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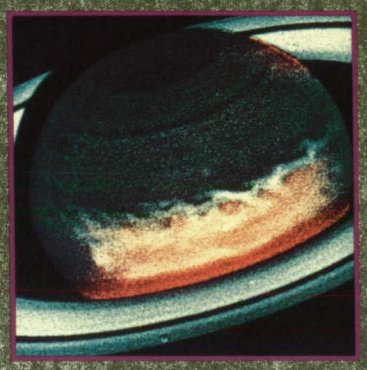
Advanced Technology for America's Future in Space



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A Review of NASA's Integrated Technology Plan for the Civil Space Program

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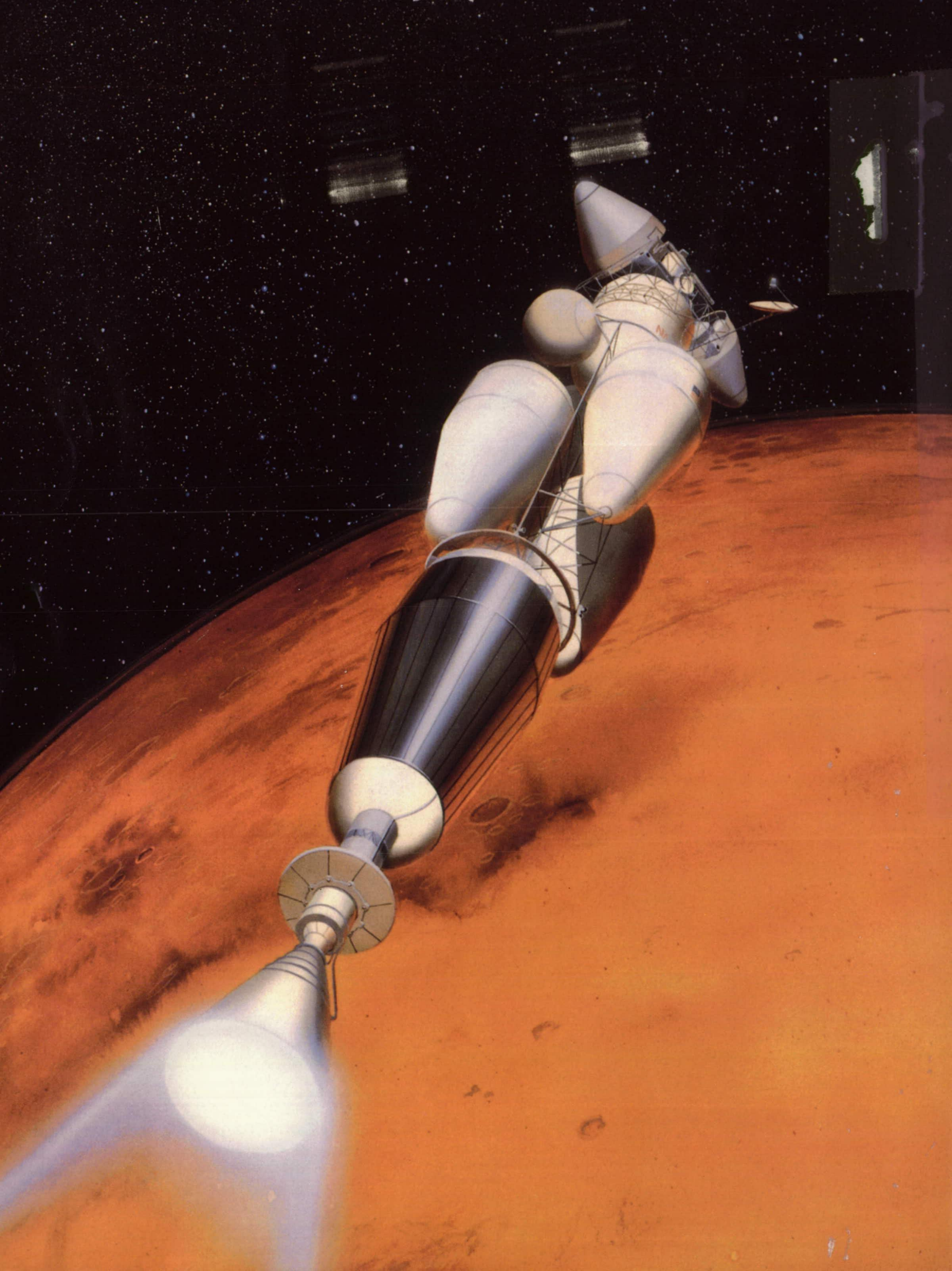
Space Systems and Technology
Advisory Committee
NASA Advisory Committee
Washington, D.C. 20546



Advanced Technology for America's Future in Space

A Review of NASA's Integrated Technology Plan for the Civil Space Program

Space Systems and Technology Advisory Committee
NASA Advisory Committee
Washington, D.C. 20546

Acknowledgements

The NASA Space Systems and Technology Advisory Committee (SSTAC) wishes to express its appreciation for the efforts of all of those who participated on the review team.

The SSTAC also expresses special appreciation for the participation of the representatives from the Department of Commerce, the Department of Energy, the Department of Defense, the Department of Transportation, and the Aerospace Industries Association in the external review of NASA's proposed Integrated Technology Plan for the Civil Space Program. Their contributions in establishing a National context were a significant factor in the overall effectiveness of the review.

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Introduction and Summary Recommendations

1.1 Introduction

The Advisory Committee on the Future of the U.S. Space Program, chaired by Mr. Norman Augustine, stated in Recommendation 8 of its report:

> *"That NASA, in concert with the Office of Management and Budget, and appropriate Congressional committees, establish an augmented and reasonably stable share of NASA's total budget that is allocated to advanced technology development. A two- to three- fold enhancement of the current modest budget seems not unreasonable. In addition, we recommend that an agency-wide technology plan be developed with inputs from the Associate Administrators responsible for the major development programs,* ***and that NASA utilize an expert, outside review process, managed from headquarters, to assist in the allocation of technology funds.****"*
>
> December 1990

In response to Recommendation 8 of the Augustine Committee Report, NASA's Office of Aeronautics, Exploration and Technology (OAET) has developed a proposed "Integrated Technology Plan for the Civil Space Program" that entails substantial changes in the processes, structure and the content of NASA's space research and technology (R&T) program.

On June 24 through 28, 1991, the Space Systems and Technology Advisory Committee (SSTAC, a subcommittee of the NASA Advisory Committee) and several other senior, expert, informed advisory groups conducted a review of NASA's proposed Integrated Technology Plan (ITP). This review was in response to the specific request in Recommendation 8 that "NASA utilize an expert, outside review process, managed from headquarters, to assist in the allocation of technology funds." This document is the final report from that review.

1.2 The External Review Team

The composition of the external review team was chosen to provide an expert examination of both the strategies proposed by NASA, as well as a detailed review of its specifically recommended research and technology efforts. The external review consisted of several plenary sessions and eleven specific technology panels, each of which examined one of the major technical discipline areas in the space R&T program. The review team included representatives from the following standing advisory committees and other experts:

- *The Space Systems Technology Advisory Committee (SSTAC)*, a subcommittee of the NASA Advisory Committee (NAC), as the primary organization responsible for organizing and conducting the review

- *The Aerospace Research and Technology Subcommittee (ARTS)*, a subcommittee of the SSTAC, providing in-depth technical expertise across the broad array of space research and technology discipline areas

- *The Aeronautics and Space Engineering Board (ASEB)*, a board of the National Research Council (NRC)

- *Representatives from the Space Science and Applications Committee (SSAC),* a subcommittee of the NAC

- *Representatives from the Aerospace Medicine Advisory Committee (AMAC),* a subcommittee of the NAC

- *Representatives from the Space Studies Board (SSB),* a board of the National Research Council (NRC)

- *Selected additional participation by other members of U.S. industry and academia and*

representatives from other government agencies (including the Department of Defense, the Department of Commerce, the Department of Transportation, and the Department of Energy).

1.3 Review Methodology

The methodology used by the review team was comprised of: (1) a review of NASA-wide technology requirements and external perspectives on advanced space technology development; (2) overview briefings from NASA on the proposed ITP; (3) separate panel reviews of each of the major technology discipline areas in detail; and, (4) development of both panel-specific recommendations and overall review team recommendations.

The strategic criteria for evaluation of the proposed program included:

- Quality of the proposed tasks
- Relevance to NASA and to National space technology needs
- Contribution to the National technology base.

In addition, several specific evaluation criteria were applied to the proposed program efforts; these were:

- Reduce space flight project/system development uncertainties
- Reduce the cost of "access" to space
- Increase the reliability/safety of future space systems
- Enhance mission performance
- Enable new capabilities
- Provide technologies with a breadth of applications
- Assure that NASA remains technically current
- Maintain the research base within NASA.

The latter, more detailed evaluation criteria reflect what the review team considered as some of the essential justifications for increasing space research and technology funding.

1.4 NASA Missions

Broadly speaking, NASA has four space related operational missions: (a) *Space Science* (including the Earth Observing System, EOS); (b) *Space Exploration* (including both Space Station *Freedom*, SSF, and the Space Exploration Initiative, SEI); (c) *Transportation* (including the Space Shuttle and expendable launch vehicles), and (d) *Space Utilization* (including support for commercial space industries).

These four operational missions are pursued by several program offices within NASA: the Office of Space Science and Applications (OSSA), the Office of Aeronautics, Exploration and Technology (OAET) Space Exploration Initiative Directorate (OAET/RZ), the Office of Space Flight (OSF), and the Office of Space Operations (OSO). Each office has developed strategic plans for challenging missions in the coming decades. In response to the Augustine Committee recommendations and as part of their participation in NASA's Integrated Technology Plan effort they have identified the priority technologies needed to make their future missions feasible, safe and cost-effective. Other parts of the U.S. government (e.g., the National Oceanographic and Atmospheric Administration), have identified technology needs that must be met for the future success of the U.S. civil space program. Moreover, in addition to the technology needs of NASA and the government, the U.S. commercial space sector has technology needs — just as does the U.S. commercial aeronautics sector — that are of equal importance for consideration in developing a strategic plan for the development of advanced space technology.

NASA also has a fifth mission that is frequently unstated: to develop new technologies to assure continuing preeminence in space and for the overall benefit of the Nation. To accomplish that goal and to support the future of the U.S. civil space program, the diverse mission plans noted and the technology needed to make those plans viable were incorporated into the development of the Integrated Technology Plan.

The external review team examined in detail not only NASA's proposals, but also compared the relevance of proposed technology plans to the future needs of the civil space program. The team's recommendations were based on this evaluation.

1.5 Summary Findings of the Review

The external review team was impressed by the amount and quality of the work which NASA had done in response to the Augustine Committee recommendations. An effective process has been established to identify the advanced technology needs of the user communities and establish a rough order of priority within individual technical disciplines and program thrusts. Two levels of funding were presented to the review: a "responsive plan;" and, a "3-fold augmentation" (i.e., "3x") plan. The *responsive plan* — which attempted to address virtually all identified technology needs — grew from current space R&T funding levels (approximately $ 283 million in fiscal year 1991) to $ 1.7 billion by 1997. The *3-fold augmentation plan* — which is targeted at the Augustine Recommendation level of three-times the current modest budget by 1997 (plus inflation) and may realistically be all that NASA can be expected to invest — grew to approximately $ 1.1 billion by 1997.

The review team consisted of experts in several disciplines. Almost uniformly, the review team found the quality of the research projects proposed was very high and that they were well integrated with other National efforts. In general, the review team recommended that more, rather than less, work should be done, even at the responsive level. ***That is a strong indication that the Augustine Committee recommendation for a significant budgetary increase is well founded and should be implemented.***

In most areas, some specific projects were questioned, along with details of the prioritization. That is natural, since the new planning process has barely completed the first cycle. The issues raised indicate the need to institute a continuing peer review process both within and outside the Agency.[1]

The proposed ITP includes efforts in two blocks: an *R&T Base* which includes discipline-oriented, and more fundamental technology activities; and the *Civil Space Technology Initiative* which is a family of focused technology projects to develop specific generic capabilities for projected future missions. The balance between the R&T Base program and focused programs — in which the R&T Base is targeted strategically to be set at a continuing level of one third of the total space R&T effort — seems appropriate, as does the new grouping of the focused programs (i.e., the revised space R&T work breakdown structure). The balance between near, mid and far term programs seems to be appropriate, but should be more clearly established. (An example might be the relative priority of investing in technology to enable SEI, compared to useful, but not essential improvements to an ongoing program.) The assessment is that the bulk of investment should be in technologies available five-to-fifteen years in the future, with more limited investment in R&T for deliverables closer than five or further than fifteen years.

Also, the means of establishing priorities across disciplines and major thrusts needs to be further clarified. For example, propulsion developments are very expensive and require a long time to mature, compared to communications or computer systems in which NASA often is adapting commercial developments to space applications. Top management policy guidance, perhaps embodied in a strategic long range plan for the Agency, will be required.

The review team also noted that the plan presented does not, in general, take new technology development through flight demonstration. Many program offices are reluctant to commit to equipment which has not flown. They also noted that flight experiments are very expensive.

It can be difficult to justify the cost and show the relevance of small, individual research tasks. Perhaps the establishment of integrated ground testbeds could be a means of focusing related projects and demonstrating readiness for application.

The review team also noted that additional ground facilities in critical technology areas will be needed for many of the programs proposed and to compensate for the lack of flight opportunities.

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[1] Note: in this report, the term "peer review" is used in the sense of overall external oversight of the program (including reviews at several levels of detail), rather than the more specialized usage found in some other contexts (for example, when the term is used to indicate external participation in awarding specific grants to universities). This review team is advocating the general use of external review only.

Summary Findings of the Review

Overall, the review team believes that Recommendation 8 of the Augustine Committee is well founded. NASA has instituted a sound planning process and the proposed **Integrated Technology Plan for the Civil Space Program** ***is a solid basis for responding to the Augustine Committee Recommendations on technology. Within each panel group, the review team found that at both the "three-fold increase" and the greater "responsive" resource levels, the proposed program was sound and that more, rather than less, resources were needed to meet the legitimate technology needs of the U.S. civil space program.***

The **Integrated Technology Plan** ***deserves as much support as the Agency and Congress can provide. We also recommend that the Augustine target of a three-fold increase in funding level be the initial goal.***

1.6 Summary Recommendations

The review team believes, as was stated by the Augustine Committee's report, that "the development of advanced technology is ... crucial to the success of the exploration and exploitation of space." NASA's proposed Integrated Technology Plan responds to this challenge. Our most important and overriding recommendation for NASA, the Administration and the Congress is:

• ***Accept Recommendation 8 of the Augustine Committee and initiate planning for the needed funding growth to triple the current level of investment in advanced space research and technology.***

In addition, the review team has the following subsidiary recommendations that arose during the review process:

• ***Continue to Improve the Integrated Technology Plan.*** NASA should continue to refine the space research and technology planning process, and increase the participation by other government agencies, industry and academia. Issues include: (1) improving technology transfer within the program, (2) establishing priorities across disciplines and thrusts, and (3) continuing and expanding the use of external, expert review of the program.

• ***Develop National Teams.*** Plan for and implement increased collaboration and teaming among NASA, industry and universities in space R&T, and coordination with other government agencies, as appropriate.

• ***Develop National Testbeds.*** Implement the concept of National Testbeds for space technology development.

• ***Revitalize Space R&T Facilities.*** Focus planning on a new generation of space technology research facilities.

• ***Increase the Use of Technology Flight Demonstrations.*** Implement policies and practices which reduce the cost and accelerate the pace of space R&T flight experimentation.

• ***Improve Technology Transfer.*** Focus management attention on developing clear, widely accepted criteria for adopting new technologies for future civil space flight programs.

The next section provides a review of the projected technology needs of future civil space missions as presented to the review team. Specific technology needs for NASA program offices (i.e., OSSA, OSF, OSO) and for the Space Exploration Initiative, are presented, including the priorities that those organizations identified for those technologies. Also provided are other civil space technology needs, including non-NASA government needs and the R&T needs of commercial space sector. (This section provides background material for Sections 4 and 5.)

Mission Needs

Broadly speaking, NASA has four space related operational missions: (a) *Space Science* (including the Earth Observing System, EOS); (b) *Space Exploration* (including both Space Station *Freedom*, SSF, and the Space Exploration Initiative, SEI); (c) *Transportation* (including the Space Shuttle and expendable launch vehicles), and (d) *Space Utilization* (including support for commercial space industries).

These operational missions are pursued by the several program offices of NASA: the Office of Space Science and Applications (OSSA), the NASA Space Exploration Initiative Office, the Office of Space Flight (OSF), and the Office of Space Operations (OSO). Each office has developed strategic plans and concepts for future missions in the coming decades. As a part of their participation in the ITP effort, each office has identified the priority technologies needed to make those missions feasible, safe and cost-effective. In addition to the technology needs of NASA, the U.S. commercial space sector has technology needs — just as does the U.S. commercial aeronautics sector — that are of equal importance in developing a strategic plan for the development of advanced space technology. These plans for the future of the civil space program and the technology needed to make those plans viable are reviewed in the sections that follow.

2.1 Office of Space Science and Applications

Overview

The NASA Office of Space Science and Applications (OSSA) has responsibility for using the unique environment of space to conduct scientific study of the universe, to understand how the Earth works as an integrated system, to solve practical problems on Earth, and to provide the scientific (and contribute to the technological) foundations for expanding human presence beyond Earth. OSSA plans to conduct a wide range of missions in the years ahead. These missions will cover a variety of scientific discipline areas, including: astrophysics, solar system exploration, Earth science, space physics, life sciences, and microgravity science. Within each of these areas, development flight projects are being planned that will be initiated in the near term (during the next five years), the mid term (the next ten years) and the far term (after the next ten years). In the paragraphs which follow, specific program objectives in each of the major OSSA areas are listed, including representative missions. (Additional specific missions are referenced in the detailed discussion of OSSA technology needs and their priorities which follows.)

Space Science Mission Plans

Astrophysics. Four Great Observatories are planned: the *Hubble Space Telescope, (HST);* the *Gamma Ray Observatory (GRO)*; the *Advanced X-ray Astrophysics Facility (AXAF);* and the *Space Infrared Telescope Facility (SIRTF)*. Of the four, HST and GRO are already in flight; AXAF and SIRTF are planned for implementation during the 1990s. The Great Observatories will observe the universe across the entire electromagnetic spectrum. As we begin to understand the implications of these data, the U.S. will lead a worldwide effort that will revolutionize human knowledge of the universe's origin and its ultimate fate. Many totally unexpected scientific discoveries will be made, and a new generation of observatories will be needed to further expand our knowledge. In addition to the Great Observatories, a number of smaller astrophysics missions will be flown as part of the *Explorer Program*, and three moderate size astrophysics missions also will be flown.

Beyond the nearer term, astrophysics mission possibilities include ground based activities, advanced Earth orbiting telescopes (successors to the Great Observatories and specialized, smaller instruments), as well as lunar telescopes and advanced interferometer capabilities.

Solar System Exploration. Over the past three decades, the *reconnaissance phase* (initial robotic mission flybys) of the exploration of our solar system has been completed, with the exception of the Pluto-Charon system. In addition, a more capable robotic *exploration phase* has been well underway for several years for the Moon (e.g., Surveyor) and Mars (e.g., Viking). Finally, an *intensive study phase* was initiated for the Moon during the Apollo era. During the coming decades, new efforts will be made in each area, including missions to both the outer and inner planets, as well as to the small bodies (e.g., asteroids) of the solar systems. Also, in preparation for future human missions, both the Moon and Mars will be studied extensively by robotic spacecraft, either on their surfaces or from low orbits.

At present, solar system exploration is being pursued with vigor. The ongoing *Magellan* mission's radar mapping of Venus continues to produce stunning results. In addition, the *Mars*

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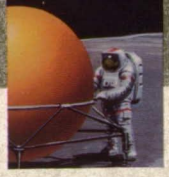

Observer spacecraft will be launched in the early 1990's to orbit Mars for at least one Martian year to provide a detailed global scientific assessment of this planetary neighbor. In the next few years, the recently launched *Galileo* spacecraft will visit Jupiter and its moons as a follow-on to the two Voyager spacecraft. The *Cassini* spacecraft will tour Saturn and its moons for a long term, close-up study and the *Comet Rendezvous Asteroid Flyby* (CRAF) mission under development will provide close observations of small bodies in the solar system. Other spacecraft will follow in their wake.

During the coming decades, a variety of useful missions are being considered, including: (1) completion of the *reconnaissance phase* of solar system exploration via a fly-by of Pluto-Charon and beginning the search for planetary systems around neighboring stars; (2) continuing the *exploration phase* through missions to Neptune and Uranus (e.g., orbiter/probe missions similar to *Cassini* to Saturn) and to the asteroids; and (3) beginning in earnest the *intensive study phase* of solar system exploration — including robotic support for the Mission From Planet Earth — through advanced orbiters and network missions (e.g., the *Lunar Orbiter* mission or a *Mars Network*), sample returns and rover missions (e.g., a *Mars Sample Return* and the *Comet Nucleus Sample Return* concept), and advanced outer planet missions (i.e., the *Jupiter Grand Tour* concept).

Earth Science. NASA's efforts over the past decades in the area of Earth science have resulted in major advances in understanding our home planet. In the very near term, additional core program, moderate size missions, such as TOPEX/POSEIDON (the Ocean Topography Experiment) and the Upper Atmosphere Research Satellite (UARS) will continue to expand our data base on the Earth. The data from these satellites will be supplemented by smaller probes, such as the Total Ozone Mapping Spectrometer (TOMS).

During the coming years, and led by the U.S., the international Mission to Planet Earth (MTPE) will build upon the information already gathered by earlier missions that have studied the nature and dynamics of the myriad of components of the Earth's biosphere. The *Earth Observing System (EOS)* and a complementary set of *Earth Probes*, major elements of the U.S. Global Change Research Program (GCRP) will provide long term, continuous observations of our planet from low Earth orbit (LEO). In the further term, advanced geostationary Earth orbit (GEO) platforms are being planned that will provide long term observations from large scale instruments at high altitudes. Combined with ground based measurements and observations, information received from these systems will advance our understanding of the Earth on a global scale.

Space Physics. The objectives of the NASA Space Physics Program include understanding the Sun, both as a star and as the dominant source of energy, plasma, and energetic particles in the solar system, the interactions between the solar wind and solar system bodies, such as the Earth, and studying solar and galactic cosmic rays. In the very near term, NASA participation in the *International Solar Terrestrial Physics* program (including NASA instruments on international spacecraft) will be undertaken. In addition, during the 1990s, the *Orbital Solar Laboratory* (OSL) is planned for launch and operations in the Space Shuttle's payload bay (providing key data on the Sun and serving as a prelude to future solar monitoring in support of the MFPE). In later years, additional ambitious missions are being planned, including dual orbiters of the planet Mercury and a possible *Solar Probe* mission.

Life Sciences. The effects of long duration space flight on living things will have to be better understood if our astronauts are to live in Earth orbit, as well as on the Moon and Mars, for months at a time. The OSSA Life Sciences Program implements ground and space research into these and related issues, including efforts to study the role of gravity on living systems in space and to expand our understanding of the origin, evolution and distribution of life in the universe. In particular, the program addresses the impact of weightlessness and natural radiation on human beings, plants, and animals.

In the near term, a variety of scientifically rich life sciences missions will be flown, including those using the Space Lab in the payload bay of the Space Shuttle. Current programs also include the ground based *Search for Extraterrestrial Intelligence* (SETI) and research into technologies related to bioregenerative life support (CELSS). Moreover, the Life Sciences Program is currently undertaking the *Extended Duration Orbiter* (EDO) medical program to insure that crews are capable of safe landing

following 13 to 16 day Space Shuttle missions. In addition, small new missions — such as the *Lifesat* concept — are being planned for the near to middle term that would fly on ELVs. In the long term, the Life Sciences Program is planning for intensive use of Space Station *Freedom* to conduct long duration microgravity studies of human crews that will directly support future exploration missions.

Microgravity Sciences. Hand-in-hand with U.S. industry, academia, other federal agencies, and our international partners, NASA plans in the coming years to build upon its past experience in using microgravity to manufacture small quantities of various products in Earth orbit. The Space Shuttle will represent a major carrier for those experimental missions during the near term. By the latter part of this decade, this pioneering research, will continue onboard Space Station *Freedom,* which will advance our understanding of fluid physics, materials science, combustion science, health science, and biotechnology.

Space Science and Applications Technology Needs

A key element for planning space science technology needs has been the annual prioritization of division-specific technology requirements within OSSA. As part of the ITP activity, the process has been strengthened within OSSA to focus on a set of advanced technology priorities endorsed OSSA-wide and by the Associate Administrator. To foster this process, an Office of Aeronautics, Exploration and Technology (OAET) liaison has been assigned to the Associate Administrator for Space Science and Applications to assist the OSSA divisions in a grassroots assembly and prioritization of technology requirements.

The preliminary OSSA technology needs identified during the directed planning effort of the past several months cover the full range of OAET focused R&T programs (Science, Transportation, Platforms, Operations, and Planetary Surface Exploration). OSSA prioritized its technology needs according to: (a) value (including criticality and commonality); and, (b) urgency (looking at the timing of when technology readiness to begin flight project development would be needed). This resulted in OSSA technology needs being categorized according to highest, second highest, and third highest priority technology, and ranging from the near to far term. These are summarized below.

Highest Priority Space Science Technology Needs. There are several near term OSSA needs which relate to the Space Science Technology Program and fall into this category. Submillimeter and microwave technology are needed by both the Earth Science and Applications and Astrophysics Divisions, for applications on the *Earth Observing System-Synthetic Aperture Radar (EOS-SAR)*, *TOPSAT*, and *Submillimeter Mission (SMMM)* spacecraft, and the Microwave Limb Sounder (MLS) and MIMR instruments for the *EOS* spacecraft. Long life mechanical and cryogenic coolers and cryogenic shielding technologies are required by the Earth Science and Applications, Astrophysics, and Space Physics Divisions for applications on *EOS-A1*, *OVLBI-NG*, *Nuclear Astrophysics Explorer (NAE)*, *SMMM*, *Submillimeter Interferometer (SMMI)*, *Large Deployable Reflector (LDR)*, *Space Telescope-Next Generation (ST-NG)*, and *IST-NG* spacecraft, the *High Energy Solar Physics Mission*, and the *High Resolution Gamma Ray Spectrometer.*

A wide range of detectors (optical, Ge, Xe, non-cryogenic 1.6 to 150 micron IR, extended-micron CCD, high energy detectors, and tunnel sensors) and sensor readout electronics will be needed for future missions. These technologies are required by the Earth Science and Applications, Solar System Exploration, Space Physics, and Astrophysics Divisions of OSSA. Advanced detector technologies must be developed for: *EOS-A2*, *TOPS-1*, *NAE*, *Hard X-ray Imaging Facility (HXIF)*, *IST-NG*, *Imaging Interferometer (II)*, and *ST-NG* spacecraft; the Geoscience Laser Ranging System (GLRS) instrument for *EOS*, solar investigators using *Explorer* missions and the *Solar Probe Coronal*

Companion; the *Pluto Flyby*, *Neptune O/P*, *Uranus O/P*, and *Jupiter Grand Tour* missions; and micro-weather stations for in situ measurements.

There also are several mid term needs in this category. Long life, stable, tunable lasers are needed by the Earth Sciences and Applications, Astrophysics, Solar System Exploration, and Life Sciences Divisions for applications in the Laser Atmospheric Wind Sounder (LAWS) and GLRS instruments for *EOS*, the *Precision Optical Interferometer*, the *Orbiting Stellar Interferometer*, a variety of interferometers for astrophysics, lunar and planetary exploration, and in the *Search for Extraterrestrial Intelligence (SETI) Program*. Interferometer-specific technology is needed by the Astrophysics, Solar System Exploration, and Life Sciences Divisions for use in a variety of interferometers in all of these areas. In addition, controls-structures interactions (CSI) and information processing and management research and technology are needed.

There also are several far term needs. Robotics technologies will be needed by the Solar System Exploration Division of OSSA for use in *Mars Sample Return* and *Comet Sample Return* missions, and a *Mars Global Network*, and by the Microgravity Science and Applications Division for containerless processing, solidification, biotechnology, and protein crystal growth. Robotics technologies may also be applicable to Life Sciences needs related to advanced in-space medical care. Interspacecraft ranging and positioning technology and precision sensing, pointing and control technology are needed by the Space Physics, Solar System Exploration, and Astrophysics Divisions for use in the *Grand Tour Cluster*, *Auroral Cluster*, *Mercury Orbiter*, *ST-NG*, and *OVLBI-NG* spacecraft. Technology development for a parallel software environment for model and data assimilation and visualization and related areas is required by the Earth Science and Applications Division for a wide range of uses in the Mission to Planet Earth and U. S. Global Change Research Programs, as well as in mission operations and data analysis applications for the Solar System Exploration Division. Also, technology developments for large filled apertures will be needed by the Astrophysics, Solar System Exploration, and Earth Science and Applications Divisions for use in the *LDR*, *ST-NG*, *SMMI*, *IST-NG*, *MOI*, *II*, *TOPS-1*, and *Precision Optical Interferometry in Space (POINTS)* spacecraft, in the *Orbiting Stellar Interferometer*, and in geostationary observations.

