| **MSFC** | (NASA) Marshall Space Flight Center |
| **NASA** | National Aeronautics and Space Administration |
| **NGO** | Non-Governmental Organization |
| **NGST** | Next Generation Space Telescope |
| **R&D** | Research and Development |
| **R&T** | Research and Technology |
| **SAM** | Space Assembly, Inspection and Maintenance |
| **SLI** | Space Launch Initiative |
| **SRD** | Space Resources Development |
| **SSE** | Space Science Enterprise |
| **SUP** | Space Utilities and Power |
| **STR** | Space Transportation |
| **TFD** | Technology Flight Demonstration |
| **THREADS** | Technology for Human/Robotic Exploration and Development of Space |
| **TRL** | Technology Readiness Level |
| **WBS** | Work Breakdown Structure |

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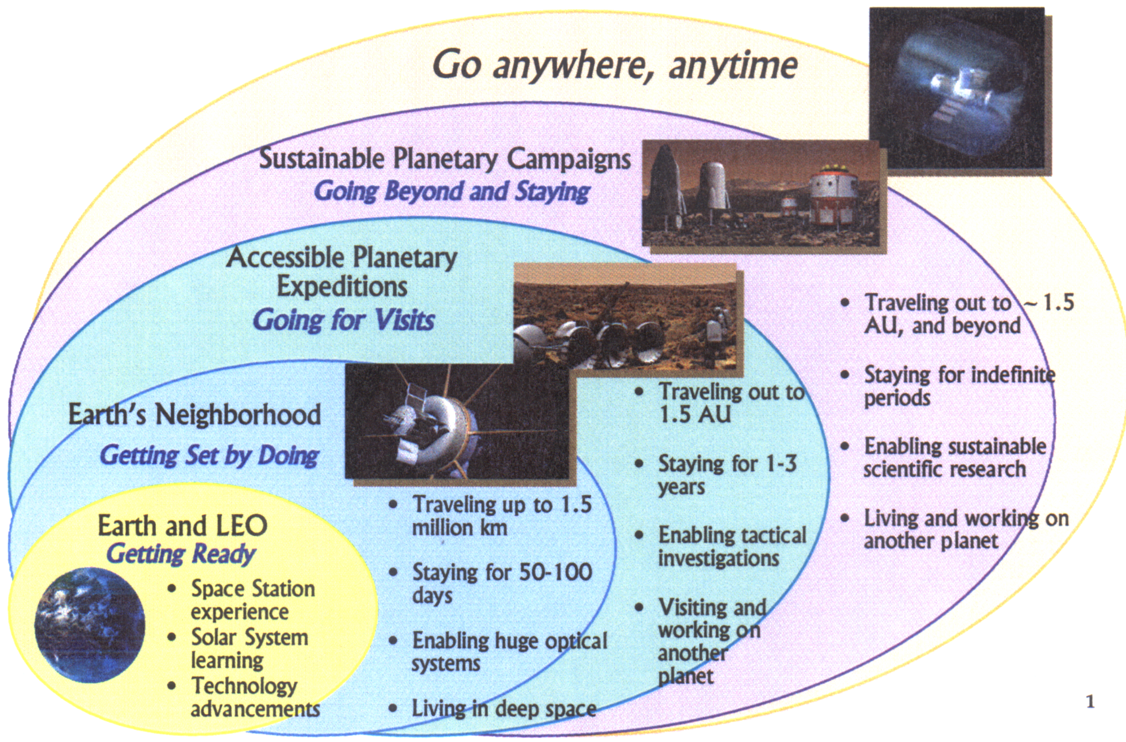