Second Highest Priority Space Science Technology Needs. There are several near term needs in this category. High-frame-rate, high resolution video and data compression technologies are required by the Solar System Exploration and Microgravity Science and Applications Divisions of OSSA for use in the full range of unmanned missions to explore the solar system, and in a variety of microgravity missions. Technology development for a 2.5 to 4 meter, 100 K lightweight *PSR (Precision Segmented Reflector)* is needed by the Astrophysics Division for use in the *SMMM* mission. Fluid diagnostics technology is needed by the Microgravity Science and Applications Division for a variety of important microgravity research missions. Space-qualified masers and ion clocks will be required by the Astrophysics Division for the *OVLBI-NG* mission.

Two mid term OSSA needs have been identified. These are auto-sequencing and command generation, and auto spacecraft monitoring and fault recovery. Both are required by the Solar System Exploration Division for use on the full range of their future missions.

There are several far term needs, as well. Superconducting-Insulating-Superconducting (SIS) 3 terahertz (THz) heterodyne receivers are needed by the Astrophysics Division for use on the *LDR* and *SMMI* missions. *SETI* technologies (microwave and optical/laser detection) will be used by the Life Sciences Division in the search for extraterrestrial life. Technologies for sample acquisition and preservation, probes, in situ instruments, drills, corers, and penetrators are required by the Solar System Exploration and Life Science Divisions for the *Mars Sample Return* and *CNSR* missions, and the *Mars Network*. Finally, X-ray optics technology is needed by the Astrophysics Division for the *HXIF* spacecraft.

Third Highest Priority Space Science Technology Needs. Several near term OSSA needs relating to the Space Science Technology Program exist. Descent imaging and a mini-camera are needed by the Solar System Exploration Division for the *Mars Network* and the *Discovery NEAR* mission. Solid-liquid interface characterization and laser light scattering will be studied by the Microgravity Science and

Applications Division. High temperature materials for furnaces and advanced furnace technology will be required by this OSSA division for several important flight experiments.

There also are two mid term OSSA needs. Non-contact temperature measurement technology will be needed by the Microgravity Science and Applications Division for experiments, and 3-D packaging for 1 MB solid-state memory chips is required by the Astrophysics Division for the *MOI* and *II* spacecraft.

2.2 Space Exploration Initiative

The NASA Space Exploration Initiative Office is responsible for developing integrated strategies for the Space Exploration Initiative (SEI). In addition, an activity to develop ideas and architectures for SEI was conducted recently by the "Synthesis Group" under the direction of Lt. General. Thomas Stafford. The four SEI "architectures" defined by the Synthesis Group will form the framework for studies of SEI mission options and technology needs during the next several years.

The Advisory Committee on the Future of the U.S. Space Program endorsed SEI, the so-called "Mission From Planet Earth" and stated in Recommendation 7 of their report:

> *"That technology be pursued which will enable a permanent, possible man-tended outpost to be established on the Moon for the purposes of exploration and for the development of the experience base required for the eventual human exploration of Mars. That NASA should initiate studies of robotic precursors and lunar outposts."*

The relevant aspects of this recommendation (i.e., those pertaining to the development of space technology) have been incorporated by the NASA Administrator into the activity to respond to Recommendation 8. The technology needs and plans for SEI therefore have been addressed in the ITP and were examined by the external review team.

Space Exploration Initiative Mission Planning

Returning to the Moon and sending the first Americans to Mars will occur as part of a long term, evolutionary civil space program. During 1990 and early 1991, the Synthesis Group defined four, broad-ranging architectural options for SEI; these were:

- ***Exploration of Mars***

The major objective of this architecture option is to explore Mars and provide scientific return. The emphasis of activities performed on the Moon is primarily for mission to Mars preparation, but includes significant Lunar infrastructure and scientific return from Lunar operations.

- ***Science Emphasis for the Moon and Mars***

The major objective of this architecture option is a balanced scientific return from the Moon and mars. Emphasized throughout are exploration and scientific activities, including complementary human and robotic missions required to assure optimum mission returns.

- ***Moon to Stay and Mars Exploration***

The major objective of this option is to establish a permanent presence on the Moon and to conduct Mars exploration. Long term human habitation and exploration in space and on planetary surfaces provide terrestrial spinoffs to improve our life on Earth and increase our knowledge of the solar system, the universe, and ourselves.

- ***Space Resource Utilization***

The objective of this architecture is to make maximum use of available resources to support SEI mission operations. In this case, SEI programs would seek to develop resources for transportation, habitation, life sciences, energy production, construction, etc., in order to reduce costs and approach self-sufficiency.

Each of these architectural options entails several of common strategic features. In all cases, SEI will begin with mission planning and technology development. Subsequently, SEI will include programs of experimentation (in particular in life sciences, but also including technology demonstrations) onboard Space Station *Freedom* and some robotic precursor missions to Mars and (in some options) the Moon. The capability will be developed to permanently live on the Moon and to visit Mars for increasingly longer periods of time.

High level planning for future human missions to the Moon and Mars has been ongoing at NASA since 1986. That planning, which includes, the development of alternative scenarios and space infrastructures — using the framework of the Synthesis Group architectures — will continue during the coming year with an increasing level of detail. Over time, detailed planning will shift from the precursor missions to the initial human return to the Moon, and eventually to evolutionary lunar scenarios, more advanced robotic missions and then to the human exploration of Mars.

In parallel with the earlier mission planning and the Synthesis Group's definition of SEI architectures, the identification of new technology needed for future human missions to the Moon and Mars has been initiated (with limited investments since 1986). Like the mission planning, the near term needs have tended to receive, in general, a higher level of priority than the far term needs.

The following paragraphs provide some top level information regarding each of the different programmatic components of SEI.

Space Station* Freedom *Based Research. The initial version of Space Station *Freedom (SSF)* will begin operation in the 1997 timeframe. From that point forward, SSF will contribute to increasing our knowledge about the long term effects of weightlessness in space on human beings, plants and animals. This knowledge is needed to complete the design of the spacecraft that will take the first Americans to Mars.

Robotic Precursor Missions to the Moon and Mars. In addition to the research done onboard *Freedom*, current planning calls for several other activities to be undertaken prior to, or concurrent with, human missions to the Moon and Mars:

- A *Mars Observer (MO)* spacecraft will gather additional data about Mars in the early 1990's

- A *Lunar Observer (LO)* spacecraft is planned to gather additional data about the Moon in the late 1990's

- In the early 2000's, a *Mars Network (MN)* may be implemented to provide data at several places on the surface of Mars

- Robotic *Mars Rovers (MRs)* may be used to gather data at several Martian locations beginning in the early 2000's and

- Samples of the surface material at two or more of these Martian locations may be gathered by a one or two *Sample Return (SR)* missions, starting at approximately the same time.

Returning to the Moon. The last two Apollo astronauts departed from the Moon in 1972, and the first American astronauts will not return there until middle of the first decade of the next century, a gap of more than three decades. A few years after we return, possibly during the latter part of the first decade of the next century, an initial *Lunar Outpost* is projected to be up and running, and Americans will begin to permanently live on the Moon. Initial objectives may include:

- To further increase our scientific knowledge of the Moon

- To set up and maintain large astronomical instruments on the Lunar surface

- To begin to determine the practical uses of Lunar material

- As a testbed for similar human activities on the Martian surface.

Missions to Mars. For planning purposes, it is being assumed that the first Americans would land on Mars during the five year period from 2014 to 2019, approximately fifty years after the first Americans landed on the Moon. The realism of

these dates is dependent upon the availability of specific technologies.

Space Exploration Initiative Technology Needs

On the basis of previous studies, the NASA SEI program office has defined a set of technology needs for exploration. The needs were prioritized on the basis of two primary criteria: (1) importance/value to a particular SEI mission or objective; and, (2) commonality across segments of SEI. In the initial prioritization, timing was not considered as a criterion for assessment. On the basis of these criteria, technologies were categorized into: (a) *highest priority* (being both extremely valuable and common to several cases); (b) *second highest priority* (being either very valuable and common to many cases or extremely valuable and unique to one or a few cases); and (c) *third highest priority* (being very valuable and unique to one or a few cases).

In addition, as part of their activities, the SEI Synthesis Group developed an independent assessment of the technologies that were needed as a part of SEI planning and identified those that could significantly enhance the implementation of SEI. The latter list included fourteen important technologies for SEI, which were not prioritized within the list.[1]

The results of each of the SEI technology needs definition activities were presented to the review team and are provided in the following sections.

SEI Office Assessment: Highest Priority SEI Technology Needs. The highest priority SEI technology needs, as identified by NASA SEI Office include the following areas:

- *Radiation Protection* — including shielding and materials

- *EVA Systems* — portable life support systems (PLSS), gloves, materials, mobility aids, dust seals

- *Nuclear Thermal Propulsion* — reactor design, fuel development, shielding and control systems

- *Regenerative Life Support* — including sensors, controls, physical-chemical process based systems and bioregenerative systems

- *Cryogenic Fluid Management, Storage and Transfer* — for space transfer vehicles

- *Microgravity Countermeasures/Artificial Gravity* — centrifuge, countermeasures equipment

- *Aerobraking* — low energy (< 12 km/s) and high energy (> 12 km/s) entry speeds.

SEI Office Assessment: Second Highest Priority Needs. The second highest SEI technology needs identified by the NASA SEI Office include:

- *Autonomous Rendezvous and Docking* — unmanned docking and verification of successful mating

- *Health Maintenance and Care* — health monitoring, emergency surgery

- *In-Space Systems Assembly and Processing* — mating and verification/checkout techniques

- *Surface System Construction and Processing* — heat transport and rejection, radiation shielding emplacement, surface stabilization

- *Cryogenic Space Engines* — space transfer vehicles and landers, restart capability, ability to throttle over a wide range, ease of maintainability

- *In Situ Resource Utilization* — targeted primarily on the production of liquid oxygen (LOX) from Lunar surface regolith

- *Surface Power* — including a variety of specific technology options; i.e., nuclear, solar, energy storage, power conversion, heat rejection, power management.

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[1] Note: Nuclear propulsion and nuclear-electric surface power technologies were identified separately as strategically crucial to the success of SEI by the Synthesis Group report, and even though the list of 14 was not prioritized, these technologies should be regarded as higher in priority than the others on the list.

SEI Office Assessment: Third Highest Priority Needs. The third highest priority technologies include several high leverage technology areas, applicable to a specific SEI architecture, include:

- *Autonomous Landing* — including guidance, navigation and control, transition from aeroassist to propulsion and landing at a fixed spot, navigation aids, hazard avoidance

- *Human Factors* — human/machine interfaces, habitability, automated training aids

- *Surface System Mobility and Guidance* — including technology for both manned and unmanned surface systems

- *Electric Propulsion* — including development of propulsion thruster development for either nuclear or solar power sources

- *Sample Acquisition, Analysis and Preservation* — including surface and subsurface lunar and Martian samples.

SEI Synthesis Group Assessment of Technology Needs. Fourteen very significantly enhancing technologies for SEI include:

- *Heavy Lift Launch* — with a minimum capability of 150 metric tons with designed growth to 250 metric tons

- *Nuclear Thermal Propulsion* — which was judged as a key technology area for humans to Mars missions

- *Nuclear Electric Surface Power* — with power levels ranging up to megawatt levels

- *Extravehicular Activity Suits* — including both Lunar and Mars surface suits, as well as in transit suits

- *Cryogenic (fluids) Transfer and Long Term Storage*

- *Automated Rendezvous and Docking — of large masses*

- *Microgravity Countermeasures*

- *Radiation Effects and Shielding*

- *Telerobotics*

- *Closed Loop Life Support Systems*

- *Human Factors* — for long duration space missions

- *Light Weight Structural Materials and Fabrication*

- *Nuclear Electric Propulsion* — for follow on cargo missions

- In Situ *Resource Evaluation and Processing.*

(Note: all of these were also cited on the NASA SEI Office technology needs list, with the exception of a heavy lift launch vehicle, which would be a development program outside of the space R&T program.)

2.3 Office of Space Flight

Overview

The Office of Space Flight (OSF) has responsibility for the development and operations of ground operations, Earth-to-orbit transportation (both expendable launch vehicles (ELVs) and the Space Shuttle), and Space Station *Freedom* development and operations planning. As a part of the ITP planning effort, OSF developed an overall strategic program schedule to support technology planning and identified an array of technology needs in numerous areas through a grassroots process. These needs were subsequently distilled with extensive participation of top OSF management.

OSF Program Planning

Transportation. Future program planning for the mid term (approximately around the end of the decade) include the *National Launch System* (NLS), and the option of an upper stage vehicle for the NLS, a *Cargo Transfer Vehicle* (CTV). A new *Personnel Launch System* (PLS) is a program option for the mid to far term.

For the far term, plans are being developed for an *Advanced Manned Launch System* (AMLS) which is projected to enter system development in the middle years of the next decade, with an operational capability approximately ten years later.

***Space Station* Freedom**. Space Station *Freedom* (SSF), currently in development, would begin its initial assembly phase in the middle 1990s, with completion of Permanently Manned Capability (PMC) around the turn of the century. Following PMC, two phases of evolutionary changes in SSF systems while on orbit are projected, including increases in power and autonomy.

OSF Technology Needs Summary

OSF technology needs were identified in each of the several major parts of the office, including Space Station *Freedom*, Space Shuttle, Expendable Launch Vehicles and Upper Stages. OSF's major technology needs included sixteen areas which OSF judged likely to be driven by NASA investments and/or to be largely unique to NASA programs. These were, in approximate order of priority:

• *Vehicle Health Management* — Advances are needed in sensors, processors and networks, in maintenance diagnostics/algorithms, and in selected system components. Overall system integration demonstrations are needed for technology maturation

• *Advanced Turbomachinery Components & Models* — Including R&T in the areas of large scale bearings, seals and structures for launch vehicle LOX, LH2 & LHC turbines and pumps, and demonstrations of smaller scale turbines/pumps for space transfer vehicles (STVs)

• *Combustion Devices* — R&T needs to address fabrication methods for thrust chambers, nozzles and injector concepts (with wide design margins), and expander cycle engines for future STVs. Moreover, technology demonstrations are needed to assure future design-to-cost

• *Advanced Heat Rejection Devices* — Thermal management research and technology is needed to develop heat pumps for microgravity operations and low mass, high efficiency heat pipes

• *Water Recovery and Management* — Life support R&T is needed for real time microbial analysis and water reclamation and waste processing technologies (such as long life membranes and filters)

• *High Efficiency Space Power Systems* — R&T is needed for Earth orbiting applications, including future SSF systems implementation

• *Advanced Extravehicular Mobility Unit Technologies* — R&T needed for suit components (such as high pressure, high operability gloves) and portable life support systems (including regenerable heat storage and rejection systems)

• *Electromechanical Control Systems/Electric Actuation* — Needs are principally in the area of avionics system component advances to support future transportation systems

• *Crew Training Systems* — Including technology needed for both ground and in-space training systems, including retraining in flight during long duration SSF missions

• *Characterization of Aluminum-Lithium Alloys* — R&T needed to support development of future large scale and/or low cost ETO transportation systems

• *Cryogenic Supply, Storage and Handling* — R&T needed in the areas of long duration storage, including insulation and refrigeration options, and for cryogen handling, including modeling and experimental model validation in flight experiments

• *Thermal Protection Systems for High Temperature Applications* — R&T needed for future transportation systems TPS

• *Robotic Technologies* — Including technology for future in-space vehicle servicing and processing operations (e.g., on SSF)

• *Orbital Debris Protection* — Including both protection and determination of the debris environment

• *Guidance, Navigation & Control* —Including both ETO and in space transportation systems GN&C

• *Advanced Avionics Architectures* — R&T needed in defining unique advanced avionics architectures for both transportation and SSF systems that could then guide government and contractor technology development.

In several areas, OSF judged that new technology development was likely to be driven by industry research rather than government efforts. Nevertheless, in those areas, some NASA investment targeted on specific applications of new technology could be needed. Five items were identified:

- *Signal Transmission and Reception*
- *Advanced Avionics Software*
- *Video Technologies*
- *Environmentally Safe Cleaning Solvents, Refrigerants and Foams*
- *Non-Destructive Evaluation.*

2.4 Office of Space Operations

Overview

The Office of Space Operations (OSO) has responsibility for the development and operations of ground and space systems for tracking, data acquisition and management, and telemetric navigation functions for NASA. As a part of the ITP planning effort, OSO identified priority technology needs in several areas, including both general needs, as well as those associated with future OSO participation in SEI. OSO identified the "drivers" of its technology needs in the same timing framework as that used for overall ITP planning. In particular,

- Near Term Needs
  - — Refine and extend state-of-the-art technology to meet demands for enhanced capabilities
  - — Upgrade existing equipment and techniques
  - — Provide more power, higher data rates, and lower error rates

- Longer Term Needs
  - — Develop new technologies needed for future missions
  - — Dependent on mission characteristics to be defined by users: Space Station, EOS, others

- Far Term Needs
  - — Technology needs linked to emergence of mission characteristics defined by users; however in general develop new technologies for lunar and Mars exploration

Also as a part of this effort, OSO reviewed its own internal "advanced systems program" (which is analogous to advanced development or planned product improvement efforts in OSF).

OSO Technology Needs Summary

OSO's major, but not SEI-specific technology needs concentrated primarily in the near and mid term. These were: high data rate communications; advanced data systems; advanced navigation techniques; and mission operations. In addition, OSO identified longer term technology needs for SEI support that fell into three very similar areas: telecommunications; information management; and navigation.

High Data Rate Communications. This technology need addressed projected requirements for very high data volumes for space-to-Earth communications as well as space-to-space transmissions. As defined for non-SEI needs, this area included optical and millimeter wave radio frequencies. These two technologies (Ka-band and optical communications) also were identified as needs in the related, but potentially farther term arena of technologies for SEI support.

Advanced Data Systems. This technology need addressed both space based and ground based data systems. For non-SEI support, this need addressed the development of advanced data storage, data compression, and information management systems. These technologies also were identified as needed for SEI support in the longer term, with the addition of power/bandwidth efficient modulation and coding techniques, unattended network operations capabilities, overall fault tolerant systems designs, and data standards and protocols.

Advanced Navigation Techniques. For non-SEI mission support, a priority need was identified for new techniques for navigation with applications to cruise, approach and in-orbit phases of robotic and future piloted deep space missions. In this same area, SEI-supporting technology needs were identified by OSO for navigation transponders, GPS-type navigation receivers, altimeters/pressure/temperatures sensors and narrow angle and wide angle cameras, advanced inertial measurement units, and stable, long life clocks and oscillators.

Mission Operations. This OSO technology need

incorporated artificial intelligence, expert systems, neural networks, and increased automation in future ground based mission operations systems. The need as defined also includes a requirement for testbed development in order to checkout advanced software, for the coordination of distributed software, and for automated performance analysis of networked computing environments.

2.5 Other Mission Plans and Technology Needs

In additional to the long range plans and technology needs of program offices within NASA, the ITP effort has addressed other civil space technology, including both the needs of other components of the federal government (e.g., NOAA) as well as the needs of the commercial space sector.

Other Government Needs

The National Oceanographic and Atmospheric Administration (NOAA) currently depends heavily upon NASA for its future space instruments and technology. Consequently, NOAA's input to this process is an important consideration. The following is a prioritized listing of NOAA remote sensing technology needs prepared by the NOAA representative on the review team:

• ***Sensor Optical Systems.*** Studies are needed of sensor optical systems, focused on visible calibration systems. *Application:* Determination of cloud and land surface properties for studies of global change.

• ***Passive Microwave Sensing.*** Studies should focus on antenna systems to allow for high resolution (e.g., approximately 10 km resolution) spatial sensing at low frequencies (e.g., 5-6 GHz). *Application:* All-weather sea surface temperature determination.

• ***Active Microwave Sensing.*** Studies should be focused on cheaper and more efficient scatterometers, altimeters, and SARs. *Application:* For scatterometers, sea surface wind speed and direction determination; for altimeters, wave height, ocean circulation; and for SARs, sea ice thickness.

• ***Laser Sensing.*** Studies should focus on efficient methods for laser wind sounding. *Application:* Determination of global wind profiles which are required for input to numerical weather prediction models.

• ***Coolers & Cryogenics.*** Studies should focus on support for precision IR sensors such as the EOS/AIRS (Atmospheric IR Sounder) to increase vertical resolution of sounding retrievals. *Application:* AIRS data are needed for impact to numerical weather forecast models.

• ***Direct Detectors.*** Studies should focus on detector technology extending to the 18 micrometer region in support of EOS/AIRS (see above).

(Note: many of these areas are common between NOAA and the OSSA Earth observing program's technology needs.)

Commercial Space Sector Technology Needs

A variety of technology needs were identified during the development of the ITP by industry participants in the planning effort. In particular, two specific areas were defined in which the ITP could and should address the development of new technologies in a manner which is analogous to the relationship of the NASA aeronautics technology efforts. These areas include the commercial launch industry (using expendable launch vehicles and chemical upper stages) and the commercial space telecommunications satellite industry.

Appendix E of this report provides an overview of the issues facing the commercial space sector in terms of competitiveness and technology and provides a preliminary assessment of some steps that could be taken to address these issues.

2.6 Integrated Assessment of Technology Needs

The preceding sections provide only an overview of the wide variety of technology needs that have been identified by the various National users of civil space research and technology — both within and outside of NASA — and which were input to OAET as part of the development of the ITP. In general, the technology needs fall into three primary categories: (1) technologies which are broadly applicable to a number of missions (these tend to be more generic in character); (2) technologies that are enabling for a specific mission concept or program objective (for example, R&T pertaining to science instruments or SEI goals); and, (3) technologies that are of high value to using offices planning similar systems (e.g., transportation technologies for OSSA deep space missions and for SEI).

Many of the needed technologies are common to several different users and their respective mission plans, differing in some cases only in the projected timing or performance requirements of specific technology program deliverables. Figure 2-1 provides an assessment of the needs that are common to two or more of the using offices within NASA, including identification of the top level common technologies that emerge from an integrated assessment of these needs.[2]

Several of the technologies that are essentially unique to a specific user office seem to be extremely important — perhaps enabling — for particular civil space programmatic objectives. These include:

- *Technologies for Future Earth and Space Science Observations.* These technologies include advanced sensors and sensor processors, telescope materials and optics, precision controls-structures interactions, and science data management and visualization, plus others.

- *Technologies for SEI Mission Objectives.* These capabilities include very high leverage areas such as radiation protection in deep space, nuclear thermal propulsion, in situ resource utilization, and planetary surface system construction and maintenance.

In planning the space technology program, it is vital to develop a strategic approach that results in a consensus regarding the right balance between investments in mission unique, but perhaps enabling, technologies and those in very high leverage technologies needed by a variety of future civil space program users.

The review team noted that the technologies identified and prioritized by the separate program offices and organizations pertain primarily to each special sphere of interest. Establishment of priorities across the breadth of possible programs is a task yet to be done. It will require articulation of both NASA and National mission priorities.

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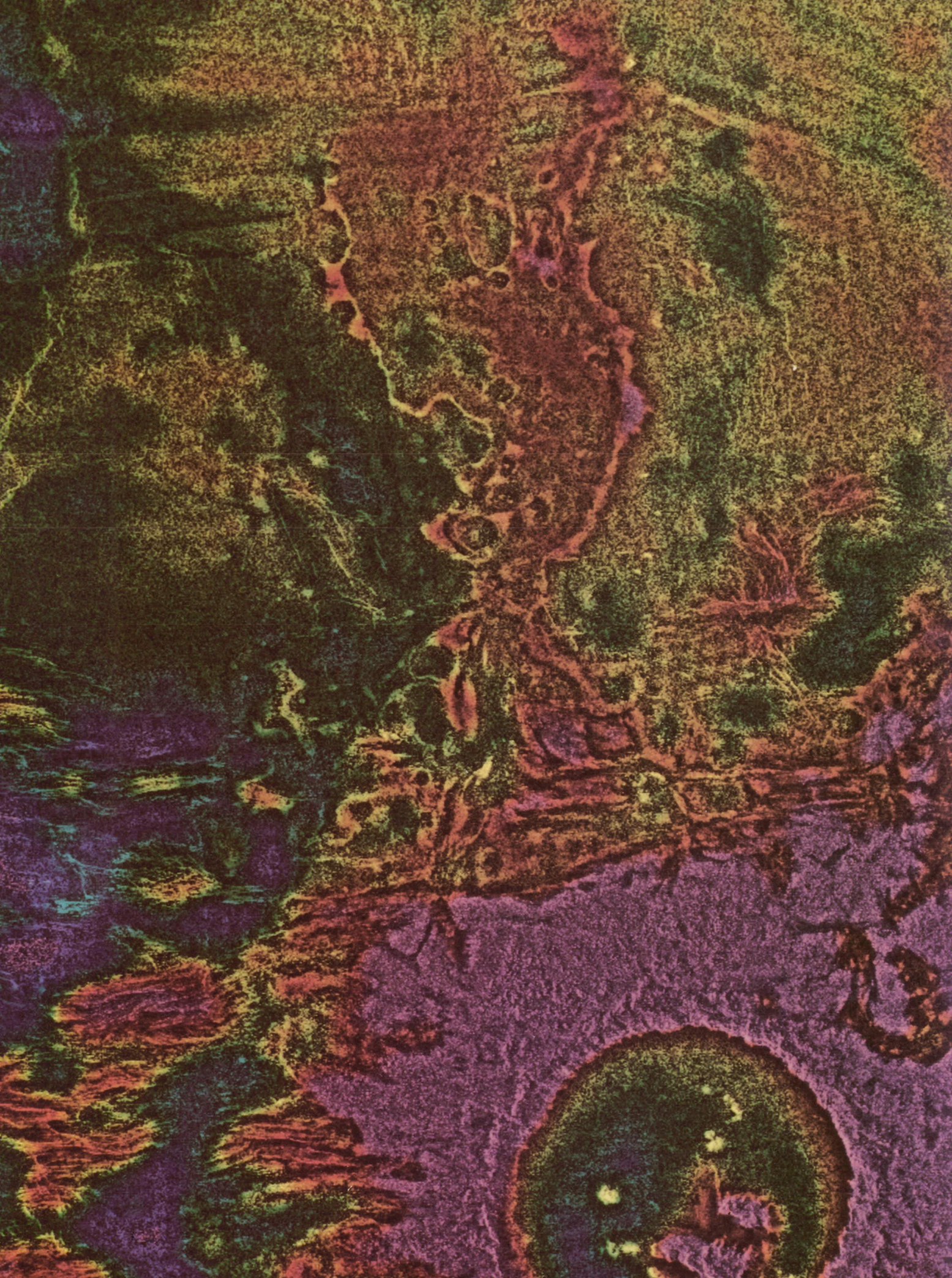
[2] Note: For non-NASA technology needs, the three clear areas of technology commonality revolve around: (1) telecommunications spacecraft R&T, (2) expendable launch vehicle R&T, and (3) NOAA R&T requirements related to remote sensing.

COMMON TECHNOLOGY NEEDS				KEY COMMON TECHNOLOGY AREAS
OSSA NEEDS	OSF NEEDS	SEI NEEDS	OSO NEEDS	
Advanced Data Systems	Vehicle Health Management	NASA/Synthesis SEI	High Data Rate Communications	ADVANCED EVA SYSTEMS
Advanced Space Structures	Advaced Turbomachinery Components & Models	Radiation Protection	Advanced Data Systems (Ground/Space)	REGENERATIVE LIFE SUPPORT
Robotics/Rovers	Combustion Devices	EVA Systems	Advanced Navigation Techniques	ADVANCED GN&C
Spacecraft Position/GN&C	Adv. Heat Rejection Devices	Regenerative Life Support	Mission Operations (AI, Software)	ADVANCED DATA SYSTEMS
Software/Data VIsualization	Water Recovery and Management	Cryogenic Fluid Management		AUTOMATION AND ROBOTICS
Nuclear Electric Propulsion	High Efficiency Space Power Systems	Micro-G Countermeasures		AEROASSIST R&T (TPS, GN&C,Aerobraking)
Advanced Solar Arrays	Advanced EMU's	Surface Power (nuclear)		STRUCTURES AND MATERIALS
Radiation Shielding for Crews	Crew Training Systems	Auto. Rendezvous/Docking		ADV. SPACE POWER (Nuclear/Solar)
Auto. Rendezvous & Docking	Characterization of Al-Li Alloys	Human Factors		THERMAL MANAGEMENT
Autonomous Landing	Cryogenic Supply, Storage andHandling	(Nuclear) Electric Propulsion		
Regenerative Life Support	Thermal Protection Systems	Synthesis SEI		
Advanced EMU's	Robotic Technologies	Heavy Lift Launch		
Micro-G Countermeasures	Guidance Navigation/Control	Telerobotics		
Sample Acquisition	Advanced Avionics Arch.	Materials and Fabrication		
Auto Sequencing		NASA SEI		
Auto S/C Fault Recovery		Cryo. Space Engines		
High Rate Comm (Optical, Ka-Band)		Aerobraking		
High Energy TPS		Surface Power (non-nuclear)		
Micro-G Medical Care		Autonomous Landing		
Thermal Control		Sample Acquisition/Analysis		
		Surface Mobility		
		Health Care		
		In-Space Construction and Processing		

These specific technology needs are (approximately) common across two or more of the NASA User Offices; The specific technology areas are shown, drawn from the various User Offices' inputs

These General Technology Areas are Common to Three or more Offices

Figure 2-1 NASA technology needs commonality assessment



The Integrated Technology Plan

Based on the technology needs identified by the several user organizations, both inside NASA and external to the Agency, OAET developed an Integrated Technology Plan for the Civil Space Program. The ITP consists of two major parts: an R&T Base (organized primarily by research discipline and that portion of the program that is targeted on emerging, high-risk but high-payoff new technology opportunities) and the Civil Space Technology Initiative (a family of focussed technology projects directed at developing and demonstrating new capabilities identified as needed by civil space technology users). This section provides an overview of the planning process and a brief summary of the ITP as presented to the review team.

3.1 Space R&T Planning Process

The OAET space R&T mission states that: "*OAET shall provide technology for future civil space missions and provide a base of research and technology capabilities to serve all National space goals.*" Accomplishing this mission entails meeting several top level objectives including:

- Identify, develop, validate and transfer technology to:
  - — Increase mission safety and reliability
  - — Reduce flight program development and operations costs
  - — Enhance mission performance
  - — Enable new missions.

- Provide the capability to:
  - — Advance technology in critical disciplines
  - — Respond to unanticipated mission needs.

To accomplish its mission and to respond to the technology recommendations of the Augustine Committee OAET created the ITP that was presented in detail to the external review team for their consideration.

The major components of the ITP planning process include: (1) an annual cycle (creation of an annual cycle for space R&T planning, involving both user office participation and external review of proposed plans); (2) a technology maturation strategy (including a flow of technology from base R&T programs, through focused R&T programs and into flight programs) which is then reflected in the work breakdown structure of the space R&T program; (3) a flight programs forecast (working with user offices, development of an integrated, thirty year forecast of civil space activities and associated technology needs); (4) a space R&T program implementation strategy (an implementation approach keyed to the flight programs forecast); (5) program decision rules (to allow detailed development of both a "strategic" ITP, which meets the identified needs of the user offices more or less fully, as well as a specific space R&T programs for alternate budget levels); and, (6) a process for program prioritization and budget development (on the basis of user-provided technology needs, and established program decision rules, explicit investment priorities for the elements of the focused programs are established, and detailed budgets developed for any overall budget guidance)[1].

3.2 ITP Content Summary

The ITP consists of two major parts: an R&T Base organized primarily by research discipline, (predominantly the "technology push" section of the program); and a collection of focused programs, entitled the Civil Space Technology Initiative (CSTI), which has been created through the merger of the existing focused programs (e.g., the Exploration Technology Program,, a.k.a., Project Pathfinder). Figure 3-1 illustrates this proposed ITP work breakdown structure.

[1] The details of the planning process and of the content of the Integrated Technology Plan are provided in one of the Appendices of this report.

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R&T Base

The space R&T Base provides the discipline foundation for the ITP, as well as resources for major, integrated university program activities and small scale technology flight experiment activities. Specific programs include:

- *Discipline Research* — which includes aerothermodynamics, space energy conversion, propulsion, materials and structures, information and controls, human support and advanced communications R&T

- *University Programs* — including the OAET University Space Engineering Research Center (USERC) program

- *Space Flight R&T* — including the In-Space Technology Experiments Program (IN-STEP)

- *Systems Analysis* — which addresses technology assessments and analysis for future space R&T planning support.

Civil Space Technology Initiative

The Civil Space Technology Initiative (CSTI) provides an investment in a family of focused programs within five major functional thrusts.

Space Science Technology. The Space Science Technology Thrust is primarily concerned with providing the technology needed for future space science missions undertaken by either NASA's Office of Space Science and Applications, or the Office of Space Exploration. Such missions are concerned with broadening our scientific understanding of the Earth, our solar system, and the universe beyond. To do this, NASA will make observations from both the Earth's surface and Earth orbit, and will send a series of increasingly sophisticated human and robotic spacecraft to a number of solar system bodies for *in situ* observations. Specific program areas include: (1) Science Sensing; (2) Observatory Systems; (3) *In Situ* Science; and, (4) Science Information — which includes planning for space R&T in the areas of massive data archiving and retrieval, and data visualization and analysis. Although none have been defined at present, technology flight experiments may be included in future Space Science technology thrust planning.

Planetary Surface Technology. The Planetary Surface Technology Thrust is primarily concerned with providing the technology needed for future human missions to the Moon and Mars that may be undertaken by NASA's Office of Space Exploration. Such missions have not yet been approved by the Congress, but may occur during the first few

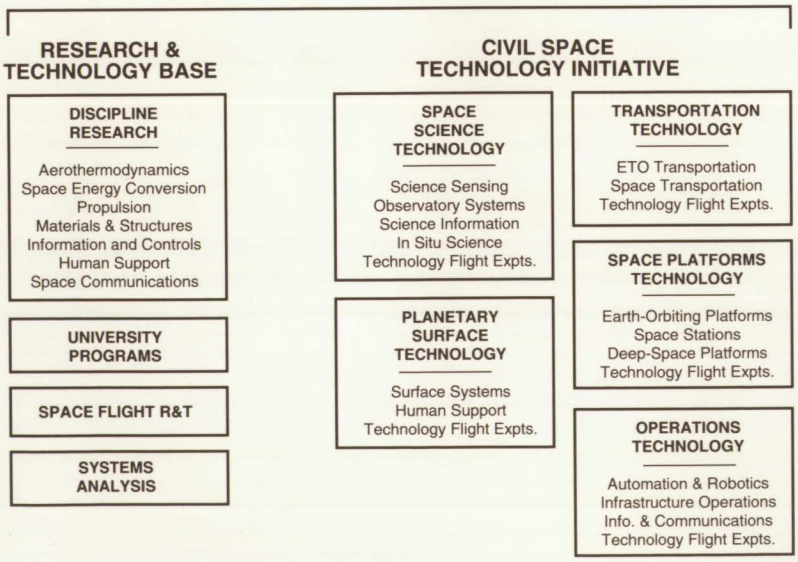


Figure 3-1 Space R&T Program

decades of the 21st Century. Specific program areas include: (1) Surface Systems; and, (2) Human Support — with planning for regenerative life support, radiation protection, extravehicular activity (for the lunar and Mars surfaces), exploration human factors (for very long duration space flight and for surface operations), medical support systems (for remote medical care) and artificial gravity. Although no flight experiments have been defined at present, they may be included in future Planetary Surface technology thrust planning.

Transportation. The Transportation Technology Thrust is primarily concerned with providing the technology needed for major future transportation improvements that may be undertaken by NASA's Office of Space Flight at the request of either the Office of Space Science and Applications, the Office of Space Exploration, or the Office of Space Operations. This could include such new transportation systems as a Heavy Lift Launch Vehicle, a second generation Space Shuttle, and a family of space transportation vehicles for transferring humans or cargo either between the Earth and the Moon or the Earth and Mars. Specific program areas include: (1) Earth-to-Orbit Transportation; (2) Space Transportation; and, (3) Transportation Technology Flight Experiments.

Space Platforms, The Space Platforms Technology Thrust is primarily concerned with providing the technology needed for future space platforms used either by NASA's Office of Space Science and Applications, Office of Space Exploration, Office of Space Flight, or Office of Space Operations. This technology will benefit both future human platforms, such as Space Station *Freedom*, and future large robotic spacecraft, such as the *Earth Observing System (EOS)*. Specific program areas include: (1) Earth Orbiting Platforms; (2) Space Stations; and (3) Platform Technology Flight Experiments.

Operations. The Operations Technology Thrust is primarily concerned with providing the future technology needed either by NASA's Office of Space Science and Applications, Office of Space Exploration, Office of Space Flight, or Office of Space Operations. This technology will support major operational improvements for future robotic and human missions, both on the Earth, in space, and on another natural body in the solar system (e.g., substantial improvements in the operation of mission control at the Johnson Space Center (JSC), improvements in communications between mission control and its spacecraft, and improvements in in-space assembly and construction techniques).

Specific program areas include: (1) Automation and Robotics; (2) Infrastructure Operations; (3) Information and Communications; and (4) Operations Technology Flight Experiments.

3.3 ITP Resource Implications Summary

Two resource levels were proposed for the ITP. The first entailed a significant effort to be responsive and address the great majority of user-identified technology needs. This potential set of resources was identified as the "*strategic*" or "full-up" ITP. The second option presented for the ITP included resources that were targeted at achieving the "*3-fold augmentation*" budget level noted in the Augustine Committee's Recommendation 8 regarding space technology. The latter budget option was significantly less than the former, "strategic" budget level.

Figure 3-2 presents a summary curve illustrating the two options and comparing them to the resource requirements of the OAET space R&T program as submitted as part of the President's FY 1992 budget to the Congress.

Figure 3-3 provides a summary (in FY 1991 dollars) of the projected FY 1997 resource requirements of the ITP at both the "*responsive*" and the "*3-fold augmentation*" levels, organized by R&T discipline program area, consistent with the individual discipline area review panels (whose summary reports are provided in the following chapter). In 1987, the National Research Council's Aeronautics and Space Engineering Board (ASEB) conducted an independent review of technology needs for future missions. For comparison, Figure 3-3 also provides the resources that were estimated to be required by this group, normalized to FY 1991 dollars.

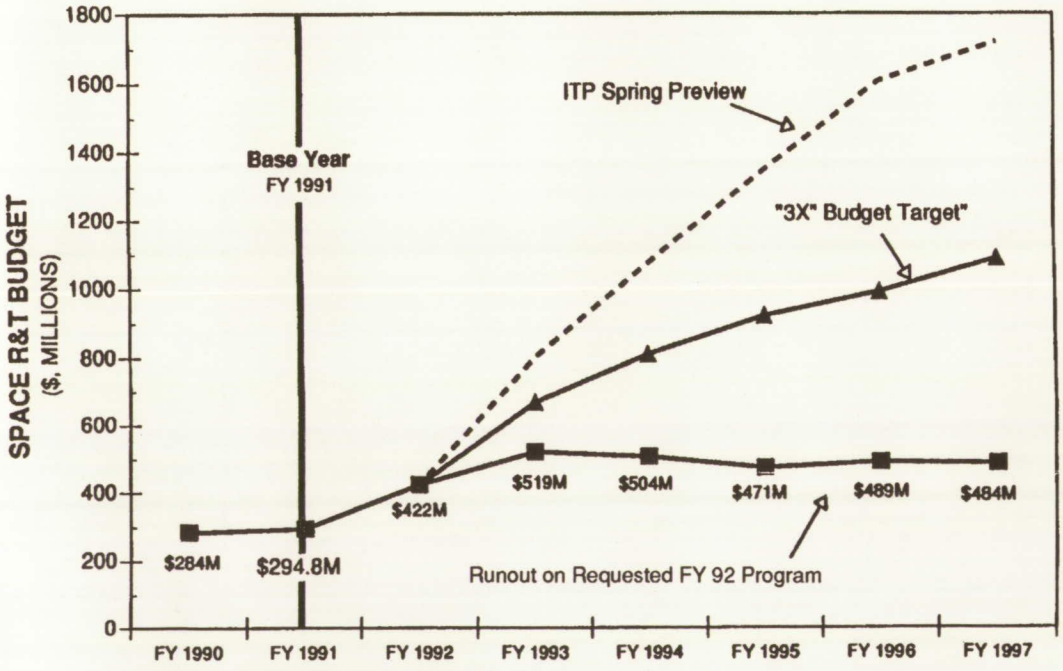


Figure 3-2 Space R&T Recommendations

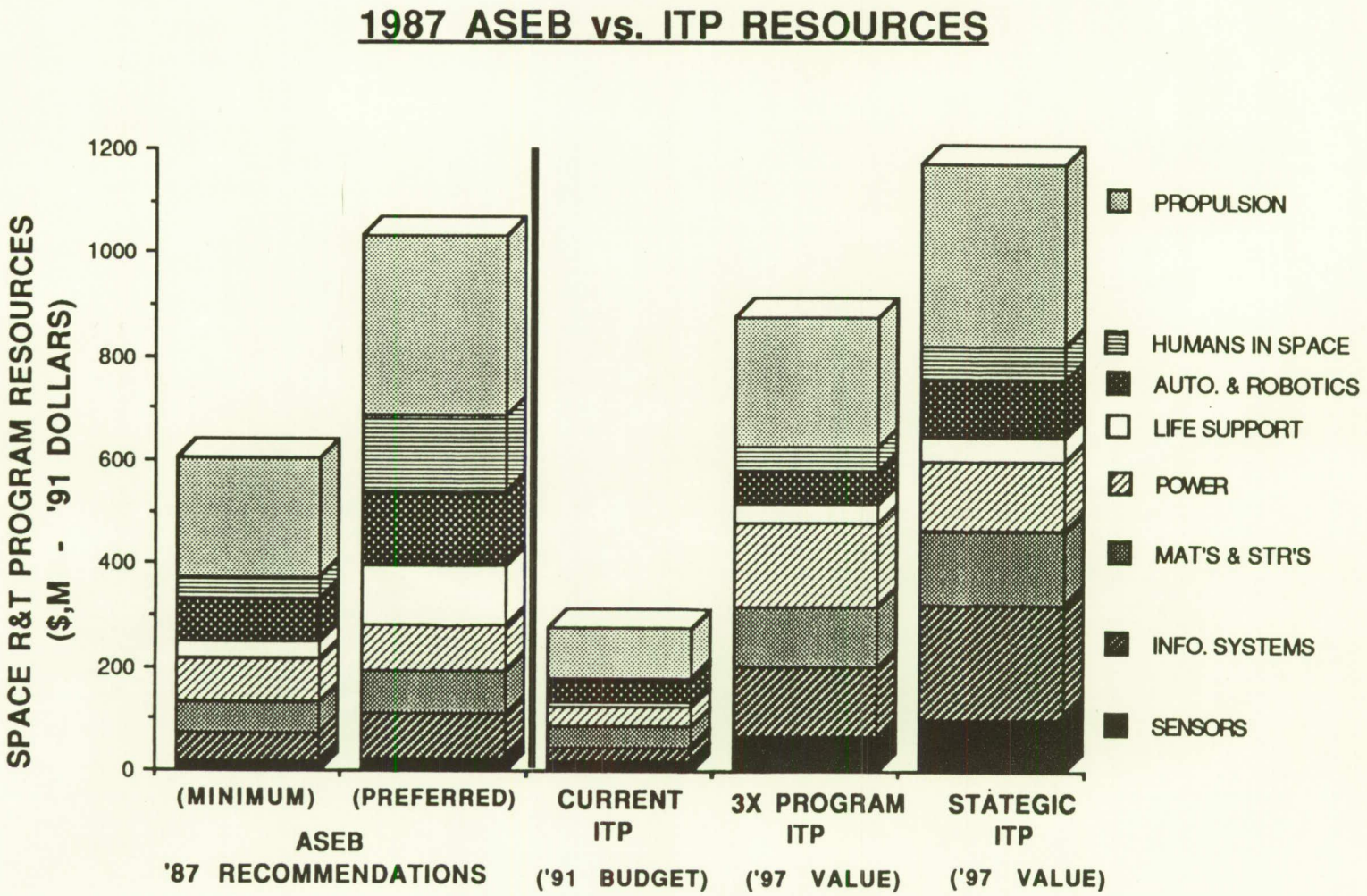
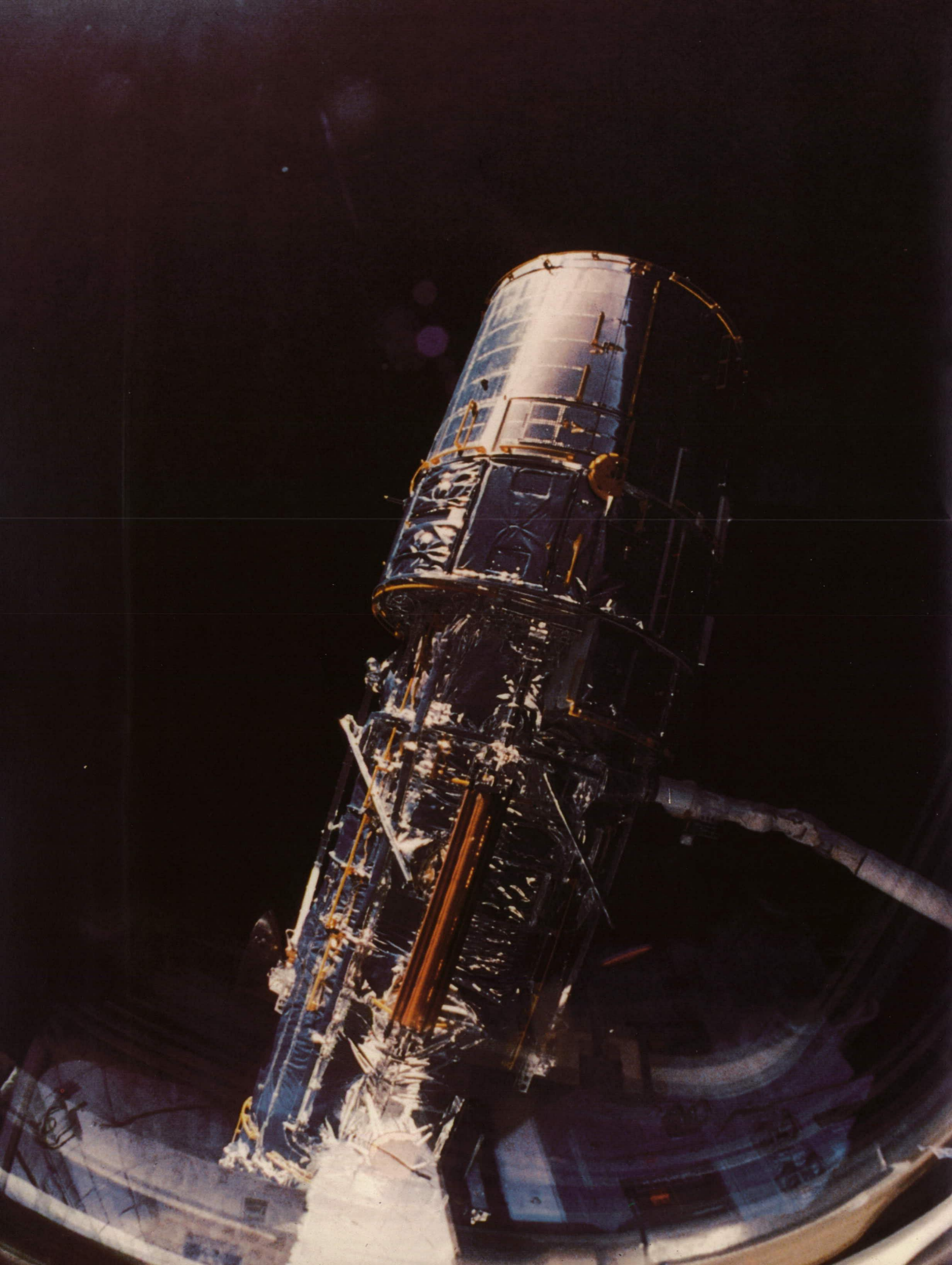


Figure 3-3 Integrated Technology Plan for the Civil Space Program
—Assessment of Previous Recommendations



Summary Reports of the Technical Panels

The external review team conducted detailed technical reviews of the proposed Integrated Technology Plan for the Civil Space Program. Each of the panels reviewed both R&T Base as well as focused R&T components of the ITP across a given area of technology. The following section provides summary reports from the several technical review panels, in the following areas:[1]

- Propulsion
- Power
- Human Support
- Automation and Robotics
- Materials and Structures
- Data Systems and Computer Science
- Communications, Photonics, and High Temperature Superconductivity
- Remote Sensing
- Guidance and Controls
- Aerothermodynamics
- Space Test Programs.

4.1 Propulsion Panel Report Summary

The Propulsion review panel was impressed by the NASA presentation, and the quality of the technical efforts described. The focused planning effort has been effective, and we hope that the technical momentum will be maintained. Specific comments on the key propulsion programs include:

• ***Low Thrust.*** This is an aggressive and well planned component of the program; low thrust propulsion is high leverage technology because of potential weight savings for many spacecraft types. This research will be directly applicable to solar electric propulsion systems (SEPS), and nuclear electric propulsion systems (NEPS). See the nuclear propulsion discussion below.

• ***Earth-to-Orbit (ETO) Propulsion.*** This focused program which points toward a new generation of H/O rocket engines beyond SSME, was thought to be a well planned and executed program of great importance to NASA, and applicable to NLS. Emphasis is on component development.

• ***Large Thrust.*** There is a large thrust propulsion program related to the ETO focused program in the R&T Base. This effort in high thrust chemical rocket R&T seems seriously underfunded. Also, the new *"Low Cost Commercial Transport Initiative"* is an excellent idea which will help the commercial industry. NASA is urged to encourage industry to participate in this effort. The level of coordination between the Lewis and Marshall Centers is gratifyingly high.

• ***Advanced Concepts.*** This component of the program is of ultimate importance for exploration of the outer solar system and beyond. This is one of the only U.S. efforts that significantly addresses the need for new options derived from novel physical approaches and several promising possibilities have emerged. This effort is sound, well managed, and very well received by external agencies (DOD, DOE).

• ***Space Chemical Engines.*** This program, too, is well planned yet has been inadequately and inconsistently funded. It would provide a badly-needed "testbed" to evaluate all components and configuration of advanced cryogenic engines. The particular engine under study would have wide throttling limits for OTV applications. This testbed approach should be given steady support at the highest feasible level, and should be consider for coordinated use by commercial users as well as by NASA. It seems possible that NASP results may have application in this R&T area.

• ***Cryogenic Studies.*** This program covers issues of cryogenic fluid management in space which are vital for future space missions. Tests in space are crucial, and NASA is urged to reconsider whether the physical issues can be dealt with in test of a scale that can be afforded with today's budget.

• ***Nuclear Propulsion.*** Nuclear thermal and nuclear electric propulsion carry the long term potential for the future of space exploration far beyond Earth. Nuclear options promise cost, performance, and flexibility of mission architecture. This is a program for U.S. leadership in planetary exploration. The

[1] The full text from each of the technical review teams are provided in the appendices of this report.

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NASA plan is broad, technically responsible, and objective. Funding levels seem appropriate for the moment. We urge that the necessary technology effort be built carefully, and that decisions be made with the greatest care, regardless of short term program pressure — they can have consequences far into the future, as the history of the civil nuclear power program teaches.

• ***General Comments.*** Certain general comments on the rocket technology programs arose in discussions. The most important is that NASA should be careful to coordinate closely with DOD (in particular, SDIO) studies that are on parallel tracks.

4.2 Power Panel Report Summary

Power technology is highly interdisciplinary and as a result, system improvements tend to be evolutionary rather than revolutionary. All space missions begin with an energy budget and are terminated when that energy budget is expended. As a result, improvements in power technology translate to increased lifetime as well as increased mission capability or reduced weight. The U.S. space program could be on the threshold of achieving an unprecedented growth in capability, but only if we are willing to make an increased investment in power R&T. NASA presented a well thought out *Power and Thermal Management Program* addressing crucial research and development needs in: power sources, energy storage, energy conversion, power management and distribution, and thermal management. Specific comments on key power technology programs include:

• ***Space Nuclear Power.*** The SP-100 project should continue as the focus of NASA's nuclear reactor space power program. Progress was made in growth and scaling capability of the reactor and in thermoelectric and other advanced conversion R&T. SP-100 appears to provide significant nuclear electric propulsion capability. Alternate reactor concepts were adequately considered. The panel recommends that NASA not pursue in a major way alternative concepts since this would be unnecessarily dilutive and non productive. NASA should however, monitor other DOD programs in space nuclear power and contribute expertise and resources as appropriate.

• ***Beamed Power.*** The review panel found the presented material on laser-electric beamed power technically interesting. A system study to address tradeoffs for various applications is needed prior to the commitment of significant funding.

• ***General Comments.*** The NASA technology program, both R&T Base and focused programs, must be significantly augmented. The program is fully responsive to requirements recommended by the Augustine Report, placing primary emphasis on a structured research and technology program meeting future NASA needs. The plan was well coordinated with potential users, addressing unmanned and manned earth orbital and planetary spacecraft, and lunar/planetary surface power.

4.3 Human Support Panel Report Summary

The area designated as Human Support within NASA's Office of Aeronautics, Exploration and Technology embraces a broad assortment of technological responsibilities and disciplines. Specific review comments regarding key human support technologies include:

• ***Biomedical Support.*** The program for Biomedical Support appears adequate to meet requirements for platforms and exploration with the exception of two areas: sensors and refrigerator-freezer development. The program uses evolutionary technology that proposes to build on the biomedical equipment being developed for the Space Station *Freedom* post-permanently manned configuration phase.

• ***Human Factors/Crewstation Design.*** Human Factors includes the allied areas of human-machine interface, habitat design, decision aiding, and training. The Human Factors Program was judged to be well conceived and well executed and responsive to mission requirements. Consequences of no action for this key technology area include higher costs for training, potential loss of mission due to catastrophic human error, and loss of data/capabilities due to inadequate human performance.

• ***Extravehicular Activity Systems.*** The EVA Technology plan adequately covers future platforms, Lunar, and Mars mission requirements. If no technology action is taken, limited platform and Lunar surface EVA's will be possible, but at significant costs and far less than optimum

productivity, operability and safety. Mars surface EVA is simply not achievable with today's systems, and technology development will be required to put this capability in place.

• ***Regenerative Life Support, Fire Safety, and Habitat Thermal Management.*** The Regenerative Life Support, Fire Safety, and Habitat Thermal Management programs address the needs of the platforms, Lunar and Mars mission requirements. For all key technology opportunities, payoffs center on sustaining human life and by providing maximum logistical and safety benefits.

• ***General Comments.*** General comments include: 1) proceed with the development of a closed loop life support system; 2) establish a robust sensors development program to meet the needs of human support systems and address chemical, microbial, and biomedical sensors, and fire and smoke detection sensors; and, (3) reprioritize all human support program elements consistent with the OAET ITP "Strategic Plan" process methodology.

4.4 Automation and Robotics Panel Report Summary

The planning presented by the NASA OAET automation and robotics (A&R) team was done with the most care, thoughtfulness and concerted effort that the review panel has seen in recent years. Several plans were presented, corresponding to several levels of officially proposed funding. One of these levels was described as the "*baseline R&T funding.*" Perhaps the most remarkable point for the review panel to note is that the share of resources going into the area of A&R at the "*3-fold augmentation funding*" level was only 20 percent above that of the baseline. This is a very serious issue. The review panel believes that powerful supervisory telerobot teams (including both humans and robots) will *have* to play a new, central role in future space endeavors. This role makes A&R a technological pillar for the future of the civil space program — along with propulsion, guidance and new materials — that must be greatly strengthened. A&R's current level of R&T funding (or the 20 percent addition proposed in the "3-fold augmentation" budget levels) is far short of what is already absolutely essential to give America any substantive advance in space exploration.

The area of automation and robotics (A&R) was presented in three major sections: *Artificial Intelligence* (AI), *Telerobotics* (TR) and *Planetary Rovers.* Specific comments on key technology issues include:

• ***Artificial Intelligence.*** The AI Program has made excellent progress, particularly toward getting AI applications transferred into important roles at the mission operational level (e.g., in mission control consoles), where the panel understands it is expected soon to begin enhancing operational performance and saving significant operational funds.

• ***Telerobotics.*** The review panel believes that what is absolutely essential for significant future American advances in space is the development of human-robot *teams* in which the human — on Earth or *in situ* — is much more powerful than before because the robot can pursue tasks that are assigned in real time at a high level. Such tasks require of the robot reasoning and decision-making as the unexpected is encountered. Only then will the human be freed from continuous hand-in-glove control of the robot's joints (which demands total attention and is exhausting for the operator), and freed to plan and command the next tasks. Building upon the (currently modestly funded) OAET Telerobotics (TR) Program to date, the integrated supervisory-human/telerobot team is a system that must be achieved. (The modest experimental research that does exist in this arena is already producing students who are superbly trained in the broad interdisciplinary synthesis of engineering *systems.*)

• ***Planetary Rovers.*** The Rover Program, which has been ongoing for several years and is absolutely essential to any planetary exploration, has been zeroed in current FY 1992 NASA baseline budgetary planning. This is of concern because stop-start funding has a devastating effect on programs, particularly in terms of maintaining expertise and skill. The review panel recommends that a continuing, core development research program be established in this area, or else planning for future planetary missions will never become reality.

• ***General Comments.*** American core research in supervisory telerobotic human/machine systems is very important. With the present American funding level — or the proposed 20 percent increase (proposed in the "3-fold augmentation" program) — the foreign competition is and will continue to be pulling away fast; and each foreign country will, in particular, get far out in front in the area of human/machine systems capabilities in its national infrastructure. This will leave the U.S. *crippled* or dependent: crippled in future space endeavors and crippled in National economic strength. The review panel strongly recommends increased emphasis on A&R in NASA technology planning, with continuing balance between R&T Base and focused development program efforts.