Figure 1 A "Stepping Stones" Strategy for the Future of Space Exploration

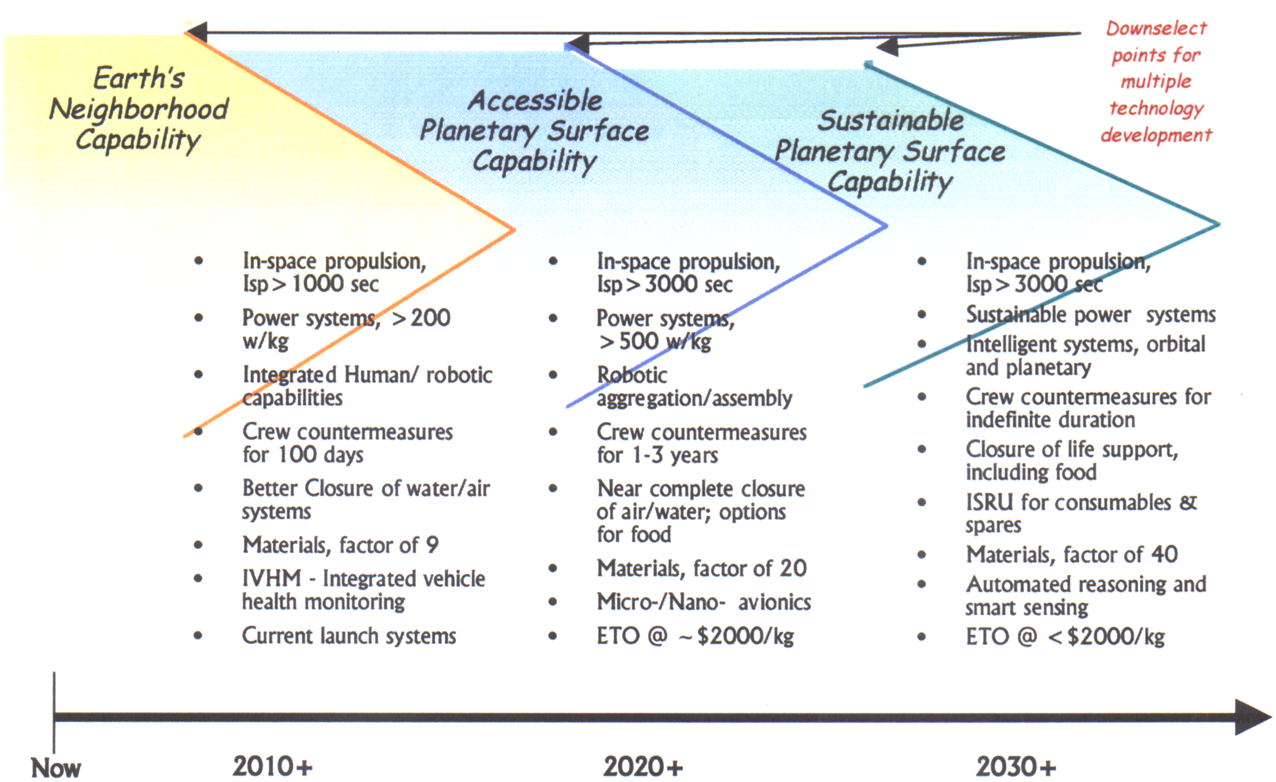


Figure 2 Strategic Technology Challenges for Future Human/Robotic Exploration and Development of Space