4.5 Materials and Structures Panel Report Summary

The Materials and Structures Programs within NASA's Space R&T effort cover a very broad spectrum of activities. Within the R&T Base, these include: material science; space environmental effects; aerothermal structures and materials; space structures; and, dynamics of flexible structures. Embedded in these topics is a broad array of activities, which include participation not only from the NASA research centers, and from NASA flight centers, as well as many universities. Specific comments on key technology issues include:

• ***R&T Base.*** With respect to the R&T Base, the review panel had the following conclusions: there is a good balance between near and far term needs; the R&T Base efforts support the focused programs; and the focused programs support user needs.

• ***Controls-Structures Interactions (CSI) Technology.*** The CSI technology program is a model for space technology. It has forged two previously disparate disciplines, controls and structures, into a single discipline. There is participation by most of the NASA centers, by industry, and universities. The CSI effort is well managed and encompasses both theory and scheduled flight experiments to validate the results of ground testing.

• ***LDEF and Space Environmental Effects.*** The review panel recommends that many activities now being conducted under the rubric of the Long Duration Exposure Facility (LDEF) be incorporated into the broader OAET program, Space Environmental Effects (SEE). A complementary focused R&T effort directed toward the creation of a *Space Materials Handbook* is needed. The review team noted with approval that NASA is working closely with the DOE laboratories in this area.

• ***Facilities.*** A major contributor to NASA's technological leadership has been its unique experimental facilities. In this regard, the review panel believes that the *Arcjet Facility* at NASA ARC should be upgraded: it is essential for the invention of new materials required for projected future missions. Planning for this upgrade should be well coordinated with other DOD facilities needs. Moreover a *Combined Space Environmental Testing Facility*, is needed to determine the extent of the synergisms on materials when subjected simultaneously to atomic oxygen, ultraviolet radiation, protons, etc.

• ***General Comments.*** The review panel wishes to reaffirm the importance of reducing structural weights at an affordable cost. There are perceived gaps in the current R&T Base program. Specifically, there are no coherent programs in: (1) launch vehicle structures; or, (2) rocket motor throats and nozzles. Programs in these areas should address: (a) materials, (b) structural concepts, (c) efficiency, (d) manufacturing, and (e) low cost and/or affordability. Also, the review panel believes that there should be a program element addressing the repair of space structures and a materials program to develop materials for the protection of equipment against the radiation of space.

4.6 Data Systems and Computer Science Panel Report Summary

The technical review panel found the overall plan and supporting presentations to be thorough and of high quality. The data systems and computer science planning presented supports both technology opportunities and the user's prioritized needs. The panel felt that the ITP effort has worked in enhancing user advocacy and in prioritizing efforts and in identifying new needs (e.g. Flight Control Operations Technology). The panel felt the program was reasonably focussed in the 1991

through 2000 timeframe, but that more consideration is needed for post-2000 options (e.g. Mars mission efforts) in the next iterations of the plan. Also, leveraging from other agencies and industry is a dominant factor in achieving technical goals in this area. Specific comments include:

• ***Onboard Memory and Storage.*** The onboard memory and storage activity objective is to develop high performance, space qualifiable data storage technologies. The panel endorses this activity and recommends that potential users be actively involved in R&T efforts. The plan for flight demonstration of the technology to demonstrate flight qualification is endorsed by the panel.

• ***Advanced Flight Computers.*** The panel fully endorses this program and commends the professional working relationships with the DOD to effect a good leverage. The long delays in realizing computer technology advancements in spacecraft computers must be eliminated. Strong funding support for this program and continued emphasis on leveraging DOD and commercial efforts are necessary for timely insertion of computer technology in spacecraft. A balanced program, as proposed, including hardware, software and system tools is mandatory.

• ***Special Purpose Processors.*** The panel endorses this program as proposed. Program relevance is clearly defined and benefits justify this investment. The program has a good balance between special processors for SAR and HIRIS and generic processors such as autocorrelator and cross correlators. Microelectronics efforts need continued emphasis, leveraging industry and relevant DOD efforts.

• ***Onboard Networking and Testbeds.*** The networking and testbeds activity objective is to develop high performance, space qualifiable networking technologies. The panel endorses the area. Architectures and standards will be driven by other developments in commercial and DOD. The program should leverage these developments by utilizing state of practice rather than developing state of the art. The establishment of a testbed, the flight systems validation laboratory, does have value in demonstrating emerging technologies.

• ***Archiving, Access, and Retrieval.*** The archiving, access, and retrieval activity is to develop technology for automated characterization, and interactive retrieval of large complex scientific data sets. The panel endorses the activity and strongly recommends the development be performed in support of the Earth Observation System (EOS) enabling insertion of this technology into the EOS/DIS system.

• ***Visualization.*** The panel endorses the proposed visualization task. The value of this task will be in cost containment by providing users with a tool that supports comprehensive use of the science data provided by a program like EOS rather than having to address issues such as the delivered data not meeting the needs of users.

• ***Neural Nets.*** The panel endorses the Neural Network Program. The panel recommends that the effort maximize its leverage of industry activity in order to reduce the cost of application development, and of DOD efforts in order to accelerate technology maturation.

• ***Software.*** The panel endorses the Software Engineering Program task with the following observations and recommendations. This task should provide the enabling NASA unique tools and the integration required to permit the establishment of a common software support environment for the agency. The panel recommends that agency-wide participation be instituted along with the program.

• ***Multi-Mission Operations Testbed.*** The panel encourages the application of R&T funds to improve operations, but concurs with the low priority of funding for the currently defined program (zero funding in fiscal years 1993 and 1994). It is recommended that the program be rescoped to include technologies such as AI and neural nets and to address a plan for technology transfer.

4.7 Communications, Photonics, and High Temperature Superconductivity Panel Report Summary

Communications

Recent internal coordination efforts have resulted in a greatly improved Integrated Technology Plan. The communications R&T program has three major customers: OSSA, OSO, and the U.S. commercial satellite communications industry. Enhancing U.S. competitiveness in the satellite communications area is becoming increasingly important when one realizes that this industry will be a $50 billion industry in the 1990's and the foreign market share in satellite manufacturing will increase dramatically from 1979 to 2000.[2] Specific panel comments on key technology areas include:

• ***RF Technology.*** This area involves work in high powered amplifiers, monolithic microwave circuits, advanced antennas and a number of other related microwave component areas. This is a very important area for space communications and could have a major impact. The consequences of not pursuing this area would be increased dependence upon foreign suppliers and less capable spacecraft.

• ***Digital Technology.*** This area has increasing importance as more signal processing is incorporated in spacecraft and on the ground to carry out more complex missions and higher performance in commercial satellite communications. The consequence of not carrying out the program in this area will be less capable spacecraft and an inability to carry out more complex scientific missions and provide higher performance commercial spacecraft.

• ***Optical Technology.*** Significant progress is being made in components and systems in this area. It is the key enabling technology for extremely high data rate communications for both deep space and near earth missions and operation. In the commercial arena, both in Europe and in the Pacific, substantial investment is being made for satellite-to-satellite links important for higher performance satellite systems. Flight validation of complete systems is important.

• ***Mobile Communications Technology.*** Mobile communications technology will be significant in future commercial satellite communications. However, although foreign activity in this area is extensive and a lack of R&T support will undermine the U.S. position, nevertheless commercial developments are outpacing NASA and may be adequate. Additional study is needed to determine whether NASA R&T is needed.

• ***General Comments.*** Systems integration, test and evaluation capabilities are the cornerstones in carrying out communications flight programs and missions and reducing risk in such flight programs. R&T to improve those capabilities should continue to receive strong support. Also, advanced communications system studies are needed to increase the effectiveness of technology planning for NASA missions, NASA operations and for increased U.S. competitiveness. Also, we recommend a broad-based communications working group be established made up of multiple centers, codes, industry, DOD and academia.

Photonics

The Photonics Technology Program at NASA was essentially zeroed three years ago when it was moved from the R&T Base and CSTI categories to the Pathfinder Program which was drastically cut, leading to deferral of virtually all photonics funding, with the exception of minimal efforts in the R&T Base. To yield results, funding at the significantly expanded levels would be essential. At more probable levels, major use of DARPA and industry sponsored work should permit some useful NASA related effort. While the program has set up valid milestone demonstrations, they are not presented as linked to real NASA projects but should be if technology transfer is to be effected. Overall, the orientation of the proposed program presented to the review panel is good; however additional coordination is needed with other government Agencies and industry. NASA, with its limited resources, should concentrate on a few near term R&T projects that can yield demonstrations defined in conjunction with potential users.

High Temperature Superconductivity (HTS)

High temperature superconductivity is a revolutionary new technology of interest for NASA's primary missions, including both Earth orbiting and deep space missions. Unique electrical and thermal properties offer possible major improvements in system performance and reliability, large reductions

[2] This subject is discussed in more detail in Appendix E of this Report.

in size, weight and electrical power requirements, and extension of mission life. As funded currently, the NASA program entails a less than optimal effort expended across a wide variety of areas; insufficient to do truly valuable research except for studies. If this continues, NASA will probably "stay smart" in the area, but will lack near term research accomplishments, thus missing possible opportunities to insert this new technology into missions. It is the panel's recommendation that NASA choose two highest priority HTS R&T projects and fund them adequately to a demonstration stage, while maintaining ongoing research to bring forward additional concepts for consideration in later years.

4.8 Remote Sensing Panel Report Summary

Remote sensing technology has been underfunded for many years, yet the Augustine Committee report cites it as one of the highest priority needs of OSSA. In addition, the National Oceanographic and Atmospherics Administration (NOAA), which has historically depended primarily upon NASA for its sensor technology, foresees a need for improvements in several sensor areas. In order to reach sensor milestones needed for these future missions, the panel recommends strong support for this critical area. Specific panel comments on key technology areas include:

• ***Submillimeter Wave Sensing.*** Submillimeter radiometry is the highest priority, near term technology need of OSSA. R&T is needed in: submillimeter mixers; tunable local oscillators in the submillimeter region; and cryogenic systems to achieve appropriately low temperatures (see below). For the mixers and tunable local oscillators, the existing program needs to be greatly augmented. The proposed program presented to the review panel makes a good start in this direction.

• ***Direct Detectors.*** Submillimeter wave detectors are some of the highest priority OSSA near term requirements. The panel also strongly endorses UV, IR array and high energy (gamma ray) detector research in areas where DOD is not already investing heavily.

• ***Laser Sensing.*** Sensors based on laser technologies are of increasing importance in determining atmospheric, land, and ocean surface variables of import to not only the Earth's future due to changing climatic conditions but to the safety of everyday aspects of life involving agriculture, transportation, health hazards, and pollution. Because of the importance of laser remote sensing and the breadth of experimental work required, we recommend strong support for this element of the science sensing technology area. However, NASA must continue to insure that their research is well coordinated with other National efforts.

• ***Sensor Electronics and Processing.*** Reducing noise and increasing the pixel format for hybrid, low temperature IR sensor readouts is extremely important. The proposed sensor electronics technology element should be integrated into or closely coordinated with the direct detectors technology element. It should focus on particular areas such as lower noise for the near and mid-IR sensors and readouts for far-IR photoconductor and bolometer arrays. NASA's requirements in these areas are virtually unique.

• ***Coolers and Cryogenics.*** Future NASA science missions that will use supercooled detectors will also need low vibration, long life cryocoolers; NASA should pursue the development of such coolers. There is excellent coordination and programmatic cooperation between NASA and the DOD in this area. The review panel recommends strong support for the Coolers and Cryogenics element, including in space demonstrations to verify operational characteristics.

• ***Passive Microwave Sensing.*** Advances in passive microwave sensing are urgently needed for future Earth observation missions and to provide complementary measurements for other space science investigations. Some enhancements of current systems can be achieved through improvements in engineering and existing components; however, the proposed program includes more fundamental advances in the state-of-the-art which are endorsed.

• ***Active Microwave Sensing.*** This program is new and currently unfunded. Its purpose is to provide NASA (and NOAA) with the ability to measure land and sea parameters of interest to the U.S. Global Change Research Program. The review panel recommends that support be provided.

• ***Sensor Optical Systems.*** This in an expanding technological field of increasing significance; however, much work has already been done, funded and/or supported by other institutions. Also, there are facilities which have a suite of costly characterization instrumentation and analytic codes which can be leveraged. The review panel advocates establishment of an optics technology R&T Base program. However, a multi-Agency coordinating optics "council" should be established to insure cost effectiveness in these pursuits.

• ***General Comments.*** The current budget for the sensor technology program is less than 5 percent of the overall NASA space R&T budget, so the recommendations for its expansion would not have a significant negative impact on the overall space R&T budget. To reduce the cost of future space missions for Earth observation, emphasis should be place on reducing the size and mass of instruments, while maintaining functionality, thereby allowing less expensive concepts to be used. Moreover, "advanced sensors" is one of eleven technologies considered critical for America's future competitiveness by the Aerospace Industries Association. It is therefore important to maintain U.S. leadership in this area. The review panel also notes that because of the widespread activity in universities and industry, sensor development is particularly appropriate for peer reviewed, competitive proposals in response to announcements of opportunity (AOs); the panel suggests that NASA expand its use of this approach.

4.9 Guidance and Controls (G&C) Panel Report Summary

The program briefed covered guidance, navigation, controls, and other avionics technology. The current program (which is strictly R&T Base) is well structured to provide basic technology across a broad range of applications in space transportation and space platforms. It has a good balance among development of analytical and computational tools; GN&C concepts and algorithms; and component technology (e.g., sensors and actuators). The program makes effective use of industry and universities, as well as their own highly competent in house staff to produce quality research and technology. The experimental facilities seem appropriate, but should be be reassessed as more focused elements are initiated. The review panel fully endorses the current R&T Base program including proposed growth. Specific panel comments include:

• ***Controls-Structures Interaction (CSI) Technology.*** The CSI technology program — although managed through the OAET Materials and Structures Division — is a joint effort with the guidance and controls personnel within the OAET Information Sciences and Human Factors Division. The CSI program was reviewed and is endorsed by this panel. The CSI effort has a good balance among analytical methods, control concepts and laboratory testing, with planning for potential future flight experimentation.

• ***Micromachines/Sensors.*** An important new technology with high potential payoff was briefed to the panel, called "micromachines/sensors". The concept is to develop extremely small machines, principally sensors, but also actuators and possible other machines, using microelectronics fabrication techniques. JPL's Center for Space Microelectronics Technology is making strong progress in this area. The panel believes that the potential benefits are so important that a small exploratory activity should be started immediately.

• ***ETO Vehicle Avionics, Transfer Vehicle Avionics and Commercial Vehicle Avionics.*** The primary motivation for these initiatives is lower space transportation costs. Advanced avionics systems technology including an open architecture, modular elements and fault tolerance is a key to reduced avionics systems/operational costs. Vehicle health management (VHM) avionics is particularly important. The proposed new efforts offer potential

reductions in operational costs of many vehicle systems, not just avionics.

• ***Autonomous Landing and Autonomous Rendezvous and Docking.*** These are enabling technologies for the unpiloted vehicle operations planned in the SSF program and SEI. Technology development and demonstration programs will be needed before these programs could commit to such unpiloted operations.

• ***Earth Orbiting Platform Controls, Deep Space Platform GN&C and Precision Pointing.*** The panel supports the requirements for the proposed new spacecraft/platform G&C initiatives. However, we recommend that additional efforts be made to obtain OSSA endorsement and definition of their needs for these technologies for the future programs.

• ***Technology Transfer.*** OAET's G&C efforts have produced significant accomplishments at the base level, but lacks major focused elements needed for transfer into high priority mission applications. Additional effort is needed to assure better technology transfer, including technology coordination efforts, such as NASA's Strategic Avionics Technology Working Group (SATWG). We recommend that OAET work with OSF and OSSA to develop better understanding of their requirements and more detailed technology insertion roadmaps.

• ***General Comments.*** NASA has done an excellent job of responding to user requirements. (For example, OSF ranked VHM among the highest of their priorities, and this technology figures prominently in OAET's ITP.) The panel endorses the proposed focused G&C elements. However, the R&T Base should not be sacrificed for the proposed new focused programs.

4.10 Aerothermodynamics Panel Report Summary

The review panel observed significant changes in the program including contacts, outlook, organization, and coordination of the OAET research center personnel with potential flight program users and other centers with complementary interests and capabilities. There was considerable increased appreciation of potential mission applications through contacts and the system and configuration analysis activities, specifically where the vehicle thrusts matched NASA's future plans. Some concerns remain, however. For example, the absence of an expanded and transferred activity of the unique computational chemistry capability developed at the Ames Research Center (ARC) to other NASA centers or to other government agencies, universities, and industry. Specific panel comments in this technology area include:

• ***Aeroassist Flight Experiment (AFE).*** Basic aerothermodynamic technology has advanced to the point that a major flight test is currently planned (i.e., the Aeroassist Flight Experiment — AFE). This flight test must be supported to its full conclusion or the investment of years of research efforts to develop this unique capability will not be exploited. The panel recommends full support for the AFE program at the highest level possible for successful completion of flight program and full analysis of the resulting data. The panel also recommends that a contingency plan be developed, possibly including a second vehicle, due to the importance of the AFE results.

• ***CFD Validation.*** The review panel strongly supports CFD validation efforts using ground and flight tests. The successful AFE flight test is a critical element for CFD and ground test validation. Aerobraking technology cannot be transferred to systems because of the lack of adequate ground test facilities and the reliance on not yet validated CFD codes. The panel believes that CFD is key to the future of this technology, systems analysis, performance estimation, and vehicle design. It must be validated in the regions of flight most critical to applications.

• ***Ground Facilities.*** Present ground test facilities are totally inadequate. Facility research and concept studies are needed to determine future ground test possibilities. Partial simulation would be valuable for specific testing of CFD validation. Increasing the present arcjet test capability is required for advanced materials testing. Ground facilities will enhance the value of future flight tests by aiding instrumentation development and analysis, and by aiding the analysis of AFE data. Facilities development must include extensive sensor and instrumentation development to provide the full benefit of generating the extreme flight conditions, either fully or partially. The panel strongly supports facility research and construction in this area.

• ***Configuration Assessment.*** In addition to the configuration and system studies which provide a very important focus of the base R&T effort, configuration assessment includes the evaluation of aerothermodynamic performance using detailed computational tools and experimental capabilities of the base program (i.e., as per the request of OSF). Consequently, validated CFD and ground based experiments are essential capabilities for this activity. This requires unique facilities, some of which are available in the base program, to optimize the important contributions of aerothermodynamics technology to NASA's goals. The review panel supports expansion of configuration and systems studies.

• ***General Comments.*** The new organizational framework is not supported by a base R&T program at a level commensurate with potential contributions, and the program is not balanced in the experimental vs. CFD activity. The review panel recommends extended sensitivity analyses of the Aerobraking concept; such analyses will help focus and establish R&T priorities. A significant increase in support is needed.

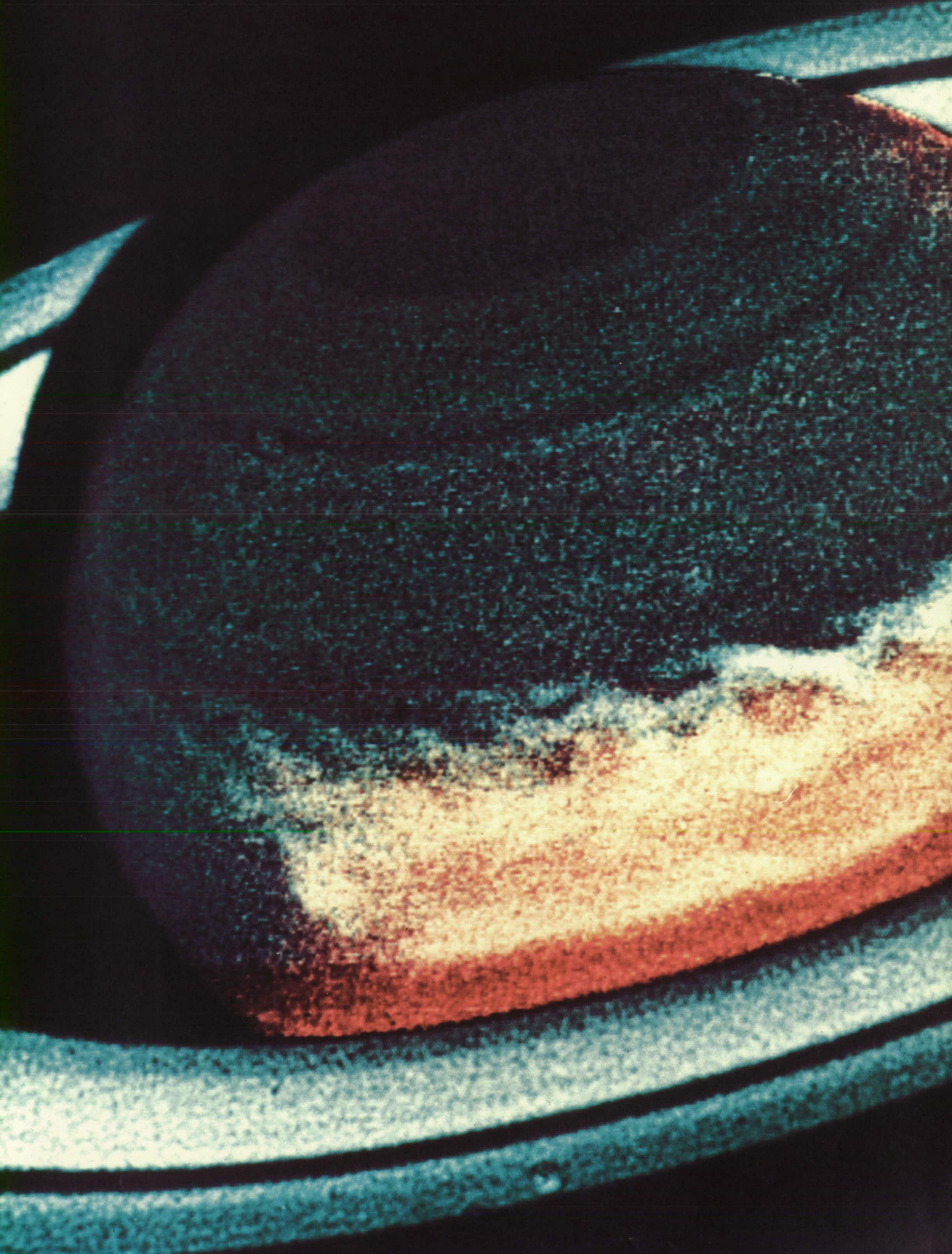
4.11 Space Test Program Report Summary

In-space technology research and technology demonstrations in the space actual environment are key components in the process of technology maturation. A family of programs for in-space testing — both in the R&T Base and in CSTI — were presented to the review team. Mission drivers are evident for most of the proposed program, including potential products for commercial participants.

The space test portion of the space R&T program could be particularly important to "space qualify" concepts and hardware. However, it is limited at present in the number of possible experiments due to high cost of flying on the Space Shuttle. Where flight experiment schedules are extended by funding problems, the technology to be demonstrated can be outpaced by mission need dates. To respond to this problem, individual experiments should either be accelerated on a priority basis or canceled. In addition, Space Shuttle established requirements should should be streamlined to be as short as possible in order to encourage application oriented technology experiments, university developed experiments, and to minimize overall space test program costs.

Moreover, as is the case with commercially oriented experiments, the potential user of the technology to be space tested should be involved in the experiment review and design process. The Announcement of Opportunity (AO) process for awarding experiments should be changed to identify the technology area of priority to NASA needs in order to be consistent with the OAET plan based on mission technology drivers and overall program priorities.

Finally, future technology flight experiments should try to utilize Space Station *Freedom* wherever possible to take advantage of longer duration in space and the man-in-the-loop advantage in experiment flexibility and operations.



Conclusions and Observations

5.1 Rationale for Investment in Advanced Space R&T

Modern society relies on a broad spectrum of technology — power, communications, data processing, transportation, appliances — to establish our standard of living. Historically, both industry and government have invested in research and technology development to create new products and services, improve existing ones, reduce costs and improve access.

Industry invests to remain competitive, develop new markets, grow and increase profitability. Government invests to develop new capabilities (e.g., DOD systems rely on advanced technology to offset numerical superiority); to provide better services (e.g., roads, power, air traffic control, weather forecasting) and to provide unique facilities to maintain national competitiveness (e.g., aeronautics research).

There is no magic formula to determine the appropriate level of investment. In industry, management must judge the potential return on investment based on how fast the technology is evolving, the state of the competition, the expected improvements in products and services, and the attractiveness of alternate investment opportunities.

Historically, the United States Government has supported the development of new technology, particularly when the investment required was excessive for private capital risk. However, today's budgetary climate creates a difficult environment in which to make judgments between vastly disparate National priorities.

The country does support the U.S. Civil Space program — fourteen billion dollars is a significant annual investment. Moreover, there is a strong and continuing consensus that investments in advanced research and technology (R&T) are essential to our future success in space. The Augustine Committee Report (1990) was only one of the latest in a long series of studies of our National space program. (Examples include the National Research Council Aeronautics and Space Engineering Board's 1987 report on *Space Technology to Meet Future Needs*, and the National Commission on Space 1986 report, *Pioneering the Space Frontier*.) Each of these reports has articulated the need for greater investments in space R&T if we are to realize the full potential benefits to the country from the NASA budget.

To the technically-oriented individuals who have conducted these studies, the need for — and benefits from — significantly increased R&T funding is obvious. For over a decade, however, little has happened. There is a body of thought that says that neither the White House's Office of Management and Budget (OMB), or the Congress, will support technology unless it is closely coupled to a specific, and approved, flight program. It is also true that in negotiating budget reductions, existing program funding is protected before the investment in technology. Whatever the reason, the arguments which have been made for a significant increase in funding for space R&T have not produced results.

The following paragraphs restate the case for increased investments in advanced space research and technology.

Broadly speaking, NASA has four space-related operational strategic missions:

- Space science, including the Mission to Planet Earth

- Space exploration, including Space Station Freedom, and the Mission From Planet Earth

- Transportation, including the Space Shuttle and expendable launch vehicles (ELVs)

- Space utilization, including the development of applications of space for use on Earth, support of DOD and our national commercial space sector, and infusion of appropriate technology into the civilian economy.

A fifth mission, implicit in the Space Act of 1958, is the development of technology to support the Agency's overall program objectives and to maintain U.S. preeminence in space. However, this latter mission has been diminished in its relative priority within NASA's activities.

Over the past 20 years, United States leadership in space has eroded. NASA programs have encountered cost, schedule and technical difficulties. In addition, our stable of expendable launch vehicles are being challenged on the world market. Finally, the technology base to support President Bush's vision of a Space Exploration Initiative does not exist.

Increased R&T investment will not solve these problems overnight, but it can have a significant affect on NASA's space programs and the Nation's space infrastructure, as well as the technological

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strength of the Nation over the long term. A well managed and focused program can be expected to provide at least the following benefits:

National Benefits

1. National competitiveness will be improved

Future U.S. competitiveness in the world economy will increasingly depend upon the speed and effectiveness with which new technologies and innovations can be brought to maturity and the marketplace. This is especially true in the commercial space industry. For example, in the 1970s, 100 percent of the world market in geosynchronous communications satellites was manufactured and sold by U.S. firms; the decade of the 1980s saw U.S. market share drop to 70 percent with the entry of serious European, Canadian and Japanese competition. Commercial launch vehicle services are also intensely competitive, with competition from Europe, Japan, China, and the Soviet Union. Similarly, the U.S. is being rapidly outstripped in the key field of automation and robotics, with more robotic systems added annually in Japan than the total inventory in U.S. industry. An investment in advanced space research and technology, including focused programs directed at rapidly developed breadboards and demonstrations, can make a contribution to National competitiveness across a wide range of the critical technology areas recently cited in studies by the White House Office of Science and Technology Policy (OSTP) and the U.S. Council on Competitiveness.[1]

2. Science and engineering education will be stimulated

Through pursuit of an advanced space research and technology (R&T) effort involving government, industry and academia, the Nation's efforts toward excellence in science and engineering education will be enhanced. For example, space R&T programs provide direct opportunities through strong university participation for exciting and meaningful undergraduate and graduate involvement. The majority of the graduates from these programs go on to become researchers in academia or the mainstream of American industry, not NASA. Thus, space R&T can help attract the best and brightest young people into technical fields and aid in the development of a critical pool of expertise and leadership for the future.

3. The technologies developed will be broadly applicable

The technologies needed for future NASA space missions also will be applicable to private U.S. civil space users and will indirectly support future DOD space mission needs. For example, NASA missions require advances in areas such as telecommunications, advanced solar power arrays, and software for the management of very large data bases — all areas of broad applicability. In this way, all our future National space endeavors will be enhanced by an investment in NASA space R&T.