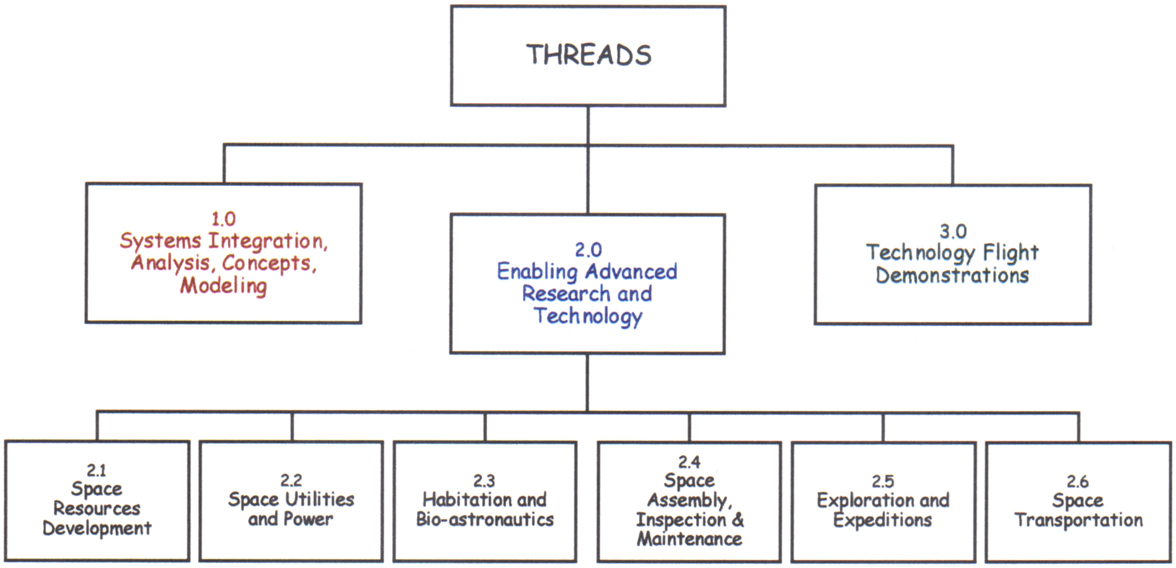


Figure 3 THREADS Strategic R&T Road Maps: High Level Work Breakdown Structure

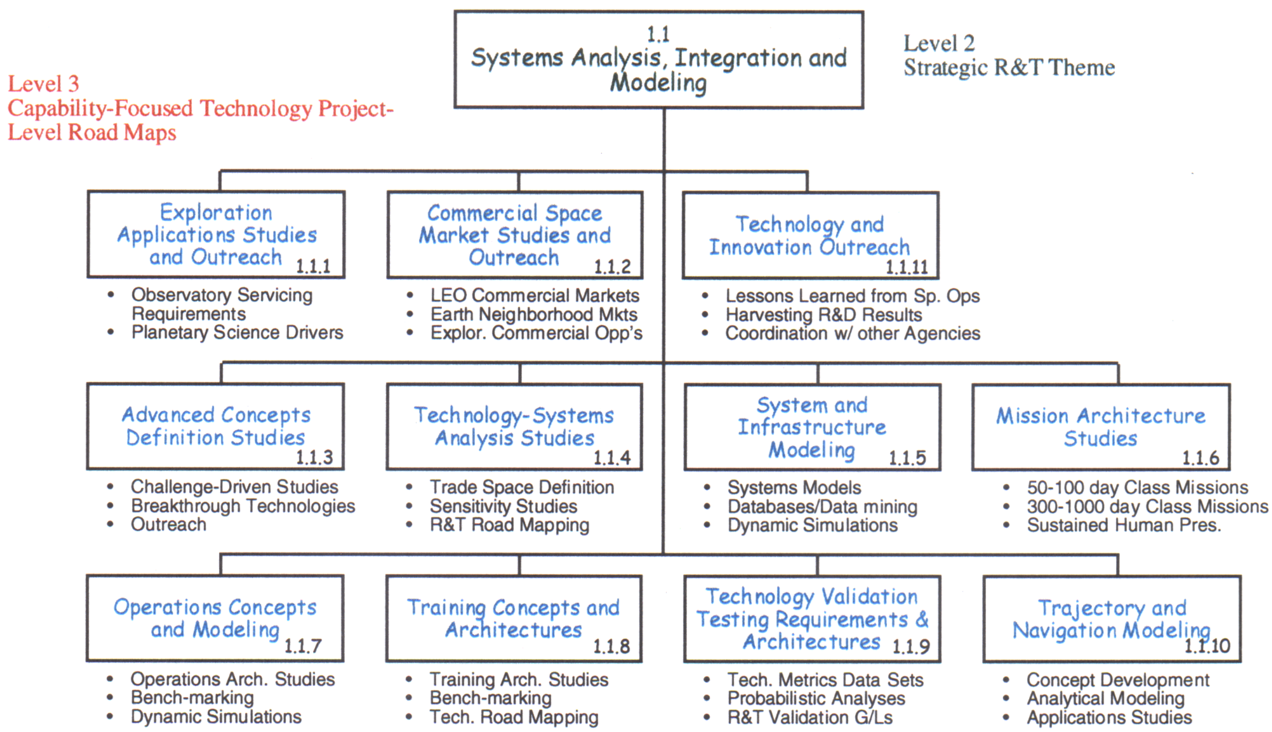


Figure 4 THREADS Strategic R&T Road Maps: Systems Analysis, Concepts and Modeling