Space Program Benefits

4. Development uncertainties will be reduced

All NASA missions involve reducing to practice research results and appropriate technology. Without a base of available new technology, each program faces the choice of either using off-the-shelf hardware (with attendant performance and, perhaps, cost penalties), or attempting to mature emerging technologies during development with attendant cost and schedule risks for the project. For example, early investment in design studies and technology development on the order of 5 percent of the ultimate project cost can result in reducing the probable error in estimating actual project costs by as much as a factor of two. An early investment in technology — before finalizing a design or starting a flight project — is the only way to insure the effective use of new capabilities without placing a project in cost or schedule jeopardy.

5. The cost of access to space will be reduced

Realistically, new technology can reduce launch vehicle costs at least two-fold. In addition, using advanced technologies, future spacecraft size and costs can be reduced for equivalent functionality, further reducing launch costs. It is conceivable that a reduction of 20 percent in spacecraft mass could translate into a savings of as much as $ 100 million in cost for a 5000 kilogram spacecraft, due to a combination of spacecraft hardware and launch cost reductions. Similarly, investments in increased autonomy and automation can significantly lower the cost of operations. Clearly, advances in a number of technology areas can reduce the costs of access to space without reducing the scope of future accomplishments.

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[1] The topic of enhancing the competitiveness of the U.S. commercial space industry is discussed in more depth in Appendix E of this report.

6. Safety and reliability will be increased

Safety and reliability are two key objectives for all our space systems. However, achieving safety with current technology can be costly. For example, a two to three week delay in the launch of the Space Shuttle while component level problems are resolved can result in millions of dollars added to the cost of a given flight; increased onboard processing combined with more, higher reliability integrated sensors may eliminate these delays in future vehicle systems. Through such advances as onboard processing and automation in the implementation of integrated vehicle health management sensors and systems, and other technologies that improve fault-tolerance, future spacecraft safety and reliability can be significantly increased while enhancing performance.

7. Mission performance will be enhanced

An enduring goal of space technology development is making new missions feasible. Future discoveries in astrophysics will depend upon improved direct detectors in areas such as infrared, gamma ray and submillimeter regimes. Similarly, robotically returning samples from other planetary bodies will require increasing the level of onboard spacecraft autonomy from a few seconds, or less, to many minutes or hours. Across a wide front — including instruments and optics, life support, data processing and telecommunications, automation and robotics, materials and structures, power and propulsion — advances in technology will result in significant enhancements in mission performance, allowing us to accomplish more in space within limited budgets.

8. NASA personnel will remain technically current

Some technologies (e.g., in the area of advanced propulsion) are peculiar to space. However, in many areas NASA adapts technology from other sectors — including military and commercial sectors — to its use. Investment is needed for NASA personnel to understand the special requirements of civil space mission applications and to define and manage flight development programs.

Earlier studies have recommended that "NASA must pursue a more balanced program with emphasis on critical long term technologies. Investment today will not just enable a broad spectrum of possible future missions, but, if properly planned will have important benefits to both the military and commercial space industry."

During the 1960's preeminence in space was a National goal. NASA was funded at almost 5 percent of the Federal budget, and Apollo demonstrated our capability to the world. In today's budget environment, the U.S. investment in space will not, and probably should not, approach the levels of the 1960s. Yet the Nation must still want to maintain preeminence in space, which has been steadily eroding because of significantly increased investments in space by other countries.

A logical strategy to maintain our competitive advantage would be to invest in superior, unparalleled space technology — as OAET has proposed to do in its Integrated Technology Plan. The DOD demonstrated during the recent Gulf War that the overwhelming application of unique technology (e.g., in communications, sensors, stealth, logistics) can triumph over the mere deployment of force. This approach should now be adopted by our civil space program to regain leadership in this arena of peaceful uses of advanced technologies which are of clear strategic importance to the Nation.

5.2 Summary Findings of the Review

Overall, the review team believes that Recommendation 8 of the Augustine Committee is well founded. NASA has instituted a sound planning process and the proposed* Integrated Technology Plan for the Civil Space Program *is a solid basis for responding to the Augustine Committee Recommendations on technology. Within each working group, the review team found that at both the "three-fold increase" and the greater "responsive" resource levels that the proposed program was sound and in fact that more, rather than less, resources were needed to meet the legitimate technology needs of the U.S. civil space program.

The* Integrated Technology Plan *deserves as much support as the Agency and Congress can provide. We also recommend that the Augustine target of a three-fold increase in funding level be the initial goal.

The SSTAC/ARTS, along with representatives of the SSAC, the AMAC, the National Research Council's ASEB and SSB, the AIA, and participants from other Government Agencies, reviewed NASA's proposed Integrated Technology Plan. The review team was very impressed by the amount and quality of the work which NASA has done in response to the Augustine Committee recommendations. An effective process has been established to identify the advanced technology needs of the user communities and establish a rough order of priority within individual technical disciplines and program thrusts. Two levels of funding were presented to the review: a "responsive plan"; and, a "3-fold augmentation" (i.e., "3x") plan. The *responsive plan* — which attempted to address virtually all identified technology needs — grew from current space R&T funding levels (approximately $ 283 million in fiscal year 1991) to $ 1.7 billion by 1997, whereas the *3-fold augmentation plan* — which is targeted at the Augustine Recommended level of three-times the current modest budget and is realistically all that NASA can be expected to invest — grew to approximately $ 1.1 billion by 1997.

The review team consisted of experts in several disciplines. Uniformly, the review team found the quality of the proposed research projects very high and generally well-integrated with other National efforts. In general, the review team recommend that more, rather than less, work should be done, even at the responsive level. That is a strong indication that the Augustine Committee recommendation for a significant budgetary increase is well founded and should be implemented.

In most areas, some specific projects were questioned, along with details of the prioritization. That is natural, since the new planning process has barely completed its first cycle. The issues raised may indicate the need to institute a continuing peer review process both within and outside the Agency.

The balance between the R&T Base program and focused programs — in which R&T Base funding is targeted strategically to be set at a continuing level of one-third of the total space R&T effort — seems appropriate, as does the new grouping of the focused programs. The balance between near, mid and far term programs seems to be appropriate, but should be more clearly established. (An example might be the relative priority of investing in technology to enable SEI, compared to useful, but not essential improvements to an ongoing program.) The bulk of investment should be in technologies to be available five to fifteen years in the future, with more limited investment in R&T for deliverables closer than five or further than fifteen years.

Also, the means of establishing priorities across disciplines and major thrusts needs further clarification. For example propulsion developments are expensive and require a long time to mature, compared to communications or computer systems where NASA often is adapting commercial developments to space applications. Top management policy guidance, perhaps embodied in a strategic long range plan for the Agency, will be required.[2]

The review team also notes that the plan presented does not, in general, take the new technology development through flight demonstration. Many program offices are reluctant to commit to equipment which has not flown. We also note that currently flight experiments are very costly.

It can be difficult to justify the cost and show the relevance of small, individual research tasks. Perhaps the establishment of integrated ground testbeds could be a means of focusing related projects and demonstrating readiness for application.

The review team also noted that additional ground facilities in critical technology areas will be needed for many of the programs proposed and to compensate for the lack of flight opportunities.

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[2] This will be especially true if nuclear propulsion options are to be pursued during the next decade.

5.3 Issues

The review team also found that several issues will need continuing attention in future technology program planning; these include:

• The need for the right balance between ground based and in-space technology development

• Planning for ground facilities and the need for ground testbeds to integrate and demonstrate technologies

• The availability of flight facilities (e.g., the Space Shuttle and Space Station Freedom) and the cost of flight testing

• Continuing determination of the requirements for technology readiness to assure user office acceptance of new technologies

• A focus in the NASA R&T program on reducing the cost of future space systems.

5.4 Summary Recommendations

The review team believes, as was stated by the Augustine Committee, that "the development of advanced technology is ... crucial to the success of the exploration and exploitation of space." NASA's proposed Integrated Technology Plan responds to this challenge. Our most important and overriding Recommendation for NASA, the Administration and the Congress is:

• ***Accept Recommendation 8 of the Augustine Report and initiate planning for the needed funding growth to triple the current level of investment in advanced space research and technology.***

In addition, the review team has the following subsidiary recommendations that arose during the review process:

• ***Continue to Improve the Integrated Technology Plan***. NASA should continue to refine the space research and technology planning process, and increase the participation by other government agencies, industry and academia. Issues include: (1) improving technology transfer within the program; (2) establishing priorities across disciplines and thrusts; and (3) continuing and expanding the use of external, expert review of the program.

• ***Develop National Teams***. Plan for and implement increased collaboration and teaming among NASA, industry and universities in space R&T, and coordination with other government agencies, as appropriate.

• ***Develop National Testbeds***. Implement the concept of National Testbeds for space technology development.

• ***Revitalize Space R&T Facilities***. Focus planning on a new generation of space technology research facilities.

• ***Increase the Use of Technology Flight Demonstrations***. Implement policies and practices which reduce the cost and accelerate the pace of space R&T flight experimentation.

• ***Improve Technology Transfer***. Focus management attention on developing clear, widely accepted criteria for adopting new technologies for future civil space flight programs.

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Glossary of Acronyms

A&R	Automation and Robotics
AC	Alternating Current
ACTS	Advanced Communications Technology Satellite
AFE	Aeroassist Flight Experiment
AI	Artificial Intelligence
AIA	Aerospace Industries Association
AMAC	NAC Aerospace Medicine Advisory Committee
AN&L	Autonomous Navigation and Landing
AO	Announcement of Opportunity
AR&D	Autonomous Rendezvous and Docking
ARC	NASA Ames Research Center
ARTS	SSTAC Aerospace Research and Technology Subcommittee
ASEB	NRC Aeronautics and Space Engineering Board
ATDRSS	Advanced Telecommunications & Data Relay Satellite System
AXAF	Advanced X-Ray Astronomical Facility
CCD	Charged-Coupled Devices
CCDS	NASA OCP Centers for the Commercial Development of Space
CFD	Computational Fluid Dynamics
CRAF	Comet Rendezvous and Asteroid Flyby
CSTI	Civil Space Technology Initiative
DARPA	Defense Advanced Research Projects Agency
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
ELV	Expendable Launch Vehicle
EOS	Earth Observing System
EOS/DIS	EOS Data and Information System
ETP	Exploration Technology Program
EVA	Extravehicular Activity Systems
FTS	Flight Telerobotic Servicer
GCRP	U.S. Global Change Research Program
GEO	Geostationary Earth Orbit
GN&C	Guidance, Navigation and Control
GRO	Gamma Ray Observatory
GSFC	NASA Goddard Space Flight Center
HCI	Human-Computer Interaction
HLLV	Heavy Lift Launch Vehicle
H/O	Hydrogen/Oxygen
HST	Hubble Space Telescope
HTS	High Temperature Superconductivity
IR	Infrared
Isp	Specific Impulse
ISRU	*In Situ* Resource Utilization
ITP	Integrated Technology Plan
JPL	Jet Propulsion Laboratory
JSC	NASA Johnson Space Center
K	(degrees) Kelvin
kg	Kilograms
KSC	NASA Kennedy Space Center
kW	Kilowatts
LaRC	NASA Langley Research Center
LCH	Liquid Hydrocarbons
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit
LeRC	NASA Lewis Research Center
LIDAR	Light Detection and Ranging
LOx	Liquid Oxygen
LLOx	Lunar Liquid Oxygen
m	Meters
µm	Micron
MSFC	NASA Marshall Space Flight Center
MTV	Mars Transfer Vehicle
NAC	NASA Advisory Committee
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NCAT	AIA National Center for Advanced Technology
NEP	Nuclear Electric Propulsion (a.k.a., NEPS)
NIST	National Inititute of Standards and Technology
NLS	National Launch System (a.k.a., Advanced Launch System)
NOAA	National Oceanographic and Atmospherics Administration

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NRC	National Research Council
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Thermal Rocket
OAET	NASA Office of Aeronautics, Exploration and Technology
OAET/RZ	OAET Space Exploration Directorate
OCP	NASA Office of Commercial Programs
OMB	Office of Management and Budget
OSF	NASA Office of Space Flight
OSMQ	NASA Office os Safety and Mission Quality
OSO	NASA Office of Space Operations
OSSA	NASA Office of Space Science and Applications
OSTP	White House Office of Science and Technology Policy
OTV	Orbital Transfer Vehicle
PMAD	Power Management and Distribution
PMC	Permanently Manned Capability
R&T	Research and Technology
RF	Radio Frequency
RMS	Remote Manipulator System
RLSS	Regenerative Life Support System
s	Seconds
SAR	Synthetic Aperture Radar
SATWG	Strategic Avionics Technology Working Group
SDIO	Strategic Defense Initiative Office
SEI	Space Exploration Initiative
SEPS	Solar Electric Propulsion System
SIRTF	Space Infrared Telescope Facility
SSAC	NAC Space Science and Applications Advisory Committee
SSB	NRC Space Studies Board
SSC	NASA Stennis Space Center
SSF	Space Station *Freedom*
SSME	Space Shuttle Main Engine
SSTAC	NAC Space Systems and Technology Advisory Committee
STME	Space Transportation Main Engine
STV	Space Transfer Vehicle (a.k.a. OTV, LTV)
TOPS	Toward Other Planetary Systems
USAF	United States Air Force
USERC	University Space Engineering Research Center
UV	Ultraviolet
VHM	Vehicle Health Management
WBS	Work Breakdown Structure

Discussion of the Integrated Technology Plan

This section provides a review of the planning process used by OAET in the development of the Integrated Technology Plan (ITP) and a brief summary of the ITP as presented to the review team.

C.1 NASA Space R&T Mission and Program Principles

Mission Statement

The OAET mission statement regarding space R&T is: "*OAET shall provide technology for future civil space missions and provide a base of research and technology capabilities to serve all National space goals*". Accomplishing this mission entails meeting several top level objectives; in particular OAET shall:

- Identify, develop, validate and transfer technology to:
  - — Increase mission safety and reliability
  - — Reduce flight program development and operations costs
  - — Enhance mission performance
  - — Enable new missions.
- Provide the capability to:
  - — Advance technology in critical disciplines
  - — Respond to unanticipated mission needs.

Also, in order to accomplish those objectives, OAET has defined several program principles which the space technology program must embody; these are:

- Stress technical excellence and quality in all activities and ensure the availability of appropriate support and facilities
- Be responsive to the customers and assure technology transfer and utilization
- Sustain commitment to on going R&T programs
- Maintain the underlying technological strengths which are the well spring of NASA's technical capability
- Assure the introduction of new technology activities on a regular basis
- Maintain balance among NASA customers, critical disciplines, and near and far term goals
- Support science and engineering education in space R&T
- Make effective use of technologies and capabilities of other Agencies, industry, academia and international partners
- Enhance the Nation's international competitiveness.

OAET embedded these principles in a set of substantially revised technology planning processes and technical plans which NASA has described as an "*integrated technology plan for the civil space program.*" This so-called "integrated technology plan" (ITP) — NASA's response to the technology recommendations of the Augustine Committee — was presented in detail to the external review team for their consideration.

The major components of the ITP planning process were:

Annual Cycle — Creation of an annual cycle for space R&T planning, involving both user office participation and external review of proposed plans

Technology Maturation Strategy — Definition and use of a specific strategy for space technology maturation, including a flow of technology from Base R&T programs, through focused programs, and into flight programs (which is then reflected in the work breakdown structure of the space R&T program)

Flight Programs Forecast — Development, working with user offices, of an integrated, thirty year strategic forecast of civil space mission activities to guide technology investment decisions

Space R&T Program Implementation Approach — Definition of a strategic implementation approach for the Space R&T program which is at the top-most-level responsive to the flight programs forecast

Program Decision Rules — Definition and application of explicit decision rules and evaluation criteria to allow detailed development of both a "strategic" ITP, which meets the identified needs of the user offices more or less fully, as well as a specific ITP program for any given budget level that may emerge from the political process

Program Prioritization and Budget Development — On the basis of user-provided technology needs, and established program decision

rules, explicit investment priorities for the elements of the focused programs are established, and detailed budgets developed for any overall budget guidance.

Each of these aspects of the planning process is described below.

C.2 Space Technology Planning Cycle

As a part of the development of the ITP, NASA defined a substantially revised annual planning cycle for the space R&T program. (See Figure C-1.) The following is brief description of this proposed planning process.

Fall. The annual cycle would begin each fall with formal inputs of strategic planning updates and resulting technology needs from the several NASA Associate Administrators responsible for NASA's flight programs, as well as from the external community. These technology needs would be used to develop a call to the NASA Field Centers for specific space R&T work proposals to meet user-identified technology needs, as well as to address new, relevant technology opportunities.

Together, the user-derived technology needs and Center proposals for new work would be integrated with the results of the previous year's technology development efforts to formulate very preliminary revisions to the past year's ITP and detailed R&T plans. At this time, initial revisions to ITP focused programs priorities (see below) would be formulated.

These preliminary planning adjustments, as well as R&T progress made during the preceding year, would then be reviewed by the external community (through the SSTAC and the ARTS) and by the user program offices within NASA. At the same time, an external review through the National Research Council's Aeronautics and Space Engineering Board would be conducted.

Winter/Spring. Following internal and external reviews, and final OMB definition of the Administration space R&T program submit for the upcoming fiscal year, a revised baseline ITP incorporating the proposed revisions would be developed and used to prepare detailed plans for the spring submission of a preview budget to the NASA Administrator.

At this point, the revised ITP and detailed plans would be reviewed once more by the external community (SSTAC). At the same time, any necessary adjustments would be made to user need inputs provided the preceding fall, and the initial ITP focused program element prioritization would be essentially finalized.

Summer. Finally, Administrator guidance as a result of the spring budget review, and the results of any required non-advocate reviews of proposed major technology projects (e.g., major flight experiments, such as the Aeroassist Flight Experiment), would be reviewed one final time by the external community and then integrated into final revisions of the ITP for the cycle and the development of a space R&T budget for Administrator approval and submission to the OMB.

C.3 Technology Maturation Strategy

The successful transfer of technology from the researcher's laboratory to a flight project system has been one of the primary issues addressed by recent external evaluations of the space R&T program. A central component of the proposed ITP is a reliance upon the definition and adherence to an explicit strategy for the maturation of space technology. Nine technology readiness levels have been defined, ranging from the observation and reporting of basic physical principles, through successful mission operations of an actual, "flight proven" system. Figure C-2 depicts the overall technology maturation strategy presented, and definitions of the technology readiness levels.

This approach to technology maturation is the basis for NASA's proposed change in the "work breakdown structure" (WBS) of the space R&T program. (See Figure C-3.)

C.4 Flight Programs Forecast

A strategic forecast of approximate dates for future flight programs over the next twenty to thirty years was developed as part of the ITP effort. The forecast addresses activities in the near term (1993 through 1997), the middle term (1998 through 2003), and the far term (2004 through 2011). Figure C-4 provides a summary of this initial ITP flight programs forecast.

As presented, the flight programs forecast forms one of the foundations for annual prioritization of proposed space R&T program investments (see

below). It is anticipated that this forecast will be the subject of continuing revisions during future planning cycles and as National space goals are further refined.

C.5 Space R&T Program Implementation Approach

The space R&T program implementation approach presented by OAET is structured in three parts: one for meeting near term technology needs; one for mid term needs and the last for far term technology needs. In each case, the emphasis is on defining what top-level actions need to be accomplished during the next five years in order to achieve certain technology objectives in the future.

For Near Term Needs: In 1993 through 1997, the approach is to complete the ongoing program that supports near term needs, and to implement key selected new tasks. During 1993 through 1997, the program will deliver selected high leverage subsystem capabilities for specific projected mission new starts. The support for this block of missions/ technology needs will be targeted as a relatively small share of the total space R&T investment.

For Mid Term Needs: In 1993 through 1997, the approach is to complete the ongoing program that supports mid term needs, to begin high priority new R&T efforts and to begin to put critical R&T testbeds and facilities into place. By 1998 through 2003, the program will deliver major new system capabilities, conduct major ground demonstrations and flight experiments, begin the use of Space Station *Freedom* for R&T experimentation and demonstrations, and prepare to leverage NASP technology and demonstrations for space system applications. The support for this block of missions/ technology needs will be targeted as the majority of the total space R&T investment.

For Far Term Needs: In 1993 through 1997, the approach is to complete the ongoing program that supports far term needs, and to begin selected, long term R&T efforts. By 2004 through 2011, the program will deliver major new systems capabilities, achieve technology readiness for human missions to Mars applications, and begin use of the Lunar outpost for R&T experimentation and demonstrations. The support for this block of missions/technology needs will be targeted with the remaining share of the total space R&T investment.

C.6 Program Decision Rules

Given the planning process components delineated above, the issue remains: how to construct a viable space R&T program from the seemingly infinite set of possible research efforts. To guide this effort, two sets of decision rules were defined, one for the R&T Base and a second for the focused technology programs in CSTI.

R&T Base

The space research and technology (R&T) Base, in line with the technology maturation strategy discussed previously, is that portion of the R&T program within which NASA proposes to conduct discipline oriented, "technology push" activities. In terms of budget, the proposed ITP would set the R&T Base at approximately one-third (1/3) of the total space R&T investment. In other words, whatever the mission derived focused programs (see below) are determined to be, the total target budget value for the R&T Base would be strategically set at approximately one-half that amount.

This budgeting approach is intended to assure that although the major focus of the NASA space R&T program in the future will be on technology development and demonstration for directly mission supporting capabilities, an adequate foundation of critical expertise and new research will still be maintained.

R&T Base Decision Rules

General Rules

• Use external reviews to aid in assuring program technical quality

• Provide stability by completing ongoing discrete efforts

Discipline Research Rules

• Assure adequate support to maintain high quality in-house research in areas critical to future missions
— Provide capabilities for ad hoc supporting R&T for flight programs

• Provide growth in R&T Base areas needed for future focused programs

— Coordinate with annual focused programs planning

• Create annual opportunities for the insertion of new R&T concepts
— Goal: provide approximately 15-20 percent "roll-over" per year

• Support technology push flight experiments where space validation is required

IN-STEP Flight Programs

• Maintain competitively selected studies/ implementation of in-house and industry/university small scale flight experiments, oriented on NASA's technology needs

University Programs

• Focus participation in NASA space R&T by U.S. universities and colleges, using competitive selection

Civil Space Technology Initiative

The CSTI focused programs, in line with the technology maturation strategy discussed previously, are that portion of the space R&T program within functionally oriented, "mission pull" activities are funded. In terms of budget, grassroots cost estimates for focused "technology projects" are estimated to achieve certain technology development and demonstration objectives on specific schedules. The decision rules are then used to prioritize and select specific activities and programs.

Focused Programs Decision Rules

General Rules

• Annually assess and fund technology projects in order of priority against mission-derived investment criteria
— External review will be used to aid in assuring quality
— Review with user offices will be used to aid in assuring relevance and timeliness

• Provide stability by completing ongoing discrete efforts

• Start a mix of technology projects with short, mid and long term objectives each year

• Assure balanced investments to support the full range of space R&T users

• Fund new technology projects that have passes internal reviews a required (e.g., non-advocate review for major experiments)

Major Flight Experiments

• Support competitively selected implementation of in-house and industry major technology flight experiments in accordance with mission derived investment criteria

• Fund major flight experiments where adequate ground-based R&T is underway or has been completed

To implement the first general rule for focused programs, a set of specific "investment prioritization criteria" were developed. (See Figure C-5.) These criteria center upon: (a) *mission need* for the proposed technology (including the degree to which the technology is needed by a number of potential users — i.e., "commonality"); (b) *programmatic and timing issues* associated with the technology development (for example, when the user needs the technology to be mature enough to use at the beginning of detailed design versus how long an R&T effort OAET planners believe will be required to reach that level of maturity; and, finally, (c) *special issues* or factors that bear on the investment decision (e.g., the R&T team's readiness to begin a focused technology project or possible interrelationships with other government programs).

C.7 Program Prioritization and Budget Development

The basic space R&T budgeting strategy used in the development of the ITP dealt with the issue of maintaining the right balance between R&T Base and focused technology development. In particular, the budget strategy was to assure that the R&T Base is to be maintained at least at a constant purchasing power, and targeted at a funding level of approximately one-third the total budget for space R&T in planning growth.

Conversely, detailed budget levels for focused programs were driven by the content of individual element plans. Building on the foundation of user-

provided mission forecasts, technology needs and priorities, and established R&T program decision rules, priorities for the elements of the focused programs are established. Figure C-6 provides a summary of the prioritization of focused program elements at the "strategic plan" level. This prioritization was both a product and a tool in the development of the ITP that was presented to the external review team.

C.8 ITP Content Summary

As noted above, the ITP, as presented, is constituted of two major parts: an R&T Base (which is organized primarily by research discipline and constitutes predominantly the "technology push" section of the program) and a collection of focused programs, entitled the "Civil Space Technology Initiative", which has been created through the merger of the existing focused programs (e.g., the Exploration Technology Program, ETP, a.k.a., Project Pathfinder). Figure C-3. illustrates this new organization.

R&T Base

The space R&T Base provides the discipline foundation for the ITP, as well as resources for major, integrated university program activities and small scale technology flight experiment activities. Specific programs include:

• *Discipline Research* — which includes aerothermodynamics, space energy conversion, propulsion, materials and structures, information and controls, human support and advanced communications R&T

• *University Programs* — including the OAET University Space Engineering Research Center (USER-C) program

• *Space Flight R&T* — including the In-Space Technology Experiments Program (IN-STEP)

• *Systems Analysis* — which addresses technology assessments and analysis for future space R&T planning support.

Focused Programs

Space Science Observations. The Space Science Observations technology thrust is primarily concerned with providing the technology needed for future space science missions undertaken by either NASA's Office of Space Science and Applications, or the Office of Space Exploration. Such missions are concerned with broadening our scientific understanding of the Earth, our solar system, and the universe beyond. To do this, NASA will make observations from both the Earth's surface and Earth orbit, and will send a series of increasingly sophisticated human and robotic spacecraft to a number of solar system bodies for *in situ* observations. Specific program areas include:

• *Science Sensing (remote)* — which includes planning for direct detectors, submillimeter-wave sensing, laser sensing, active microwave sensing, passive microwave sensing, sensor electronics and processing, and optoelectronics sensing

• *Observatory Systems* — with planning for telescope optical systems, sensor optical systems, coolers and cryogenics, precision instrument pointing, and microprecision controls-structures interactions (CSI)

• *In Situ Science* — including planning for R&T for sample acquisition, analysis and preservation and for future planetary probes and penetrators

• *Science Information* — which includes planning for space R&T in the areas of massive data archiving and retrieval, and data visualization and analysis.

Planetary Surface Exploration

The Planetary Surface Exploration Technology Thrust is primarily concerned with providing the technology needed for future human missions to the Moon and Mars that may be undertaken by NASA's Office of Space Exploration. Such missions have not yet been approved by the Congress, but may occur during the first few decades of the 21st Century. Specific program areas include:

• *Surface Systems* — which includes planning for space nuclear power, high capacity power, surface power and thermal management, planetary rovers, *in situ* resource utilization, surface habitats and construction, and laser-electric power beaming

• *Human Support* — with planning for regenerative life support, radiation protection, extravehicular activity (for the Lunar and Mars surfaces), exploration human factors (for very long duration space flight and for surface operations), medical support systems (for remote medical care) and artificial gravity

Transportation

The Transportation Technology Thrust is primarily concerned with providing the technology needed for major future transportation improvements that may be undertaken by NASA's Office of Space Flight at the request of either the Office of Space Science and Applications, the Office of Space Exploration, or the Office of Space Operations. This could include such new transportation systems as a Heavy Lift Launch Vehicle, a second generation Space Shuttle, and a family of space transportation vehicles for transferring humans or cargo either between the Earth and the Moon or the Earth and Mars. Specific program areas include:

• *Earth-to-Orbit Transportation* — which includes planning for Earth-to-orbit propulsion, ETO vehicle structures and Materials, ETO vehicle avionics, and low cost commercial transports

• *Space Transportation* — with planning for advanced cryogenic engines, nuclear thermal propulsion, nuclear electric propulsion, aerobraking/ aeroassist, cryogenic fluid systems, autonomous landing, autonomous rendezvous and docking, transfer vehicle avionics, and transfer vehicle structures and cryogenic tankage

• *Transportation Technology Flight Experiments* — including planning for the Aeroassist flight experiment (AFE), the Cryogenic Orbital Nitrogen Experiment (CONE), a future Cryogenic Orbital Hydrogen Experiment (COHE), potential Solar Electric Propulsion System (SEPS) flight experiments, and a High Energy Aerobraking Flight Experiment in the far term.

Space Platforms

The Space Platforms Technology Thrust is primarily concerned with providing the technology needed for future space platforms used either by NASA's Office of Space Science and Applications, Office of Space Exploration, Office of Space Flight, or Office of Space Operations. This technology will benefit both future human platforms, such as Space Station *Freedom*, and future large robotic spacecraft, such as the *Earth Observing System (EOS)*. Specific program areas include:

• *Earth Orbiting Platforms* — which includes planning for power and thermal management, platform structures and dynamics, material science and environmental effects, nondestructive evaluation (NDE) and nondestructive inspection (NDI), and platform controls

• *Space Stations* — with planning for zero gravity physical-chemical life support systems, advanced zero gravity extravehicular mobility units (EMUs), station-keeping propulsion, and for *SSF* user support subsystems (such as advanced refrigerator systems)

• *Platform Technology Flight Experiments* — including planning for a future orbital debris mapping flight program.