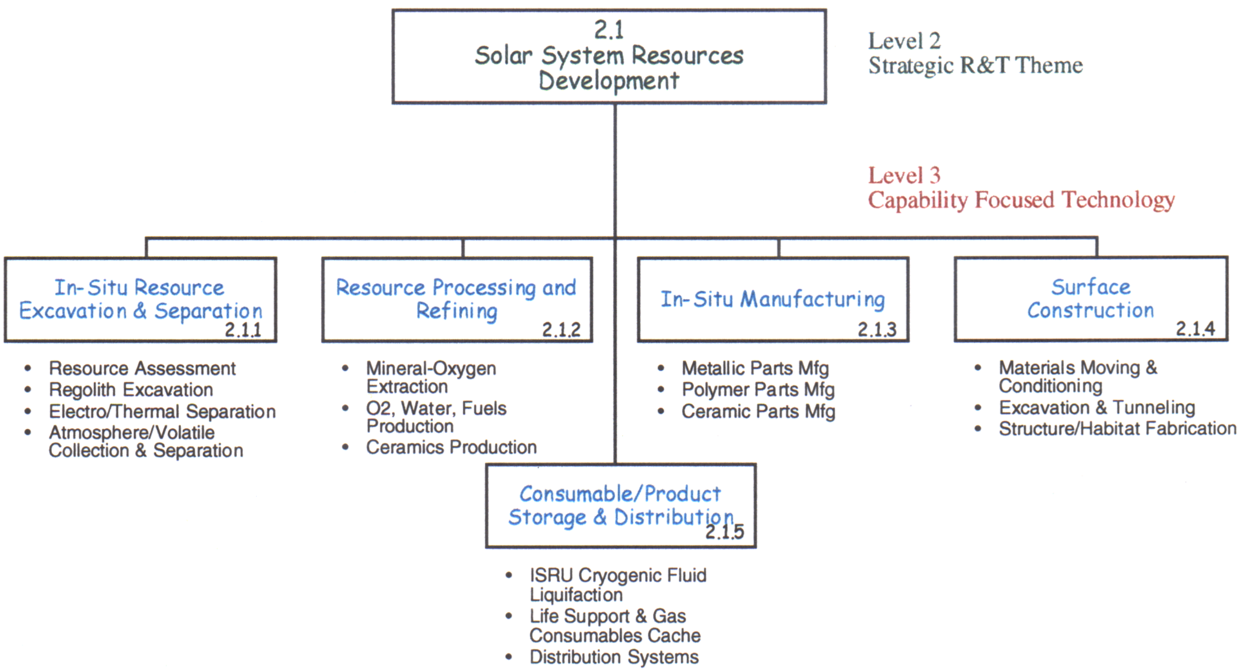


Figure 5 THREADS Strategic R&T Road Maps: Space Resources Development

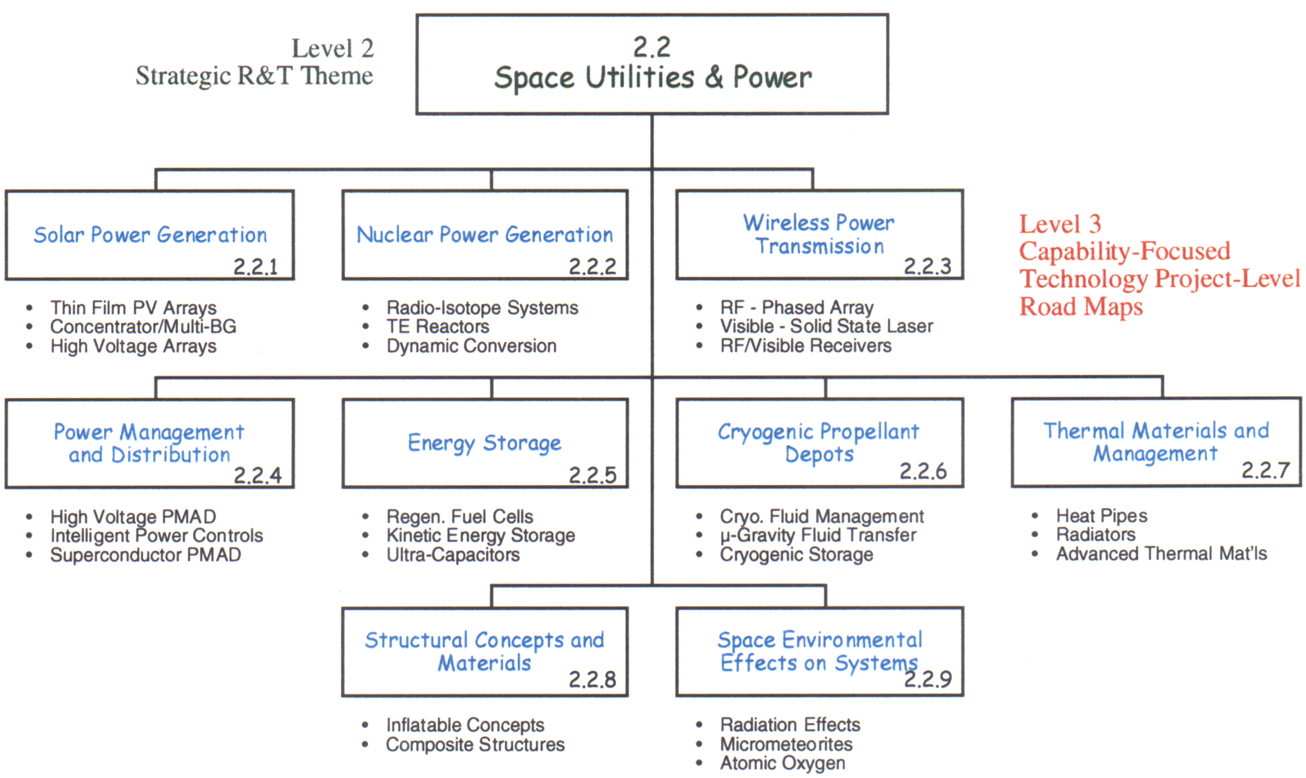


Figure 6 THREADS Strategic R&T Road Maps: Space Utilities and Power

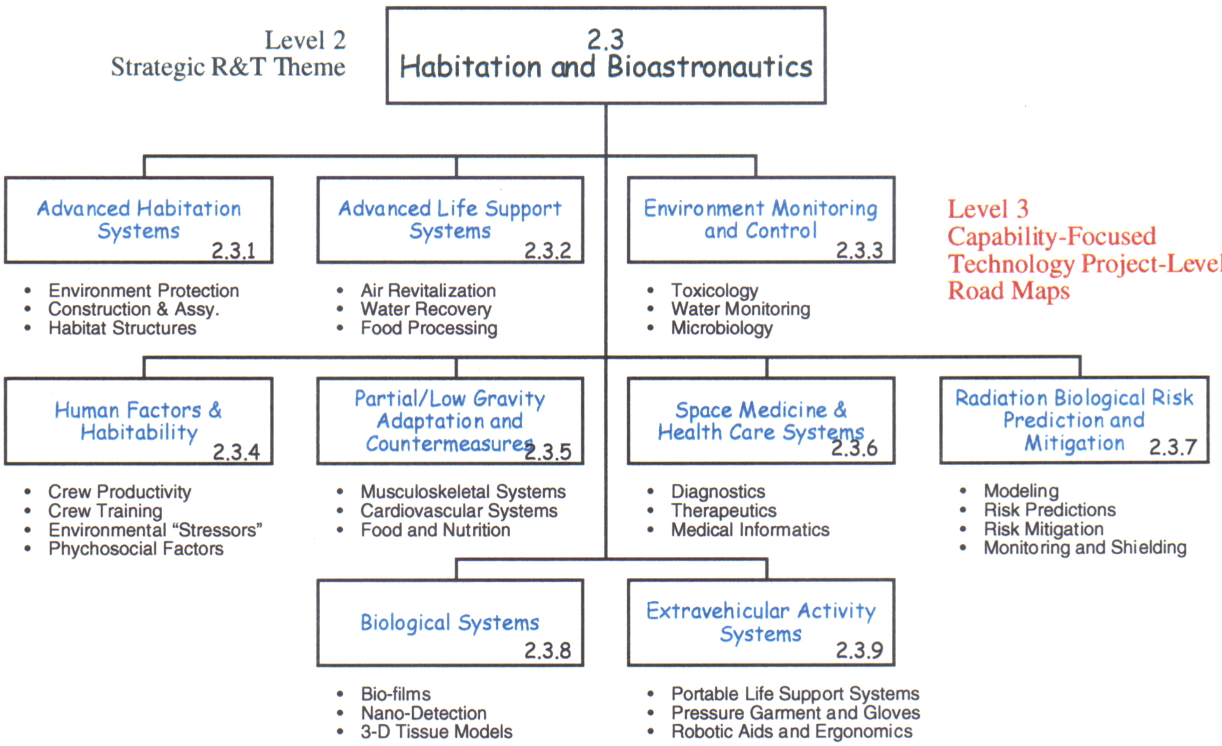


Figure 7 THREADS Strategic R&T Road Maps (Human) Habitation and Bioastronautics

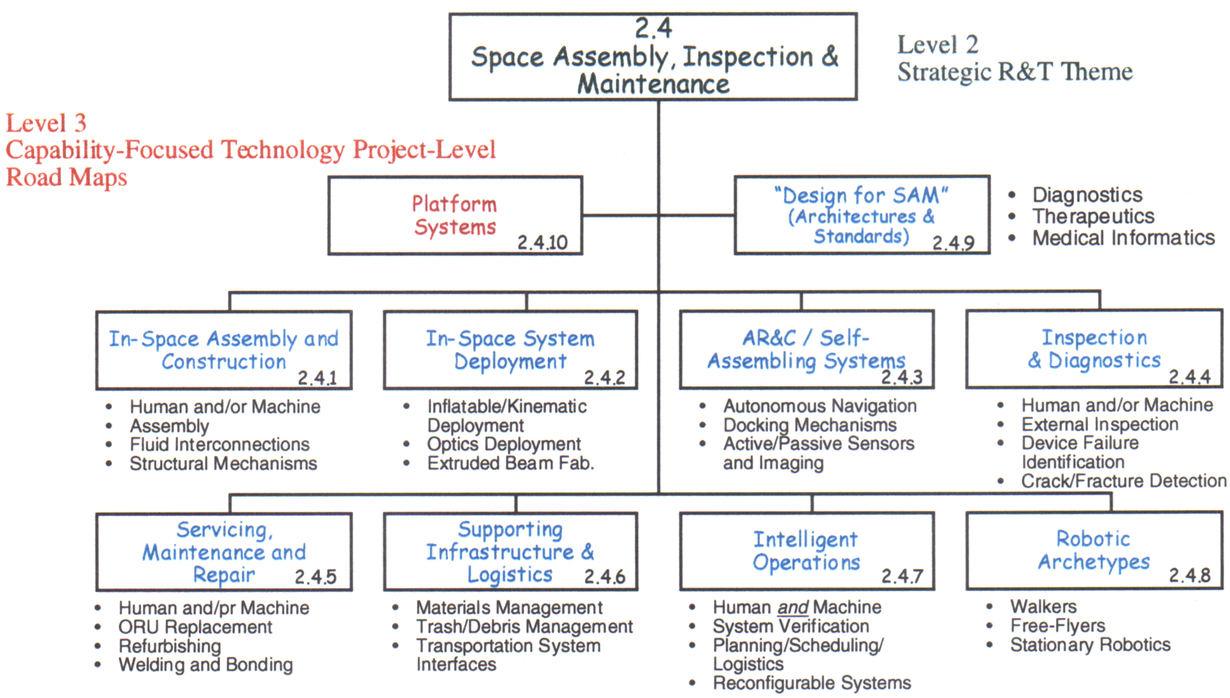


Figure 8 THREADS Strategic R&T Road Maps: Space Assembly, Inspection and Maintenance