Operations

The Operations Technology Thrust is primarily concerned with providing the future technology needed either by NASA's Office of Space Science and Applications, Office of Space Exploration, Office of Space Flight, or Office of Space Operations. This technology will support major operational improvements for future robotic and human missions, both on the Earth, in space, and on another natural body in the solar system (e.g., substantial improvements in the operation of mission control at the Johnson Space Center (JSC), improvements in communications between mission control and its spacecraft, and improvements in in-space assembly and construction techniques). Specific program areas include:

• *Automation and Robotics* — which includes planning for both telerobotics and artificial intelligence technologies

• *Infrastructure Operations* — with planning for R&T in the areas of in-space assembly and construction, ground test and processing, flight control and space operations, space processing servicing of systems, and training and human factors (focusing on ground crew systems)

• *Information and Communications* — including planning for space data systems, ground data systems, high rate communications, photonics systems, commercial communications satellite communications R&T, and navigation and guidance (focusing on radiotelemetry GN&C)

• *Operations Technology Flight Experiments* — which includes planning for the Flight Telerobotic Servicer (FTS), future optical communications flight experiments, and future commercial telecommunications satellite communications R&T flight experimentation.

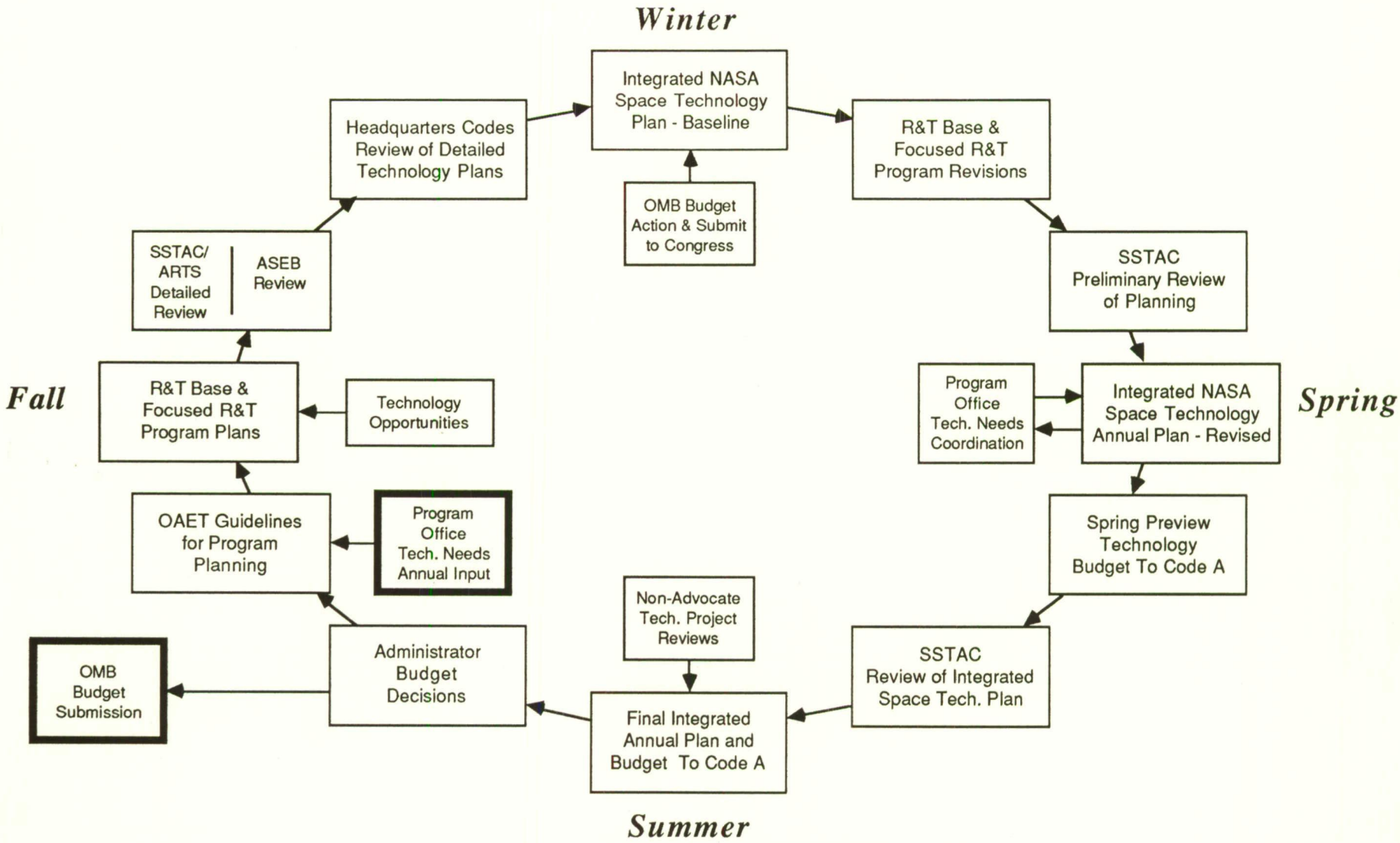


Figure C-1 Integrated Technology Plan for the Civil Space Program
Annual Space R&T Planning and Budgeting Cycle

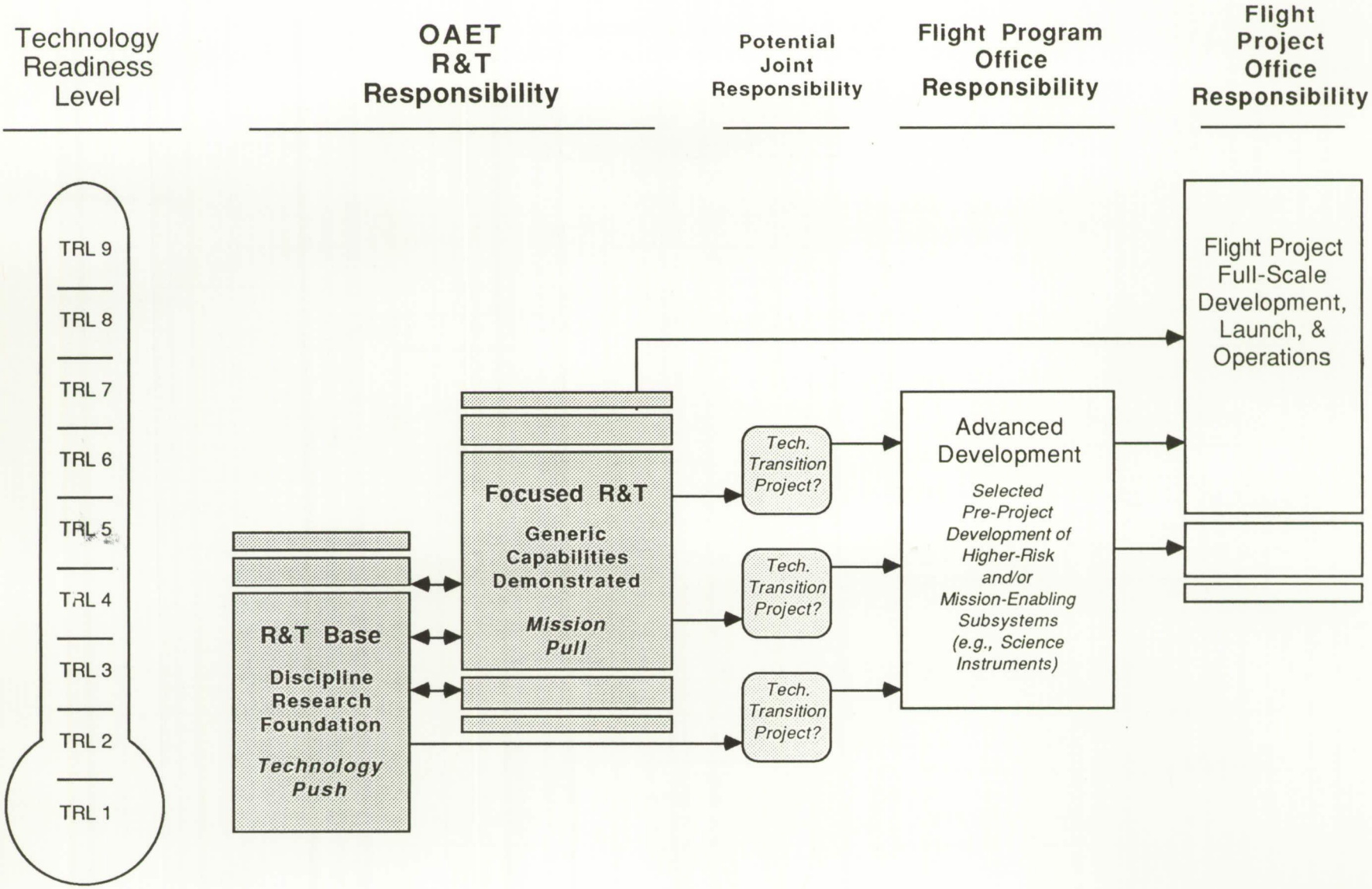


Figure C-2(a) Integrated Technology Plan for the Civil Space Program
NASA Technology Maturation Strategy

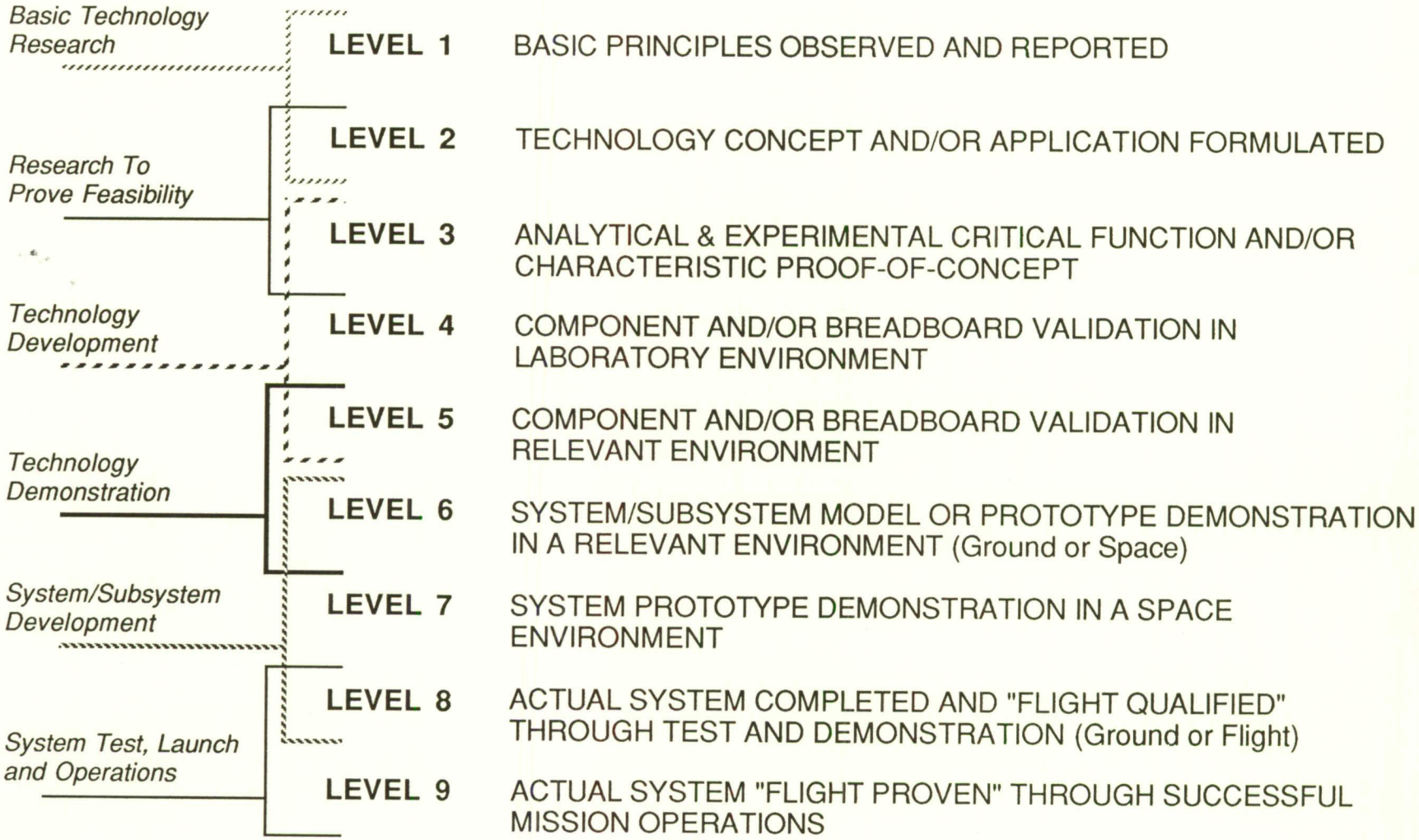
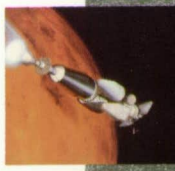


Figure C-2(b) Integrated Technology Plan for the Civil Space Program Technology Readiness Levels



WORK BREAKDOWN STRUCTURE

RESEARCH & TECHNOLOGY BASE

DISCIPLINE RESEARCH

Aerothermodynamics
Space Energy Conversion
Propulsion
Materials & Structures
Information and Controls
Human Support
Space Communications

UNIVERSITY PROGRAMS

SPACE FLIGHT R&T

SYSTEMS ANALYSIS

CIVIL SPACE TECHNOLOGY INITIATIVE

SPACE SCIENCE TECHNOLOGY

Science Sensing
Observatory Systems
Science Information
In Situ Science
Technology Flight Expts.

PLANETARY SURFACE TECHNOLOGY

Surface Systems
Human Support
Technology Flight Expts.

TRANSPORTATION TECHNOLOGY

ETO Transportation
Space Transportation
Technology Flight Expts.

SPACE PLATFORMS TECHNOLOGY

Earth-Orbiting Platforms
Space Stations
Deep-Space Platforms
Technology Flight Expts.

OPERATIONS TECHNOLOGY

Automation & Robotics
Infrastructure Operations
Info. & Communications
Technology Flight Expts.

Figure C-3 Space R&T Program Work Breakdown Structure

FLIGHT PROGRAMS FORECAST

- **5-YEAR FORECAST INCLUDES**

'93 THRU '97: LIMITED NEW STARTS

COMPLETION OF INITIAL SSF
SOME SHUTTLE IMPROVEMENTS
INITIAL EOS & EOSDIS
SELECTED SPACE SCIENCE STARTS
NLS DEVELOPMENT
INITIAL SEI ARCHITECTURE SELECTION
EVOLVING GEO COMMERCIAL COMMSATS
MINOR UPGRADES OF COMMERCIAL ELVS

- **10-YEAR FORECAST INCLUDES**

'98 THRU '03: MULTIPLE NEW STARTS TO BE LAUNCHED IN 2003 THRU 2010

SSF EVOLUTION/INFRASTRUCTURE
FINAL SHUTTLE ENHANCEMENTS
ADVANCED LEO EOS PLATFORMS/FULL EOSDIS
MULTIPLE SPACE SCIENCE STARTS
NLS OPERATIONS/EVOLUTION
EVOLVING LAUNCH/OPERATIONS FACILITIES
INITIAL SEI/LUNAR OUTPOST START
DSN EVOLUTION (KA-BAND COMMUNICATIONS)
NEW GEO COMMERCIAL COMMSATS
NEW COMMERCIAL ELVS

- **20-YEAR FORECAST INCLUDES**

'04 THRU '11 MULTIPLE OPTIONS FOR NEW STARTS TO BE LAUNCHED IN 2009 THRU 2020

SSF-MARS EVOLUTION
BEGINNING OF AMLS/PLS DEVELOPMENT
MULTIPLE SPACE SCIENCE STARTS
DSN EVOLUTION (OPTICAL COMM)
INITIAL MARS HLLV DEVELOPMENT
EVOLVING LUNAR SYSTEMS
MARS SEI ARCHITECTURE CHOSEN
LARGE GEO COMMSATS
NEW COMMERCIAL ELVS

Figure C-4 Integrated Technology Plan for the Civil Space Program
Research & Technology Stategy

MISSION NEED

Engineering Leverage

- Performance (Including Reliability) Leverage of the Technology to A System
- Importance of That Technology/System Performance To A Mission And Its Objectives

Cost Leverage

- Projected Cost Reduction For A Given System/Option
- Projected Cost Reduction for A Mission of That Savings

Breadth Of Application

- Commonality Across Missions/Systems Options
- Commonality Across Systems in Alternative Mission Designs

PROGRAMMATICS & TIMING

Timeliness Of Planned Deliverables

- Timing of the Mission Need for Technology Readiness
- Projected Duration of R&T Needed To Bring Technology to Readiness

Criticality Of Timely R&T Results To Mission Decisions

- Timing of Mission Planning Need for Technology Results
- Importance of Technology To Mission Objectives/Selection

Uncertainty in Planned R&T Program Success/Schedule

SPECIAL ISSUES

Readiness to Begin A Focused Technology Project
Commitment To An Ongoing R&T Program
Interrelationships To Other Government Program(s)
Projected "National Service" Factors

Figure C-5 Integrated Technology Plan for the Civil Space Program Investment Prioritization Criteria

Space Science Technology	Submillimeter Sensing	Direct Detectors	Active µwave Sensing	Sample Acq., Analysis & Preservation	Passive Microwave Sensing	----	Optoelectrncs Sensing & Processing	Probes and Penetrators	----
	Cooler and Cryogenics	Sensor Electronics	Laser Sensing	Data Archiving and Retrieval	Data Visualization	----	Precision Instrument Pointing	Sensor Optical Systems	----
		Microprecision CSI	Telescope Optical Systems						
Planetary Surface Technology	Radiation Protection	Regenerative Life Support (Phys-Chem.)	Space Nuclear Power (SP-100)	High Capacity Power	Planetary Rovers	Surface Habitats and Construction	Exploration Human Factors	----	Artifical Gravity
	----	----	Extravehicular Activity Systems	Surface Solar Power and Thermal Mgt.	In Situ Resource Utilization	Laser-Electric Power Beaming	Medical Support Systems	----	----
Transportation Technology	ETO Propulsion	Nuclear Thermal Prop.	Aeroassist/ Aerobraking	Transfer Vehicle Avionics	ETO Vehicle Avionics	ETO Vehicle Structures & Materials	Autonomous Rendezvous & Docking	COHE	Auxiliary Propulsion
	Cryogenic Fluid Systems	Aeroassist Flight Expt	Low-Cost Commercial ETO XPort	Nuclear Electric Propulsion	CONE	----	Autonomous Landing	TV Structures and Cryo Tankage	HEAb
		Advanced Cryo. Engines							
Space Platforms Technology	Platform Structures & Dynamics	Platform Power and Thermal Mgt.	Zero-G Life Support	Platform Materials & Environ. Effects	Station-Keeping Propulsion	----	Spacecraft On-Board Propulsion	Earth-Orbiting Platform Controls	Advanced Refrigerator Systems
	----	----	Zero-G Advanced EMU	Platform NDE-NDI	Deep-Space Power and Thermal	----	Spacecraft GN&C	Debris Mapping Experiment	----
Operations Technology	Space Data Systems	High-Rate Comm.	Artificial Intelligence	Ground Data Systems	Optical Comm Flight Expt	Flight Control and Operations	Space Assembly & Construction	Space Processing & Servicing	Photonics Data Systems
	----	CommSat Communicat'ns	TeleRobotics	Operator Syst./Training	Flt. Telerobotic Servicer/DTF-1	CommSat Communicat'ns Flight Expts	----	Ground Test and Processing	----
					Navigation & Guidance				
	HIGHEST PRIORITY ◊◊◊			2nd-HIGHEST PRIORITY ◊◊			3rd-HIGHEST PRIORITY ◊		

Figure C-6 ICSTI Categorization
Stategic Plan/User Key Requirements

Technical Review Panel Reports

The external review team was tasked to conduct an overall and detailed technical review of the proposed Integrated Technology Plan for the Civil Space Program. Each of the eleven review panels assessed the R&T Base and the focused R&T components of the ITP. Informal guidance directed each panel to prepare reports that addressed background, status, key technology applications, potential payoffs, consequences of no action, specific recommendations and priorities. This appendix provides the review panel reports for each area:

- Propulsion
- Power
- Human Support
- Automation and Robotics
- Materials and Structures
- Data Systems and Computer Science
- Communications, Photonics, and High Temperature Superconductivity
- Remote Sensing
- Guidance and Controls
- Aerothermodynamics
- Space Test Programs

D.1 Propulsion Panel Report

The propulsion panel observed that a focused and effective planning effort was underway. The panel's discussion of key propulsion programs follows.

Low Thrust. This is a high leverage technology because of the potential weight savings. Chemical and electric (high and low power) thrusters are vital for all spacecraft types. The program is established, successful in influencing NASA, DOD, and commercial vehicles. Funding at the strategic level would be a sound investment in the future of the hot rocket and arcjets, both near and far term. Electric propulsion work will be directly applicable to SEPS, and ultimately NEPS. Considering the importance of Isp of 500 to 3000 seconds, the wide impact, uniquely high payoff, and demonstrated success of this aggressive and well-planned program, the panel recommends funding at three times the current level.

Advanced Concepts. This program is of ultimate importance for exploration of the outer solar system and beyond. This is one of the only U.S. efforts that significantly addresses the need for new propulsion options derived from novel physical approaches. Several promising possibilities have emerged from this work, including a nuclear reaction triggered by a realistically small amount of anti-matter, and work to exploit the new science of molecular clusters, notably C_{60}. This work, though visionary, is sound, well managed, and well received by external agencies (DOD, DOE). The panel urges support of the 3 times Level, or preferably that 15 percent of base R&T in Propulsion be set aside for this program. It is a NASA leadership program, and the panel urges a wider awareness within NASA of its activities.

Earth-to-Orbit (ETO). This focused program ,which points toward a new generation of H/O rocket engines beyond SSME, was viewed as an extremely well planned and executed program of significant importance to NASA, and applicable to NLS. Emphasis is on component development.

Large Thrust. This is a related base R&T program emphasizing advanced propellants, and also hybrids if 3X funding augmentation is achieved. The new "Low-Cost Commercial Transport Initiative" is an excellent idea that will help the commercial industry. NASA is urged to encourage industry to participate in this effort. In general, the Base R&T for high-thrust chemical rocket work is seriously underfunded. The level of coordination between the Lewis and Marshall Centers is gratifyingly high.

Space Chemical Engines. This program, too, is well planned yet has been inadequately and inconsistently funded. It would provide a badly-needed "testbed" to evaluate all components and configuration of advanced cryogenic engines. The particular engine under study would have wide throttling limits for OTV applications. This testbed approach should be given steady support a the highest feasible level, and should be consider for coordinated use by commercial users as well as by NASA. It seems possible that NASP results may have application in this R&T area.

Cryogenic Studies. This program covers issues of cryogenic fluid management in space which the panel continues to see as vital for future space missions. Tests in space are critical and NASA is urged to reconsider whether the important physical issues can be dealt with in tests of a scale that can be afforded with the current budget.

General comments on the rocket technology programs arose in the panel's discussions. They include the following:

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• NASA must be more careful to relate to DOD and SDIO studies that are on parallel tracks

• NASA Centers should be encourage to continue and expand their excellent efforts, through workshops and conferences, to exchange information and ideas with each other and with the broader industrial and academic community

• More attention must be paid to the environmental impacts of testing

• The panel often found the word "enabling" a troublesome concept, with its hidden implications about the value of the thing enabled.

Nuclear Propulsion. Nuclear Thermal and Nuclear Electric Propulsion relate directly to the Mission From Planet Earth. The programs carry the long term potential for the future of space exploration far beyond Earth. Commitment to that goal and commitment to some form of nuclear propulsion are connected. Nuclear options arguably promise cost, performance, simplicity and flexibility of mission architecture. This is a program for U.S. leadership in planetary exploration.

The technical challenges however, must not be underestimated. The history of civil nuclear power teaches this lesson. Therefore, the strongest possible technical and managerial team must be built by NASA. The team must be capable of dealing effectively with interface issues involving DOE. The panel recommends that the necessary technology effort be developed carefully, and that subsequent decisions be made with the greatest care, regardless of short term program pressure - they will have great consequences far into the future, as the civil nuclear power program has shown.

The NASA plan presented to the panel was new. NASA is engaged now in studying concepts and projected capabilities. This effort is impressively broad, technically responsible, and objective. Funding levels seem appropriate for the moment. The panel is concerned that as funding increases, other NASA programs may suffer. The panel urges that nuclear electric, and other, non-nuclear, options be fully considered, since any one of them may have greater long range potential than nuclear thermal.

The panel encourages this initiative, but with concern that NASA reach out for and support needed technology development in proportion to the immense stakes. It goes without saying that environmental, safety, and public relation issues will require all the wisdom that NASA can bring to bear.

Note: In addition to the above position taken by the propulsion review panel, there was also a minority view in the power technology review panel that nuclear thermal propulsion might not ever be acceptable for deep space missions.

D.2 Power Panel Report

Background

Power technology is highly interdisciplinary and as a result, system improvements tend to be evolutionary rather than revolutionary. All space missions begin with an energy budget and are terminated when that energy budget is expended. As a result, improvements in power technology translate to increased lifetime as well as increased mission capability.

The NASA program in Power and Thermal Management addresses critical research and development needs in the areas of power sources, energy storage, power management and distribution, and thermal management. The panel concluded that the program is fully responsive to the requirements recommended by the Augustine Committee Report, placing primary emphasis on a structured research and technology program to meet future NASA needs.

The plan is well coordinated with potential users. It addresses the generic mission classes of unmanned and manned Earth orbital and planetary spacecraft platforms, and lunar and planetary surface power.

The program plan in power and thermal management provides a range of highly promising technology options. NASA is to be commended for their efforts to build the program plan around present and future user (program office) needs.

Status

Future missions will require high performance, long life space power systems to meet power needs ranging from hundreds of watts to tens of megawatts. Future missions will require improvements in solar array/battery power systems, nuclear power systems, energy storage, power management/distribution/control and thermal management (waste heat acquisition, transport and rejection). The Nation is on the threshold of achieving an unprecedented growth in capabilities from only modest increases in the current NASA budget.

Key Technology Opportunities

The review panel identified many key technology opportunities which will mitigate risk, enhance performance, reduce technical uncertainty, lower mass and cost and in some cases enable future missions. These opportunities include:

- Large area 30 percent efficient solar cells
- 150-250 watt hr/kg batteries
- High performance regenerative fuel cells
- < 10 kg/kw PMAD
- < 5 kg/m^2, < 5 kg/kw space radiators
- < .50 kg/kw power converters
- High temperature/radiation hard electronics
- Readily scalable SP-100 space nuclear power at 25 to 50 watts/kg.
- < 20 kg/m^3 cryogenic storage for 10 year lifetime
- Stirling and Brayton turbomachinery
- Solar dynamic power systems
- RTG's for lunar and planetary surface exploration rovers
- "Utility type" AC distribution systems
- Autonomous operations
- Long life pumps and bearings
- Integrated system advanced technology demonstrators.

Potential Payoffs

The immediate payoff of implementing the proposed plan in the near term will be a threefold increase in solar array/battery specific power (i.e., from 5 to 15 watts/kilogram), a potential twofold increase in space nuclear reactor specific power (i.e., from 25 to 60 watts/kilogram) and dramatic improvement in heat rejection and transport. Viable power component technologies will be available for near, mid, and far term mission use. Power management and distribution weight will be reduced by factors of 3 to 5 with reduced volumes of 40 to 60 percent while improving efficiency and reducing parts count by 60 to 80 percent.

Consequences of No Action

The panel concluded that if the programs are not executed, power technology to meet real mission needs will continue to languish. Critical mission power requirements will not be met except by incurring tremendous weight penalties. Some missions will have to be abandoned or the science scaled back due to power constraints. Space platforms and missions such as ATDRSS, EOS, SSF and SEI would be adversely impacted. Transportation cost penalties will be incurred due to poor power system and thermal management system performance. The competitive position of NASA, DOD, and U.S. Industry will erode in an increasingly competitive world environment.

Recommendations

Increased Power Interest. The panel was encouraged that the mission/user agencies are becoming increasingly aware of the importance of power systems in adding to the cost, mass and performance of space platforms. Significant benefits to the user are made possible by improvements in power technology.

Augmentation. The panel fully agrees with the Augustine Committee Report in its recommendation that the NASA technology program be significantly augmented. NASA's ability to meet low cost and low mass performance enhancements can only be accomplished by significant budget increases. A modest increase could provide enhancement of NASA's capabilities and should be focused on technology that will provide significant cost reduction, performance improvements or enablement. Programs providing little near term benefit of low success potential should be relegated to low cost study or be terminated.

Space Nuclear Power. The SP-100 project should continue as the focus of NASA's nuclear reactor space power program. The panel was encouraged to see the growth and scaling capability of the reactor and the progress being made in thermoelectric and other advanced conversion technology. SP-100 also appears to provide significant NEP capability. Alternate reactor concepts were adequately considered in initial program formulation and in subsequent evaluations. Based on these findings, the panel recommends that NASA should not invest significantly in alternative concepts since this would be unnecessarily dilutive and non productive. NASA should however, monitor other DOD programs in space nuclear power and contribute expertise and resources to them.