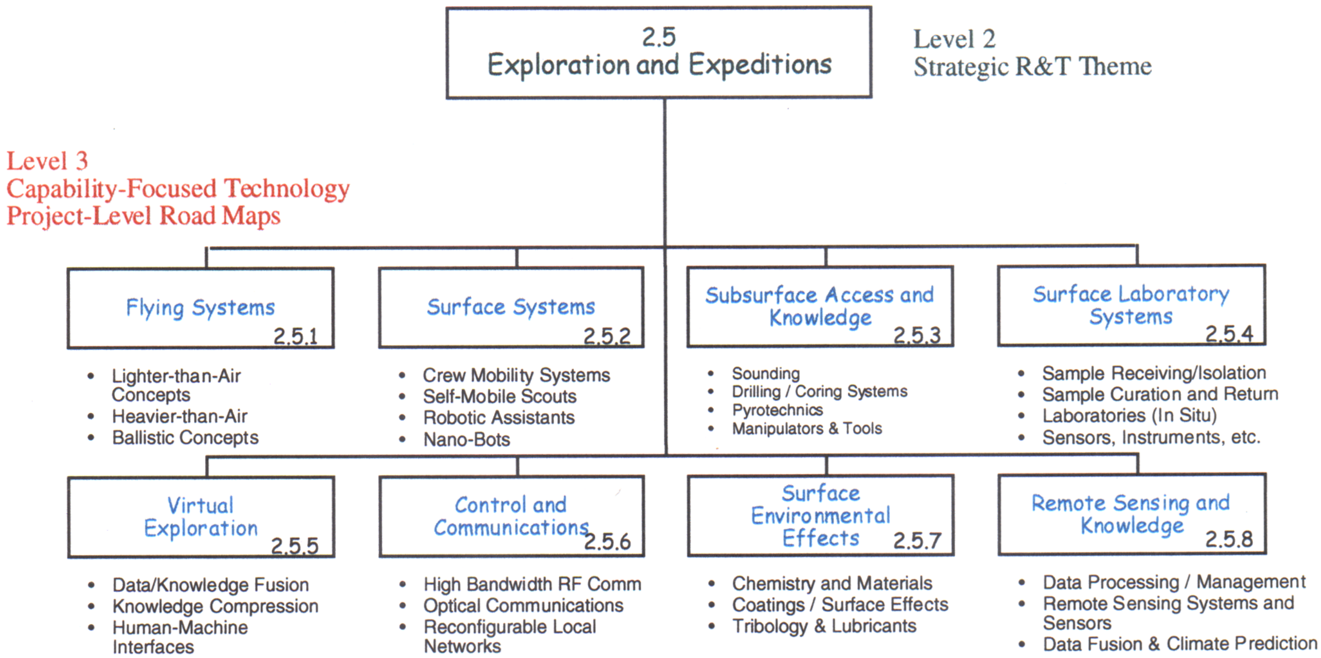


Figure 9 THREADS Strategic R&T Road Maps: Exploration and Expeditions R&T

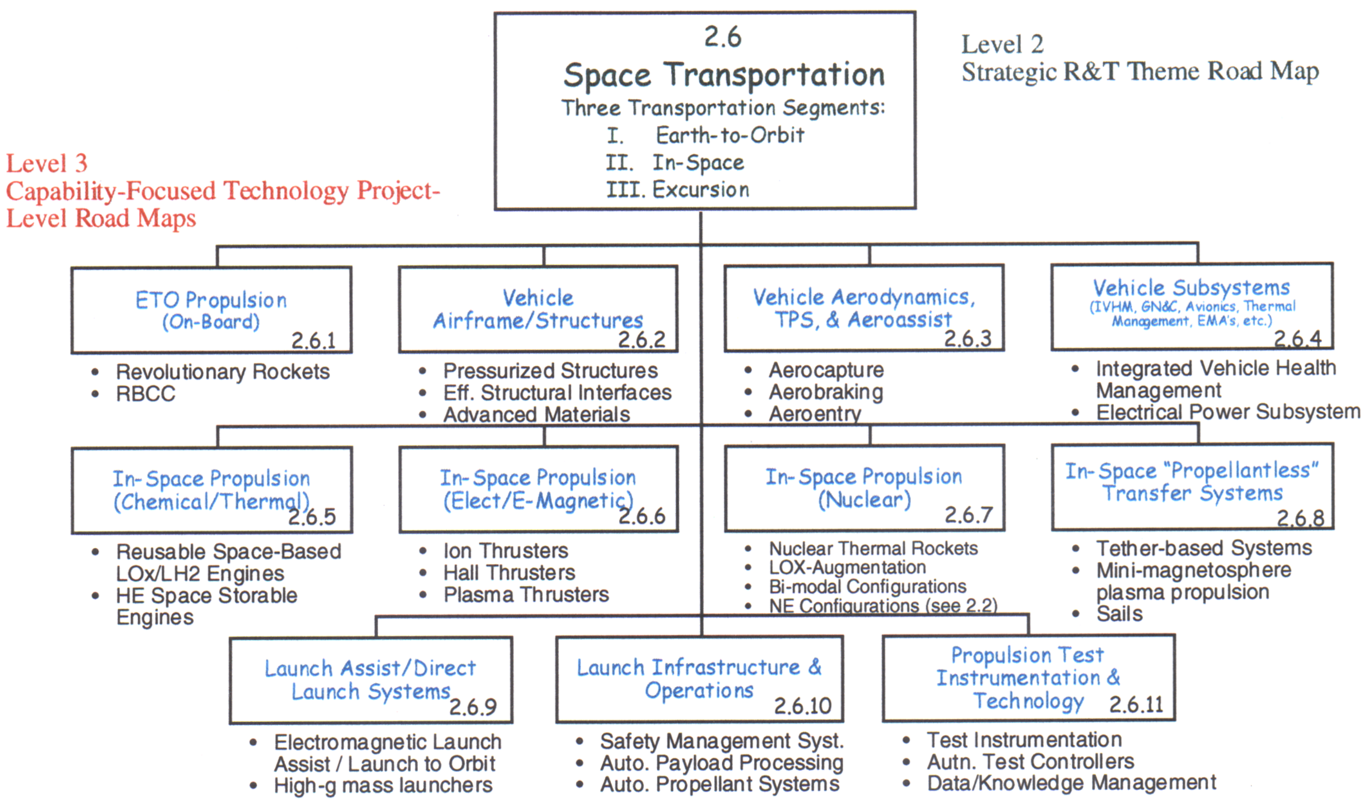


Figure 10 THREADS Strategic R&T Road Maps: Space Transportation R&D

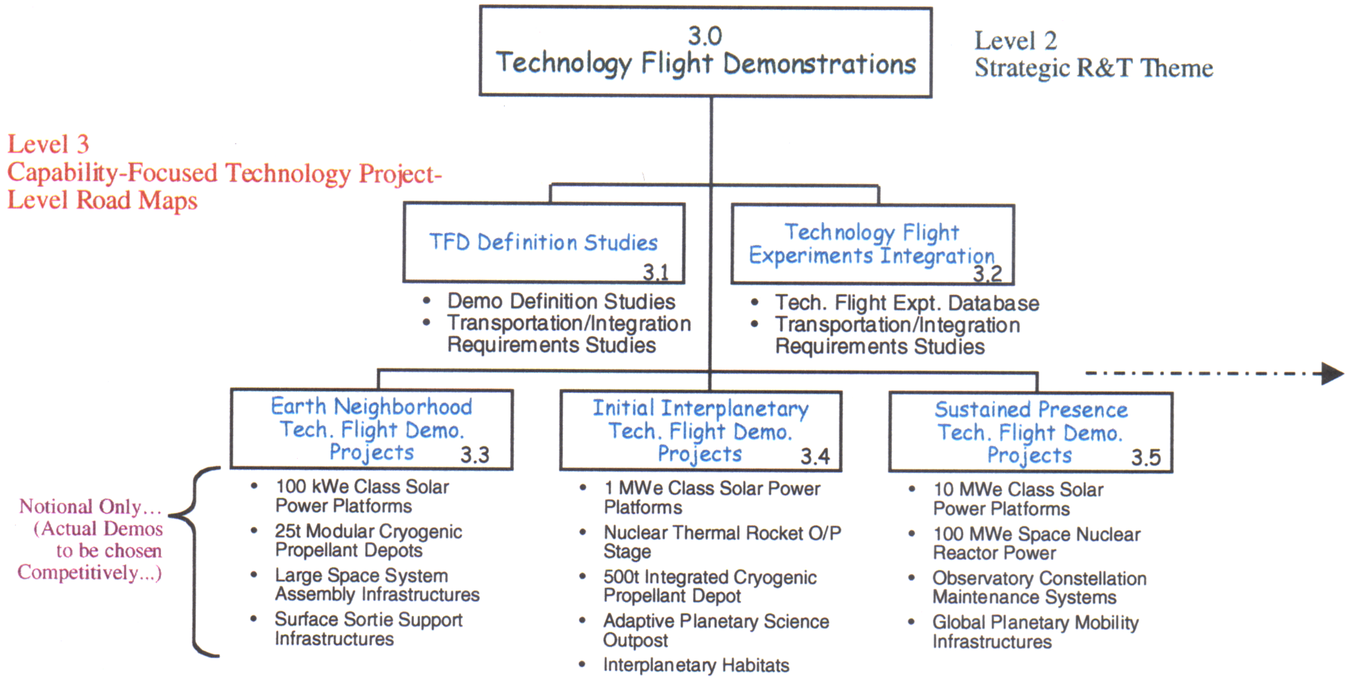


Figure 11 THREADS Strategic