NASA Technology Integration. The panel applauds NASA/OAET in its action to integrate the technology needs of other Program Offices such as OSSA and OSF. This activity should continue and be expanded to include a formal means of reporting on the status, of the activity and prioritizing the technology needs.

Beamed Power. The review panel found the presented material on laser-electric beamed power to be technically interesting. A system study to address tradeoffs for various applications is needed prior to

the commitment of significant funding.

Program Reporting. Several advancements are being made, some in areas with low funding and visibility. Results need to be provided to the user. NASA also needs to exploit synergism with other programs, with DOD and industry to capitalize on their investments.

Technology Planning Guidelines. The panel provides the following guidelines in NASA's technology planning:

- Emphasize performance and simplicity over complexity
- Have clearly defined technological and cost benefits/justification
- Maintain strong in-house technical capability
- Emphasize performance at an affordable cost
- Always factor in manufacturability/practicality
- Consider maintenance and logistics
- Provide program advocacy and clear decision making
- Take advantage of flight opportunities
- Avoid duplication
- Recognize the importance of PMAD and total systems concepts.

Assessment of the Plan

In view of the funding limitations that can be expected, the review panel believes it is important that NASA perform a careful screening of the technology in terms of cost and benefits so that the technology with the best merit is promoted. Technology with undetermined benefits and limited focus should be curtailed.

D.3 Human Support Panel Report

Background

The area designated as Human Support within NASA's OAET embraces a broad assortment of technological responsibilities and disciplines. The principal categories include the following:

- Human Factors/Crewstation Design
- Extravehicular Activity (EVA) Systems
- Regenerative Life Support
- Fire Safety
- Biomedical Support
- Habitat Thermal Management.

These technological categories have important enabling roles in long duration human missions. In fact, humans will function safely and effectively on such missions only with the capabilities that can be provided by these technologies. Therefore, human support technologies must be considered by the Agency as overriding in their importance to long range human missions. In addition to OAET's responsibility for the development of human support technology, the Life Sciences Division, within OSSA, is responsible for developing the scientific foundation for expanding human presence in space and for the provision of operational medical support to all space missions involving humans. The efforts of OAET are closely coordinated with those of the Life Sciences to ensure that the necessary components of these human support programs are undertaken (i.e, requirements are identified, technology development proceeds and programs are implemented).

Status

Technologies relating to crewstation design and EVA systems have been applied to successful missions. Fire safety has been a strong concern ever since the Apollo 204 accident in 1967. However, very little technological development has been emphasized for more than a decade, and long-duration mission scenarios greatly increase the risk from fire hazards. Biomedical support on past missions has been minimal, and, again, requirements that will be associated with future long-duration missions will drive the need for advanced technological developments. Regenerative life support systems (RLSS) have had the least mission application in NASA's flight programs to date. A four-bed molecular sieve was flown on Skylab in the early 1970's for the removal of excess carbon dioxide from the breathable atmosphere. That is the extent of flight experience accrued by RLSS thus far. Furthermore, none of the subsystem candidates that have received developments attention over the past 20 to 25 years has progressed beyond Level 4 readiness.

The status and technology development requirements for human support have been effectively addressed and reported in several documents, including: (1) "Human Performance for Long-Duration Space Missions," the Final Report of the SSTAC Ad Hoc Committee on the Human Performance for Long-Duration Space Missions (May 3, 1991); (2) "Space Technology to Meet Future Needs," by the ASEB Committee on Advanced Space Technology, NAS/NRC, Academy Press (1987); (3) Exploring the Living Universe: A Strategy for the Space Life Sciences, NASA Advisory Council (1988); and, (4) Space Science in the

Twenty-First Century: Imperatives for the Decades 1995-2015 - Life Sciences, NAS/NRC, Academy Press, 1988. In addition, the advanced life support technology program is being reviewed by an SSTAC Ad Hoc Review Team and will be reported during the summer of 1991.

Biomedical Support. The planned program, in OAET, presented for Biomedical Support appears adequate to meet both the near and far term requirements for platforms and exploration with two exceptions, i.e., sensors and refrigerator-freezer development. Efforts within the OAET program are being closely coordinated with the OSSA Life Sciences Program. The Biomedical Support Program uses evolutionary technology building on the biomedical equipment being developed for the Space Station post permanently manned capability (PMC) phase. The failures of the life support refrigerator-freezer on a recent Spacelab flight highlights the need for basic technology development of a freezer with a non-toxic refrigerant. The difficulty of monitoring the environment of the space vehicles or planetary habitats for toxic contaminants dictates basic technology development of sensors to meet this requirement. The consequences of not developing a toxic monitoring sensor could place the astronaut at risk or greatly complicate the operation.

Human Factors/Crewstation Design. Human factors includes the areas of human-machine interface, habitat design, decision aiding, and training. The overall objective is to provide for optimum human performance, productivity, comfort, and safety. The Human Factors Program, as presented, was judged to be well conceived and well executed and responsive to mission requirements. Key technology opportunities include virtual reality or data visualization displays; intelligent decision aiding and tutoring systems; simulation technology; and human-computer interaction (HCI), specifically for information management, system control, and operations (e.g., telescience). The potential payoffs for virtual reality technologies are in workstation prototyping and fidelity training. Payoffs for intelligent aiding/tutoring include reduced workload, reduced errors, and training refresh. Payoffs for HCI include improved integration of humans with automated systems. Payoffs for simulation technology include more effective and economical training, and the ability to rehearse complex mission operations in-flight. Consequences of no action for these key technology opportunities include higher costs for training, potential loss of mission due to catastrophic human error, and loss of data/capabilities due to inadequate human performance.

Extravehicular Activity Systems. The EVA Technology plan adequately covers future platforms, Lunar, and Mars mission requirements. The key technology opportunities within EVA systems include improved life, maintainability, and logistics characteristics for platforms and Lunar surface applications; and lightweight, regenerable systems for Mars missions. The payoff for platforms and lunar surface missions is improved mission effectiveness as measured by astronaut productivity and support logistics. In the Mars missions, the payoff is in providing a viable EVA capability, which is not achievable with the current technology status. If no technology action is taken, platform and lunar surface EVA's can be accomplished, but at less than optimum productivity conditions. Without technology development, Mars surface EVA is not achievable with today's systems.

Regenerative Life Support, Fire Safety, and Habitat Thermal Management. The Regenerative Life Support, Fire Safety, and Habitat Thermal Management programs address the needs of the platforms, Lunar and Mars mission requirements. Key technological opportunities include: the development of sensors for chemical and biological contamination monitoring, and smoke and fire detection; a safe, effective water reclamation system to produce potable water from onboard metabolic wastes and hygiene waste-water; and enhanced systems analysis and a testbed facility for systems integration. These received high priority ranking based on the potential for new and improved capabilities, the needs of potential customers (i.e., platforms, Lunar and/or Mars missions), and the developmental urgency. Solid waste management technology should also receive development attention, but with a secondary level of priority. For all these opportunities, payoffs center on sustaining human life and by providing maximum logistical and safety benefits.

Recommendations

- Proceed with the development of a closed loop life support system
- Establish a robust sensors development program to meet the needs of human support systems
- Continue development of chemical, microbial, and biomedical sensors
- Continue development of fire and smoke detection sensors

• Reprioritize all human support program elements consistent with the OAET ITP strategic planning process methodology;

• Continue the coordination of efforts across the OAET Human Support and the OSSA Life Sciences Programs.

D.4 Automation and Robotics Panel Report

The planning presented by the NASA OAET automation and robotics (A&R) panel was done with the most care, thoughtfulness and concerted effort that the review panel has seen in recent years. Several plans were presented, corresponding to several levels of officially proposed funding. One of these levels was described as the "*baseline R&T funding*". Perhaps the most remarkable point for the review panel to note is that the share of resources going into the area of A&R at the "*three-times funding*" level was only 20 percent above that of the baseline. This is a very serious issue. The review panel believes that powerful supervisory telerobot teams (including both humans and robots) will *have* to play a new, central role in future space endeavors. This role will make A&R a technological pillar for the future of the civil space program — along with propulsion, guidance and new materials — that must be greatly strengthened. A&R's current level of R&T funding (or the 20 percent addition proposed in the "three-times" budget levels) is far short of what is already absolutely essential to give America significant advances in space.

American core research in supervisory telerobotic human/machine systems is very important. With the present American funding level — or the proposed 20 percent increase (proposed in the "three-times" program) — the foreign competition is and will continue to be pulling away fast; and each foreign country will, in particular, get far out in front in the area of human/machine systems capabilities in its national infrastructure. This will leave the U.S. *crippled*: crippled in space endeavors and crippled in National economic strength.

The review panel strongly recommends increased emphasis on A&R in NASA technology planning, with continuing balance between R&T Base and focused development program efforts.

Background

In the future space operations that this Nation contemplates, the humans in command will require the support of major new levels of automation for (1) the information upon which they base their decisions in real time, and (2) the human-robot teams that carry out the actions decided upon. For decision-making and for action, the secret is in achieving reliably greater autonomy at the lower levels, so that the human can focus full attention and energy at higher levels. Thus, the goal of OAET's program in *Artificial Intelligence* (AI) is to advance in many dimensions the systems of support which humans in space and humans in mission control can continually depend upon to make real time, optimal decisions.

In *Telerobotics*, the review panel believes that what is absolutely essential for significant future American advances in space is the development of human-robot *teams* in which the human — on Earth or *in situ* — is much more powerful than before because the robot can pursue tasks that are assigned in real time at a high level (i.e., "supervisory telerobotics"). Such tasks require of the robot reasoning and decision-making as the unexpected is encountered. Only then will the human be freed from continuous hand-in-glove control of the robot's joints (which demands total attention and is exhausting for the operator), and freed to plan and command the next tasks. Building upon the (currently modestly funded) OAET Telerobotics (TR) Program to date, the integrated supervisory-human/telerobot team is a system that must be achieved.

The review panel believes that the new central role in space that displays for decision-making and powerful supervisory telerobot teams will have to play makes automation and robotics a technological pillar — along with propulsion, guidance and new materials. These discipline areas must be supported at a much stronger level in NASA's R&T programs in the immediate future. This is true not only to enable viable levels of human safety and productivity and to reduce the costs of future space operations, but indeed to make true advances in space discovery possible at all.

Status

The NASA A&R Program was established in 1985 as the result of a Congressional mandate (Public Law 98-371). It is currently the only space-related AI and robotics research and development program in the Nation. In the six years since its inception, NASA's A&R work in artificial intelligence, telerobotics, and planetary rover vehicles (PRVs) has, considering its very low level of funding, made very important beginnings in this

critical area of research.

This section provides a brief summary of the current status of each of the three program segments as the panel perceives them from the careful presentation made by OAET.

Artificial Intelligence. AI is an emerging discipline that embraces intelligent management of information *per se* and of the process of drawing conclusions, making decisions, and structuring task strategy. AI's embodiment is in the software that it creates to carry out each mission. The NASA AI Program appears to have made significant strides since its initial beginning. The program has developed a balance between fundamental and applied research. It has attracted the talents of a number of good people, and has an effective working relationship between the in-house researchers and the NASA user community. The AI Program has thereby been effective in helping transition NASA from an Agency that did not use AI to one which now uses the data management of AI operationally in varying degrees at all the NASA field centers.

The mission control center at the Johnson Space Center (JSC) was significantly affected by the infusion of data management technology in an AI-supported program that has involved, as design partners, current Space Shuttle mission controllers. That team effort provided new software for the data management displays for about half of the mission operations consoles at JSC. In this context, new AI-based systems now diagnose failures in less time than the old system took to update the relevant parameters.

The AI Program has made similar advances in aiding the control for unmanned satellites from the Jet Propulsion Laboratory (JPL). The AI program has also developed tools that have provided space scientists with the ability to analyze more data than previously possible. Other AI tools are under development to help mission controllers for manned and unmanned missions. For example, an AI-based scheduler will be used next year to save time and money in the scheduling of Space Shuttle refurbishment at the Kennedy Space Center (KSC). A tool to aid astronomers in the conduct of scientific experiments on the Space Shuttle and on Space Station *Freedom* has already been tested on the ground and will be tested in space in 1992.

The Ames Research Center (ARC) has a strong intramural AI research team and also support basic university research in AI. That fundamental research is important to efficient space operations, to the value of future mission science data, and to American economic strength in the coming years.

The AI Program has made excellent progress—particularly toward getting concepts transferred into important roles at the mission operational level (e.g., in mission consoles, where we understand it is expected soon to begin enhancing operational performance and saving significant operational funds). In this respect, the AI Program could serve as valuable model for its partner effort, the *Telerobotics* program in OAET, which is at an earlier stage in programmatic maturation, since the development of each new hardware system concept requires inherently longer gestation times than needed for software-only systems.

The Telerobotics Program. Developing the power of high-level supervisory telerobotic system capabilities is at an early stage. One essential component — at the mechanical-manipulation level — is, of course, the pure robot. Robots that can follow either programmed sequences or joint-rotation inputs from hand-in-glove human generation are a necessary, primitive first step. However, a fully capable system will require: (1) advanced robots with the needed new level of autonomous capability to follow commands generated at the task level — with resourcefulness and robustness; and, (2) a rich interface that, in real time, connects the operator easily to the robot at the high task-command level. The interface also will convey to the operator a full sensation of being at the scene (and allow commands via point in space), and provide a succinct choice context for intelligent planning options.

A human is always in control of the robot; in a good next-generation telerobot that can be developed, the human may be able to move easily from high-level task commands (with some time between commands) to intermediate-level commands of preprogrammed tasks, to move-by-move control. In a robust future human-robot system, these varying types of control will be a continuum.

This capability has emerged at the experimental proof-of-concept level under OAET university funding. It is now urgent that it move to the technology development phase, drawing upon experienced robot-in-space mission operators (astronauts) as design partners, while in parallel strengthening significantly the basic research that must support it.

At the same time, manipulative capabilities *per se* must advance considerably beyond the current state-of-the-art. The OAET program is addressing this vigorously with the funding available. Pathfinding

work is developing the basic concepts for: totally cooperating two-arm manipulators that readily adapt to load changes; systems in which very large, flexible manipulators (like the Space Shuttle RMS) carry graceful, human-size arms which in turn carry quick, precise mini-manipulators; free-flying robots that cooperate with each other in teams under high-level human supervision.

Telerobotics will, without question, be a central part of the Nation's space infrastructure in the future; and NASA *must* have a robust telerobotics research program that will provide a solid new concept base and, with strong members of the user community as design partners, will take these new system capabilities that the community must have to a "technology ready" level of confidence.

The Planetary Rover Program. This program was initiated in FY 1989, and has since made significant strides in developing and evaluating autonomous wheeled and legged rover vehicles. In a short space of years, the program has generated two roving vehicles to test mobility concepts. This has been a small effort, including work at JPL and university research, but it is essential to the success of future planetary exploration missions. This effort has been zeroed-out in current FY 1992 program planning. Stop-start funding has a devastating effect on programs, particularly in terms of maintaining expertise and skill. The review panel recommends that a continuing, core development research program be established in this area.

Comments and Recommendations

The Aerospace Industry Association's (AIA's) forecast of pivotal technologies for the 1990's, as well as every major agency advisory report on NASA's future technology needs, have placed automation and robotics high on the list of critical technologies. NASA's mission projects are growing in complexity and duration. Tomorrow's capability in A&R will affect very central the mission content, quality, productivity, and cost of tomorrow's National space endeavors.

Because of severely constrained funding, NASA is missing badly the opportunity that automation and supervisory telerobotics needs so compellingly to provide. With the present NASA funding level — or the proposed 20 percent increase that is provided in the "three-times" program presented to the review team — the foreign competition is, and will continue to be, pulling away fast. Moreover, the economic effect of human-robot system capability being in the economic arsenal of Japan and Germany — and not in that of the United States — will be profound. If the U.S. doesn't make a step change in government support of American research in space A&R, this Nation will be left behind in *integrated* space capability, and in global economic development as well.

The review panel recommends that the AI and TR programs in basic and applied research be doubled in funding at once from the FY 1991 levels, and increased over the next five years to three-times the FY 1991 levels, and the Planetary Rover program be continued with increased funding. (This recommendation is independent of flight experiment programs, which are discussed at the end of this section.) In particular, with regard to AI, NASA's program has only begun to realize the benefits that are latent in this area.

Artificial Intelligence. Specific recommendations for the AI Program include the following:

- Develop vigorously AI techniques to aid in the problem of developing, testing, and maintaining NASA's mission management and control software base

- Develop a greater integrated architectures capability for robust decision-making and control

- Develop internal applications of AI technology

- Increase collaborative activities with NASA operating groups and with industrial laboratories; and at the basic research level, support and draw much more strongly on university research.

The Telerobotics Program. Specific recommendations for the Telerobotics Program include the following:

- Develop strong supervisory human-telerobotic system technology base, and strengthen the fundamental research base that must support it

- Develop total cooperating two-arm manipulator systems that readily adapt to load changes

- Develop and demonstrate system concepts for controlling incisively large, flexible manipulators that carry much smaller quick and precise end-effecters

• Develop conceptually and demonstrate the control of teams of free-flying robots cooperating as a team under high-level human guidance

• Provide near term basic support to the specific tasks of the flight telerobotic servicer flight test.

The Planetary Rover Program. For the planetary rover vehicles, the panel recommends further development of this innovative program.

General Comments. The balance between basic research and technology development must be maintained. To do its job, an R&T program must be be very strong in two distinct categories of effort: (1) basic, core search, and (2) technology development in support of mission needs. These must be funded in balanced proportion and partitioned from one another to maintain their crucial balance. It is the purpose of the core research program to provide the solid, leading-edge base on which to build understanding at the fundamental level. It is the core research base that facilitates the development of innovative concepts. The development of new creative concepts is primarily the role of universities. It is at the university where small groups of talented, creative individuals can rapidly explore a range of creative, new ideas. It is not an expensive part of the program; many small groups can be sponsored for a cost that is small compared to the cost of the development parts of the program. Funding should be increased by fourfold (whereas in the strategic program it is increased by only about 20 percent). The review panel supports the OAET proposal to transfer this component into the R&T Base segment of the space R&T program.

Technology development to support mission needs is conducted at two levels: ground testing and flight testing. The former should be conducted at focused testbed facilities, and no more than two NASA centers should be involved for a given system area. Selected flight testing is conducted to insure that development is based on reality. Experimental flights (the minimum necessary) are essential to reaching operational capacity (i.e., providing verification and confidence). Flight experiments are expensive and must be selected and implemented with rigor and under the supervision of experienced individuals.

In order for a program to achieve a new level of capability it is important that all three components (i.e., core research, new concepts, and technology development) must be present in balanced measure, or the program will not succeed. A funding balance has to be achieved and the three components require partitioning from one another.

It is also important that universities participate in a major way in the basic research, with NASA centers building on emerging concepts at the applied research and developmental level.This will ensure the opportunity of new technology applications to space operations.This will require carefully structured collaboration between the particular center and university laboratory involved in each project. Headquarters should provide guidance and strong motivation for such collaboration.

Due to the very constrained current funding environment, NASA is not able to take advantage of the opportunities that the Automation and Robotics Program could provide to NASA missions. Currently, the human is absorbed only in moving robot joints, however, it is possible for the human to command at the task level. Future exploration missions will require a more developed human-robot team. When they are a team, the human (i.e., whether nearby or far away) will be freed to focus on what is unexpected, to judge and to make high level decisions. This is because the robot has a level of autonomous capability to follow commands, resourcefully and robustly, and because a rich interface connects the operator easily with the robot and to supporting scene presentation and planning options in real time. A good system would allow the human to move from high level task commands across the range of intermediate levels of control all the way down to move-by-move control. This level of capability needs to be pursued at the technology development level with strong support in the basic research program for supporting new concept development.

Projects in the R&T program need to be conducted in closer collaboration with experienced operational personnel as design partners, not merely with increased coordination. The collaboration should involve experienced operational individuals as design partners. Headquarters should provide the motivation to the mission part of the team including direction, incentives, career-value guidance and funding. Without this, the invaluable creative ideas of mission experienced individuals will not occur, and the technology will not get transferred. This essential component has been absent from the telerobotics program.

D.5 Materials and Structures Panel Report

Background

The Materials and Structures programs within the NASA OAET Space R&T effort cover a broad spectrum of activities including:

- Material Science
- Space Environmental Effects
- Aerothermal Structures and Materials
- Space Structures
- Dynamics of Flexible Structures.

Embedded in these topics is a broad array of activities, ranging from *Computational Chemistry* (which is fundamental science in that results are obtained by numerically solving Schroedinger's equation) to *Vibration and Acoustic Isolation* (which is more directed to applied engineering research). The Materials and Structures efforts, in both the R&T Base and the OAET focused programs, embraces participation from the NASA research centers (LeRC, LaRC, and ARC), and also from NASA flight centers (JPL, MSFC, and JSC), as well as from many universities.

Recommendations

R&T Base - General. With respect to the R&T Base, the review panel had the following conclusions:

- There is a good balance between near and far term needs
- The R&T Base efforts support the focused programs
- The R&T Base supports user needs.

There is a concern that the focused programs, being easier to understand and justify, may drain resources from the R&T Base. To ensure that this does not occur, the R&T Base should be vigilantly protected and carefully nurtured. There are however, some gaps in the R&T Base as addressed below.

Controls-Structures Interactions (CSI) Technology. The review panel would like to cite the CSI technology program as a model for other space technology programs. It has forged two previously disparate disciplines, controls and structures, into a single discipline. There is participation by most of the NASA centers, industry, and universities. This well managed effort encompasses both theory and scheduled flight experiments to validate the results of ground testing.

The review panel also encourages continued systems cost benefit analyses in the CSI area. These assessments provide continuing guidance for program content, and a foundation for future advocacy of the program.

The review panel suggests that materials be included as a variable in the optimization studies which are an integral part of the CSI technology development. This should take the form of specifying Young's Modulus over a range of values with the variation of other parameters, such as structural configuration and control parameters.

LDEF and Space Environmental Effects. The review panel recommends that many activities currently conducted under the rubric of the Long Duration Exposure Facility (LDEF) be incorporated into the broader OAET program, Space Environmental Effects (SEE). The LDEF, which is the only significant project now being accomplished in the SEE area, needs a complementary focused R&T effort directed toward the creation of a *Space Materials Handbook*. This *Handbook* could present the data from LDEF and other facets of SEE activities in forms for direct use by future spacecraft design teams. Other materials handbooks such as MILHNDBK 5 and MILHNDBK 17 can serve as models for the philosophy, publication and maintenance of such a new *Space Materials Handbook*.

There is a perception that the study of LDEF by itself, is a sufficient effort to address all the important space environmental effects issues on materials. However, the review panel believes that overall SEE efforts are in need of expansion in the near term to include: (a) activities to provide data on the invention of space durable materials; and, (b) activities to validate analytical models and ground experimentation. In addition, there is a need for a *Combined Exposure Facility* which would allow the simultaneous exposure of materials to atomic oxygen, ultraviolet light, protons, etc., to determine the extent of potentially negative synergisms.

The review panel noted with approval that NASA is working closely with the DOE laboratories in the area of space environmental effects.

R&T Base - Gaps. The review panel stresses the importance of reducing structural weights at an affordable cost. To this end, the panel calls attention to some gaps in the current R&T Base program. Specifically, there are no coherent programs in either launch vehicle structures, or rocket motor throats and nozzles. Programs in these areas should address:

(a) materials; (b) structural concepts; (c) efficiency; (d) manufacturing; and, (e) low cost and affordability.

The review panel enthusiastically supports the creation of a cooperative industry and government program for the application of composite materials for space. This effort should be modeled, in part, on the successful programs which have been focused for aircraft structures. The review panel also believes that there should be a program element addressing the repair of space structures and a program element to develop materials for the protection of equipment against the radiation of space. One area of near term importance is in-space welding. This technology is currently funded at a low level and is unlikely to be developed by industry using their own resources.

The Agency's Facilities. A major contributor to the Nation's technological leadership has been NASA's unique experimental facilities. These have enabled the agency to obtain basic research data as well as to provide a testing service for other experimenters. NASA and the Nation are in danger of losing this technological leadership because these experimental facilities have not advanced with the evolving needs of research. The review panel believes that the *Arcjet Facility* at NASA ARC should be upgraded. This facility is essential for the invention of new materials required for projected future missions. Moreover, as has already been noted, a *Combined Space Environmental Testing Facility*, is needed to determine the extent of the synergisms on materials when subjected to environmental hazards such as ultraviolet and galactic cosmic radiation.

Observations and Recommendations. The Materials and Structures review panel recommends that NASA substantially enhance its efforts (e.g., as it has for commercial aviation) to make the U.S. competitive in the international marketplace with respect to launch services and spacecraft. This is urgently needed since the U.S. now enjoys only a small share (i.e., approximately 10 percent of the commercial space market). NASA needs to reduce the overhead and long schedule times associated with launch services, reductions which may not be possible with an internal restructuring. Other Nations are investing in new technology and have made national commitments to compete for the launch services and spacecraft business.

The review panel also recommends that the scope and criteria need to be better delineated for the focused technology programs. At present, there is no clear line of demarcation between a focused program and one which is needed by a project office in a relatively near term schedule. Another factor is the tendency of the sponsors of focused programs to withdraw sponsorship when their overall budgets are reduced. It is impossible for the R&T Base to absorb the focused programs since the level of funding for a focused technology project is generally larger than that of a line item in the R&T Base budget.

In order to infuse new technology and new goals into the technology of Large Space Structures, the review panel recommends that NASA sponsor a workshop involving industry, universities and other government agencies. Nearly twenty years ago, NASA identified Large Space Structures as an important area. The subsequent research and advanced technology program has made much progress in this Nation's ability to configure structural systems for large antennas, power systems and platforms. One of the outstanding accomplishments has been the integration of control and structures into a single discipline. Additionally, the erection of large truss structures has advanced to the stage of readiness and application demonstration. New demands from exploration missions and high performance, multi-payload platforms are being inadequately addressed. Some efforts, such as deployable structures, are virtually at a standstill. Momentum has been lost due to the fits and starts of this Nation's space program. The workshop would be a first step to revitalize the technology of Large Space Structures. Such workshops were held with great success in the 1970's.

An additional problem is that of flight experiment costs. The present costs inhibit the flight verification of experiments subjected to a one gravity environment, and other effects, present on Earth but not in space.

The panel believes that for the most part, NASA's advanced technology programs are aimed at increasing the Nation's capability to accomplish future space missions. This is indeed the case for the Materials and Structures program. Concomitantly, there is a need for a directed emphasis on reducing the costs of future space missions. OAET should take a leadership role in overcoming the mindset which views costs as of secondary importance.

Finally, the ITP states that one-third of the overall Materials and Structures budget is planned allocated to the R&T Base efforts, while focused technology programs will be allocated the remaining two-thirds. The panel believes this is a reasonable division of funds. The justifications for these two categories of activities however, are different. Both should be defensible on their own merits, yet with regard to their relevance for specific applications, it

is stronger for the focused programs than for the R&T Base. The applicability of results from the focused programs to a particular spacecraft, launch vehicle, or platform, and their attendant missions, needs to be more sharply apparent. In particular, the linkage between a focused program and key NASA missions must be such that the importance can be justified to persons outside NASA and the SSTAC/ARTS committees.

D.7 Data Systems and Computer Science Panel Report

General Comments/Observations

The technical review panel found the overall plan and supporting presentations to be thorough and of high professional quality. General comments follow.

The review panel concluded that the Data Systems and Computer Science (DSCS) Program area generally hit the mark in responding to the push-pull framework and to the user's prioritized needs. Recommendations for integration or broadening of emphasis are included in the detailed element comments. The panel recommends the funding at the 3X level and additional funding of a redefined flight control/operators technology element.

Leveraging from other agencies and industry is a dominant factor in achieving the goals of the DSCS program. The panel encourages NASA to increase emphasis on this leverage, with specific emphasis in the software and operations technology areas. In the same vein, strong interaction with the National Critical Technology Initiatives programs is important. Many of the goals presented cannot be achieved without such leveraging and interactions.

The technology areas of software engineering and flight control operations have the potential, if focused, of providing large payoffs in terms of cost reductions. These cost reductions would be in large NASA software and operations areas for relatively general technology costs. The panel recommends that this leverage be exploited through Agency-wide support for technology needs definition and planned technology insertion, as appropriate, in the operational environment. The artificial intelligence and neural network technology efforts also bear directly on the operations.

The review panel believes that the user driven technology thrust framework has worked in enhancing advocacy and in prioritizing efforts. It also has succeeded in identifying new needs (e.g. Flight Control-Operations Technology). The panel believes that the near term program (i.e., 1991-2000) was reasonably focussed but that more consideration is needed for the technology consolidations of the out years (e.g. Mars environment efforts) in the next iteration of the plan.