R&T Road Maps: Technology Flight Demonstrations

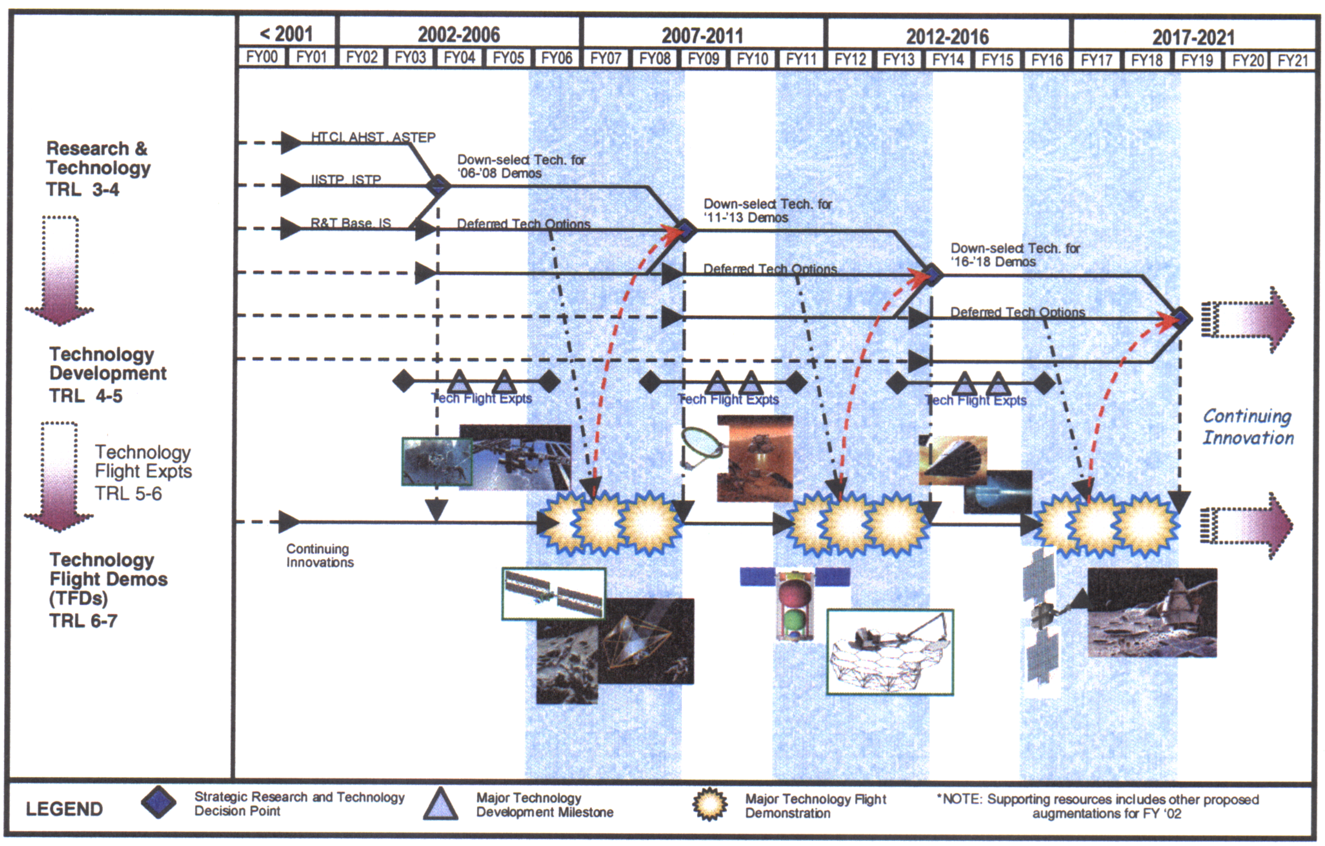


Figure 12 THREADS Time-Phased Strategic R&T Road Maps