Specific Program Element Comments

The panel presents the following assessments of the specific program elements:

Onboard Memory and Storage. The onboard memory and storage activity objective is to develop high performance, space qualifiable data storage technologies. The technical review panel endorses the areas of investigation in this activity, the optical disk drive and solid state recorder. The advantage of the technologies are increased storage capacity, smaller size, increased reliability, and operating functionality. The panel believes the effort is focused, with clear milestones and that the technology has value. This area is also leveraged by support of the technology development by the DOD. Since the attributes of the technology are strongly configuration and user dependent, the panel recommends potential customers be identified and involved in the development process. The plan for flight demonstration of the technology to demonstrate flight qualification also is endorsed by the panel.

Advanced Flight Computers. The panel fully endorses this program and commends the professional working relationships between NASA and the DOD to effect a good leverage. The long delays in realizing computer technology advancements in spacecraft computers must be eliminated. Strong funding support for this program and continued emphasis on leveraging DOD and commercial efforts are necessary for timely insertion of computer technology in spacecraft applications. A balanced program, as proposed, including hardware, software and system tools is mandatory.

Special Purpose Processors. The panel endorses this program as proposed. Program relevance is clearly defined and benefits justify this investment. The program has a good balance between special processors for SAR and HIRIS and generic processors such as autocorrelators and cross correlators. The microelectronics efforts, ASICS in particular, needs continued emphasis on leveraging the ASIC industry and relevant DOD efforts.

On Board Networking and Testbeds. The networking and testbeds activity objective is to develop high performance, space qualifiable

networking technologies. The panel endorses the areas of investigation in this activity, with the following comments. Architectures and standards will be driven by other developments in the commercial and DOD sectors. The project should leverage on these developments utilizing state of practice rather than developing state of the art developments. The establishment of a testbed, the flight systems validation laboratory, does have value in demonstrating emerging technologies.

Archive, Access, and Retrieval. The objective of the archive, access, and retrieval activity is to develop technology for automated characterization, and interactive retrieval of large complex scientific data sets. The panel endorses the areas of investigation in this activity. Mass storage data organization, automatic data characterization, browsing mechanism, object oriented data base management, and a research tool set are technologies that support the handling of large science data sets. Because of this support, the panel strongly recommends the development be performed in support at the Earth Observation System and that insertion of this technology into the EOS/DIS system be enabled. It should be noted that archival and retrieval of science data in an efficient manner is already a problem. Therefore, the potential payoff of this activity is considered high by the panel.

Visualization. The visualization activity will provide supporting functions to enable a user's success of the data provided in the Mission to Planet Earth to navigate (i.e., access) the data of interest and use it as so desired. The panel endorses this activity. The visualization activity should be closely coordinated with the task on data archival, access, and retrieval so that both build on the capabilities offered by each other. The value of this activity will be in cost containment. The user will be provided with a tool that supports comprehensive use of the science data involved in the EOS mission, rather, than having to address issues such as the delivered system not meeting the users needs.

Neural Nets. The panel endorses the Neural Network Program. This technology matured through previous efforts to the point that the architectural definitions and transition to operational applications is guaranteed and offers significant cost savings potential. The panel believes that the effort should maximize its leverage of the commercial offerings of industry in order to reduce the cost of application development. This work is currently leveraging DOD efforts in order to accelerate the technology to a functional state. Both synchronous and asynchronous applications offer large potential operations savings. The panel is concerned that the early funding is inadequate for the anticipated rush of applications particularly in the area of operations support.

Software. The panel endorses the Software Engineering Program with the following observations and recommendations. This program should provide the enabling NASA unique tools and the integration required to permit the establishment of a common software support environment for the agency. This is an important activity for containing and reducing agency development costs and should receive any additional budget necessary from operational budgets that would benefit from the offered technology. Effective transition of the technology from research to the operating centers will require a high degree of teamwork. This is important for defining requirements, validating techniques and tools, and incorporating into operational systems. Agency wide support to this technology program is vital. The panel recommends that this agency wide participation be instituted along with the program.

Multi-Mission Operations Testbed. The panel recognizes and encourages the application of R&T funds to improve operations. Nevertheless, due to the constrained budget environment, the panel concurs with the low priority of funding for the currently defined program (i.e., zero funding in both fiscal years 1993 and 1994). It is recommended that the program be rescoped and replanned to include other technologies, such as AI and neural nets, during the next two years. The program should also address a plan for technology transfer. The needs and potential payoffs justify a program rescoping effort that would focus the program on the technologies that provide operation support tools (e.g. AI, neural nets, and expert systems) that can optimize savings in operation costs to the agency. A broader and more focused program would justify the increased funding outlined in the Strategic Plan.

Advocacy/Justification Avenues

The review panel identified three justification arguments that support the DSCS program areas. These include the following:

1. The technology investments are required to let NASA leverage and capitalize on National critical technology, other agencies and industrial activities

2. Modest technology investments in software engineering and on focused flight control operations

technology have high potential for cost reduction and control in NASA operational areas

3. The program emphasizes bringing technology to a demonstration/proof of concept level, including flight testing, which facilitates technology transfer to programs and operations.

D.8 Communications, Photonics, and High Temperature Superconductivity Panel Report

D.8.1 Communications

This year's coordinated review process has resulted in a greatly improved and integrated technology plan. The Communications program has three major customers: OSSA, OSO, and the U.S. commercial satellite communications industry. OSSA has the objective of providing communications and technology to support deep space and near Earth missions and return scientific data to Earth. OSO, the space operations group, has the objective of supporting NASA networks and internal communication needs. The U.S. commercial satellite communications industry has the objective of enhancing U.S. industry competitiveness.

Enhancing U.S. competitiveness in satellite communications has become increasingly important. This will be a $50 billion industry in the 1990's and the foreign market share in satellite manufacturing will increase fourfold from 1979 to 2000.

The scope of the communications program includes the following areas:

- RF Technology
- Digital Technology
- Optical Technology
- Mobile Communications Technology
- Systems Integration, Test and Evaluation
- Advanced Systems Studies.

RF Technology. The RF technology area involves work in high powered amplifiers, monolithic microwave circuits, advanced antennas and other microwave component areas. RF technology is an important area for space communications and one in which technology gains have a major impact on communications performance, planning, and execution. The existing funding needs to be increased to support the important projects in this area and the 3X and strategic funding levels, which are nearly the same, would provide marginal funding for the activities being carried on and planned. The panel therefore recommends an increase in level of funding level in this area. The consequences of not pursuing this area would be increased dependence of foreign suppliers and heavier spacecraft able to carry out less scientific experiments.

Digital Technology. The digital technology area includes such activities as modems, codecs, artificial intelligence, digital signal processing, networking, and autonomous control. This area's importance is increasing as more signal processing becomes incorporated in spacecraft and on the ground to conduct missions of greater complexity. It is also important because of the higher performance involved in commercial satellite communications. The review of this area revealed good program focus, planning and execution. The panel believes that increased emphasis should be placed on ground based autonomous control and on reliability, power consumption and cost, as more processing is incorporated into the spacecraft. The panel recommends that general flight validation is not necessary in this area, and in light of budget constraints, effort should be placed on ground validation whenever possible. This area also requires increased funding levels to conduct the identified activities, with the 3X and strategic funding levels marginally acceptable for the tasks identified. There are several consequences if this program is not carried out. These include a less capable spacecraft, and the inability to both to conduct more complex scientific missions and to provide higher performance commercial spacecraft.

Optical Technology. Optical technology represents an exciting area making significant progress in components and systems. It is the key enabling technology for higher data rate communications for both deep space and near Earth missions and for operations. In the commercial area, both in Europe and in the Pacific, substantial investments in optical technologies are being made. These investments are based on the recognition that satellite-to-satellite links will become increasingly more important for future higher performance satellite systems. The major thrust in this area is the ability to generate higher power coherent sources which can be efficiently modulated. Pointing and tracking as well as better detection are also important areas of pursuit. For this technology, flight validation of complete systems is important and an opportunity to fly a system on the ATDRSS satellite, which requires a program start in fiscal year 1993, should not be missed. Present funding levels

do not permit flight demonstrations even at the 3X level. The panel therefore recommends that this area be funded at the planned strategic level indicated in the plan.

Mobile Communications Technology. Mobile Communications technology is one of the fastest and most important areas in commercial satellite communications. Lack of support, in this area, will undermine the U.S. position as foreign activity is extensive. The NASA program includes investigation of Ka-band mobile systems for aeronautical, land mobile and personal communications and limited experimental validation being planned on the ACTS satellite. In addition, propagation measurements, system studies and development of critical ground terminal components are being carried out. Direct broadcast audio satellite systems, of considerable worldwide interest, are also being pursued. Good work is being conducted in this area both in system studies and technology development for ground terminals. Increased emphasis is needed on system studies and technology development for ground terminals. Increased emphasis is also needed on system studies and L band LEO systems. Emphasis on aeronautical Ka band mobile experimental evaluation is important. Funding at the 3X and Strategic level is marginal when one includes the important area of experimental validation. As this area is of such importance to U.S. industry, it is recommended that funding levels be increased over present levels.

Systems Integration Test and Evaluation. Systems integration test and evaluation includes the Site Project system simulator for the ACTS satellite, component integration and test, and network evaluation. This area is a cornerstone for conducting communications flight programs and missions and for reducing risk in such flight programs. It should therefore continue to receive strong support. This area is adequately funded for the ACTS program only, and would require additional funds to support other flight programs.

Advanced Communications System Studies. Advanced communications system studies are needed to increase the effectiveness of technology planning for NASA missions, NASA operations and for increased U.S. competitiveness. An increase in emphasis should be made on coordinated system studies which include multiple program offices, centers, CCDS's and industry. Study results provide essential guidance for the R&T program. For the U.S. commercial satellite industry, system studies must include market research and analysis, competitive technology assessment and be repeated annually due to the dynamic nature of both the market and technology. Such advanced system studies are a key ingredient in the strategic planning process and need to receive increased emphasis especially when planning needs to be well focussed.

General Comments

The following are some general comments about the communications program. As a result of the reorganization within NASA of the communications program between OAET and the Office of Commercial Programs (OCP) increased emphasis should be placed on interoffice coordination. The Space Communication Steering Committee is already in place. The panel recommends that a communications working group be established. This group would be comprised of multiple centers, program offices, industry, DOD and NASA/OCP-sponsored Centers for the Commercial Development of Space (CCDS). In addition, a multicenter working group should be established to facilitate the coordination process, which is currently done on an informal basis.

In many scientific missions, communications is considered of secondary concern and addressed at a later time in the mission planning process. It is recommended that communications requirements be considered at the time of program definition to ensure that the right communications system will be available for the mission.

The panel observed, in general, that the different technology areas in the communications program suffer from small budgets. If these budgets cannot be increased, it is recommended that prioritization and focussing of the R&T programs in these areas be conducted to ensure success of the higher priority programs within each of the areas.

A related area of crucial importance to the U.S. Commercial Satellite industry is the development of low cost expendable launch vehicles (ELV's). We therefore recommend that the development of such low cost ELV's be given a high priority within NASA.

D.8.2 Photonics Technology

The Photonics Technology program was essentially zeroed three years ago when it was moved from the Base and CSTI categories to the Pathfinder program which was drastically cut, leading to deferral of all photonics funding. The emphasis of the program was to be related to technologies that were essential to SEI and anticipated budgets starting at $2.4 million and reaching $10 million in

five years. This year the plan envisions a return to Baseline at $600 thousand in 1991-92, moving to an increase of $3 million in 1993 and 8.6 million in 1997. Additional increments of $4.6 - $6.8 million and $4.0 - 8.0 million are planned for space science sensors and processing and communications in 1995 through 1997. The emphasis in the R&T Base includes: (1) materials and devices; (2) high capacity fiber optic networks and high speed processors; (3) optical information processing related to advanced pattern recognition; and, (4) photonic sensors. In the materials and devices area, the primary emphasis is on devices. This is appropriate, but expenditures on materials should be limited to better understanding of the characteristics of material development, which is being funded substantially by both DARPA and industry. To yield results from the ample subsets shown in the WBS, funding at the significantly expanded levels would be essential, yet perhaps not enough. At more probable levels, major use of DARPA and industry sponsored work should permit some useful NASA related effort.

One of these is an inspection support project in pattern recognition which could have early application in aerospace manufacturing. This could well consume all available funds at the current level. The second area of direct NASA benefit lies in the development of opto-electronic circuits at JPL. This program should benefit from the extensive DARPA / Lockheed / Intel work in this area. Data analysis of the LDEF exposure for fiber optics is fundamental and should be continued, though it should not be particularly expensive. Another intriguing application, smart skins at LaRC also should augment NASP funding for viability demonstration, and then could become a major priority.

While the photonics technology program has set up useful milestone demonstrations, they are not presented as linked to real NASA projects. Milestone demonstrations should be linked to projects if the technology transfer is to be effected. Overall, the panel found that the orientation of the program is good but should be adjusted by determining more fully what is occurring in other government laboratories and industry. Since it is overly ambitious, it should concentrate on a few projects that can yield demonstrations defined in conjunction with potential users in a relatively near term. Longer term activity should not be started without adequate valid projections of funding, and except for R & PM for educational purposes, investment should be limited by NASA to no more than two centers plus JPL.

D.8.3 High Temperature Superconductivity (HTS)

High temperature superconductivity is a revolutionary new technology of great potential to NASA's primary missions including, LEO, planetary, and deep space. A wide variety of space applications have been identified in the areas of communications and data systems, sensors and cryogenic systems, and power and propulsion systems. Unique electrical and thermal properties offer possible major improvements in such areas as system performance and reliability, large reductions in size, weight and electrical power requirements, and extension of mission life. Although the HTS technology is still in its infancy, rapid improvements in thin film and bulk materials, and detailed system studies have clearly demonstrated potential payoffs and justify funding of device development and demonstration prototyping.

The current program, funded in aggregate at about a $4 million level, is distributed among a number of potential application areas. RF communications utilize approximately one half of the funding. Sensor and cryogenic systems are allocated approximately one eighth each, and the remaining quarter is distributed among propulsion and other application areas. As currently funded, there is a subcritical level expended for each area which is sufficient to conduct a minimum level of research studies. Furthermore, with no line item authority, there is a lack of focus and projects are funded from a set of diverse short term funding sources. In almost all cases, the money is reprogrammed last minute from other sources, and lacks continuity.

If continued in this way, NASA will probably stay smart in the area, but will lack any system demonstration projects in the near term. As a consequence, NASA will miss major opportunities made available by this new technology.

It is the panel's recommendation that NASA choose its two highest priority HTS projects and fund them adequately from the initial research phase to a demonstration stage and develop two prototypes using HTS technology. The panel recommends the following two projects: Low Noise Receiver/Phase Array Antenna System (LNR); and, Cryoleads.

If successful, the payoff in LNR is that it would significantly enhance the design trade space by at least a factor of two or more. This means significantly higher data rates, lower power, greater range, lower weight, and smaller aperture.

Depending upon the application, one or several of the above could be optimized, providing unquestioned new capabilities to deep space and satellite communications missions. It should be noted, that the latter application area is also very significant to the Nation's competitiveness, and NASA has traditionally provided a leadership role in this technology. By the same token, developing HTS cryoleads will enable NASA to extend the mission life of many of its flights, by as much as 25 percent. Although both of these projects still require a fair amount of engineering, it is felt that the proof of principle had been shown, and an infusion of funding will result in demonstrations in the near term with minimum risk.

It is the panel's estimate that the 3X program will be minimally sufficient to adequately fund these two top priority projects. It would also sacrifice all other work in HTS, thus cutting off any new opportunities in the future. To this panel, that would not be a prudent choice, since HTS technology is only five years old, and only recently have new materials been available in suitable form for exploration of new concepts.

The panel recommends that NASA accept the strategic plan program, which would allow the necessary funding for the two projects, and yet have sufficient funds for ongoing research to bring additional concepts for consideration in the out years, as these two projects are being completed.

D.9 Remote Sensing Panel Report

The ITP process has shown NASA's ability to provide excellent internal communications between all elements of the program. This process is difficult for single organizations and quite difficult for a diverse multi-element agency like NASA. Needs were solicited, collected, ranked, and resource dispersed for baseline, 3X and strategic plan options. The review panel agreed that we had seen a well presented plan.

Remote sensing technology has been underfunded for many years, yet it is worth noting that several of the sensor technology elements are in the "highest priority, near term" category presented by OSSA. In addition, the National Oceanographic and Atmospherics Administration (NOAA), which depends primarily upon NASA for its sensor technology, foresees a need for improvements in several sensor areas. (These needs will be discussed in more detail below.) Consequently, in order to reach sensor milestones needed for future NASA and NOAA space missions, the review panel recommends overall funding at the strategic plan level for this critical technology area.

A NASA optics technology group/program should be established to generally support and coordinate areas such as sensors. The panel is concerned that without such an activity the ability to specify, measure or incorporate optics technology will not be adequately addressed. An "*Optics User Group*" involving outside access to other government agencies should also be established. The review panel recommends that an optics initiative be funded starting in fiscal year 1992, rather than waiting until fiscal year 1994 as was proposed in the NASA presentation.

In the area of direct detector technology, the review panel endorses the importance of the OSSA highest priority near term requirements for submillimeter wave detectors and cryogenic-coolers. The panel also strongly endorses ultraviolet (UV), Infrared (IR) array and high energy (gamma ray) detector research in areas where DOD is not already investing heavily.

In the area of solid state lasers (including laser diodes), NASA and NOAA have definite future mission requirements (e.g., wind sensing, wind shear detection, ranging, high rate communications). Some related work is ongoing at DOD and DOE laboratories (e.g., Phillips Laboratory and Lawrence Livermore National Laboratory). NASA must insure that their research centers are either complementary or conducting NASA-specific research. (Note: NASA representatives are well versed in this area, although their visibility and participation should be increased at significant meetings where these subjects are treated.)

Reducing noise and increasing the format for hybrid, low temperature IR sensor readouts is extremely important. The proposed Sensor Electronics technology element should be integrated into, or closely coordinated, with the Direct Detectors technology element. The effect should focus on particular areas such as lower noise for the 4 to 10 K near and mid IR sensors and 2 to 4 K readouts for far IR photoconductor and bolometer arrays. The wavelength regions covered by these sensors are of nearly unique interest to NASA and result in little overlap with other agencies.

The review panel notes that advanced sensors represent one of the critical U.S. technologies of the Aerospace Industries Association (AIA). The panel also notes that because of the widespread activity in universities and industry, sensor development is particularly appropriate for peer reviewed,

competitive proposals in response to announcements of opportunity (AOs). The panel suggests that NASA expand its use of this program approach.

Specific Program Comments and Recommendations

Direct Detectors. The Direct Detectors Program encompasses wavelengths from gamma radiation to the far infrared. This program has been seriously underfunded for years, causing such missions as the Advanced IR Sounder (AIRS) to restrict its wavelength coverage (i.e., 15.5 versus 17 μm as the upper limit). The result is a reduced science return because a suitable detector is not available. With additional funding, a new detector (HgZnTe) being developed under this program would allow AIRS to achieve its full scientific potential. Similar anecdotes can be told for other detectors in this program.

The review panel had a few observations with respect to the presentation of the direct detectors element, recognizing that its scope is wide ranging. First, technology needs were sometimes given in terms that were not sufficiently specific. For example, the potential benefits of a microgravity environment for the production (i.e., growth) of materials with improved properties (e.g., purity, lifetime, crystallinity or structure) should be quantified. The state of the art, limitations, and the required capability were usually presented, but the rationale was occasionally omitted regarding the relationship between capability and specific need. Second, the broadband detector work for the 1-1000 micrometer regime is significantly advanced, but its need was not adequately justified to the review panel. Third, the panel notes that there may be some activity at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, in the far IR spectral region for standards development that would be appropriate for coordination.

Taking all of this into account, the review panel recommends that, because of the potential value of the Direct Detector program to NASA and the limited overlap with work by DOD and other government agencies, it should be funded at the strategic plan level.

Submillimeter Wave Detectors. Submillimeter radiometry has applications ranging from measurements of the Earth's upper atmosphere to astrophysics. It is also the highest priority, near term technology task of OSSA. Research and technology development are needed in three areas: (1) submillimeter mixers; (2) tunable local oscillators in the submillimeter region; and, (3) cryogenic systems to achieve appropriately low temperatures. For the mixers and tunable local oscillators, the existing program needs to be greatly augmented. This augmented program should include an official AO to get new ideas from universities and industry.

Appropriate cryogenic systems are currently being developed with NASA and non-NASA support, but non-NASA support for submillimeter wave mixers and tunable local oscillators is nearly non-existent. Consequently, a major increase in R&T funding is urgently needed to the strategic level in order to meet milestones for upcoming flight projects.

Laser Sensing. Sensors based on laser technologies are of increasing importance in determining atmospheric, land, and ocean parameters. These are important for not only the Earth's future due to changing climatic conditions, but to the safety of everyday aspects of life involving agriculture, transportation, health hazards, and pollution. The need for measurements on a global scale is recognized by NASA in its Earth Observing System (EOS) program, and by NOAA in its support of the U.S. Global Change Research Program (GCRP).

This is a growth area as technology for laser sources improves (e.g., efficiency, lifetime) affording higher resolution (i.e., smaller grid size) and, therefore, increased information content. This area (i.e, laser source development, including diode array pumping and new materials) has considerable activity within DOD and industry which should be leveraged. For example, tunable mid IR, solid state lasers are being developed under the USAF Pilot program at the Phillips Laboratory. This applies as well to optics reliability. Space qualification procedures for lasers and associated optical systems should be undertaken by NASA in order to permit such equipment to be considered intelligently for future NASA and NOAA missions. This should involve NASA's Office of Safety and Mission Quality (OSMQ).

The panel recommends that NASA review in depth the DOD and DOE research on laser induced damage before embarking on a laser damage study program of its own. NASA would then be in a position to determine is best course of action.

The laser program presentation sometimes referred to twofold improvements but did not provide a quantitative value for state of the art. The panel recommends that such sub-elements of the Laser Sensing Program strive toward quantitative

milestones which will produce specific benefits for spaceborne systems. The panel observed that in the laser sensing element NASA is well versed in the DOD and DOE program through membership in the Advisory Group on Electronic Devices, technical meetings, and site visits. The review panel recommends that these types of interactions be continued, and even expanded, in order to ensure that NASA funds in laser R&T will be used most effectively. Because of the importance of laser remote sensing and the breadth of experimental work required, the panel recommends that this element of the Science Sensing technology area be funded at the proposed strategic level.

Coolers and Cryogenics. Future NASA science missions that will use supercooled (i.e., approximately 2 to 4 K) detectors will need low vibration cryocoolers. NASA should pursue the development of such coolers. There is excellent and exemplary coordination and programmatic cooperation (including funding transfer) between NASA and the USAF in the cryocooler area. It appears that DOD has no requirement for a 2 to 4 K cooler, whereas NASA has unique future requirements at these extremely low temperatures and is the sole sponsor of coolers intended to operate in this temperature range.

The review panel recommends that the Coolers and Cryogenics element be funded at the strategic level. It is further recommended that spaceborne demonstration experiments of advanced cryocoolers be performed in order to verify their operational characteristics.

Passive Microwave Sensing. Advances in passive microwave sensing are urgently needed for future Earth observation missions (i.e., LEO as well as GEO) and to provide complementary measurements for astrophysics and space science investigations. Earth-looking microwave sensors can yield a wide variety of important information such as, precipitation over the oceans and land, water vapor and temperature profiles, ocean surface wind speed, cloud base height and water content, stratospheric winds, snow cover, and ocean currents. Key technologies include: (1) large deployable antennas; (2) synthetic aperture antennas; (3) electronic steering; and, (4) detectors with improved sensitivity.

The review panel believes that some enhancements in passive microwave sensing technology (e.g., deployable antennas and lower noise electronics) could result from a better choice of materials, engineering design, and available components rather than fundamental advances in technology. The proposed augmentation, however, includes advanced thrusts such as synthetic aperture radar (SAR), precision membrane reflector antennas, implementation of monolithic-microwave integrated circuits (MMICs), and the use of piezoelectrics to control the antenna surface. These proposals would markedly advance the state of the art.

Since there are several future NASA missions that will require advanced passive microwave sensing, and it ranks second-highest in NOAA's priority list (see the discussion below), the review panel recommends that this effort be fully funded at the strategic plan level presented.

Sensor Optical Systems. The review panel advocates establishment of an optics technology R&T Base program to support not only sensor but other areas which employ optics. This in an expanding, enabling technological field of increasing significance however, much work has already been done either funded or supported by other institutions. A requirements assessment, followed by a survey of the technical community should be accomplished before hardware or instrumentation development is undertaken. There are facilities which have a suite of costly characterization instrumentation and analytic codes which can be leveraged. NASA can then identify optics technologies which need to be developed to satisfy their specific mission needs. A multi agency coordinating optics council should be established, especially in these times of reduced funding, to insure cost effectiveness in these pursuits.

The review panel recommends that the sensor optics technology element be funded at a level of $100 thousand in fiscal year 1992 and $200 thousand in fiscal year 1993 in order to develop a strategy for this long term program and interact with optics groups within DOD and DOE. This will ensure that the NASA program will be complementary rather than duplicative. By 1994, the full proposed strategic level program should be initiated.

Active Microwave Sensing. This program is new and currently unfunded. Its purpose is to provide NASA and NOAA with the ability to measure land and sea parameters of interest to the U.S. Global Change Research Program. Several of the parameters measurable by active microwave techniques cannot be measured by alternative spaceborne techniques.

The review panel recommends that some resources be identified in fiscal year 1992 to start a dialogue and begin technical interactions with others working in this field. This should be an area of

increasing importance for weather assessment and altimetry with less susceptibility to degradation by adverse weather when compared to optical and IR sensors. Funding beyond fiscal year 1991 should be at the full strategic level proposed.

Sensor Electronics. The sensor electronics presentation, although well organized and presented, was simplistic and not strongly quantitative. For example, better estimates can be made for the cost and complexity of doubling an aperture size than presented. Although DOD has been developing sensor electronics for many years, low-temperature operation is fairly unique to NASA requirements. For its higher-temperature applications, interaction with DOD would be useful. Funding for this effort should be at the strategic level.

NOAA Requirements

NOAA currently depends upon NASA for its future space instruments and technology. Consequently, NOAA's input to this process is an important consideration. The following is a prioritized listing of NOAA remote sensing technology needs prepared by the NOAA representative on this panel:

• ***Sensor Optical Systems.*** Studies are needed of sensor optical systems, focused on visible calibration systems. *Application*: Determination of cloud and land surface properties for studies of global change.

• ***Passive Microwave Sensing.*** Studies should focus on antenna systems to allow for high resolution (e.g., approximately 10 km resolution) spatial sensing at low frequencies (e.g., 5-6 GHz). *Application*: All-weather sea surface temperature determination.

• ***Active Microwave Sensing.*** Studies should be focused on cheaper and more efficient scatterometers, altimeters, and SARs. *Application*: For scatterometers, sea surface wind speed and direction determination; for altimeters, wave height, ocean circulation; and for SARs, sea ice thickness.

• ***Laser Sensing.*** Studies should focus on efficient methods for laser wind sounding. *Application*: Determination of global wind profiles which are required for input to numerical weather prediction models.

• ***Coolers & Cryogenics.*** Studies should focus on support for precision IR sensors such as the EOS/AIRS (Atmospheric IR Sounder) to increase vertical resolution of sounding retrievals. *Application*: AIRS data are needed for numerical weather forecast models.

• ***Direct Detectors.*** Studies should focus on detector technology extending to the 18 micrometer region in support of EOS/AIRS (see above).

Rationale for Research Efforts

The review panel advocates strong and consistent support of the NASA Sensors technology program at the full strategic plan funding levels presented for the following reasons:

• This program will enable and enhance future science missions for NASA and global monitoring and prediction missions for NOAA.

• The current cost of the sensor technology program is less than 5 percent of the overall NASA space R&T budget. Future funding at the full strategic plan level presented will result in important and necessary technological advances, yet not affect the overall budget significantly.

• To reduce the cost of future space missions for Earth observation, emphasis should be placed on reducing the size and mass of instruments, thereby allowing less expensive Lightsats to be used.

• Space demonstration flights should be performed for some elements of the Sensor technology program (e.g., mechanical cryocoolers) in order to verify operational characteristics prior to implementing them in a space science or global monitoring mission. The in-space portion of the OAET program makes this possible.

• Finally, as indicated in the AIA briefing to the ITP External Review Team, advanced sensors is one of eleven technologies considered critical for America's future competitiveness by the National Center for Advanced Technology (NCAT) of the AIA. It is therefore important to maintain U.S. leadership in this area, and NASA/OAET is responsible for the U.S. civil space sensor R&T.

D.10 Guidance and Controls Panel Report

Background General Recommendations

The program briefing covered guidance, navigation, controls, and other avionics technology. The current program (which is strictly R&T Base) is well structured to provide basic technology across a broad range of applications in space transportation and space platforms. It has a good balance among the development of analytical and computational tools including, GN&C concepts and algorithms and component technology (e.g., sensors and actuators). The program makes effective use of industry and universities, as well as their own highly competent in-house staff to produce quality research and technology. The experimental facilities seem appropriate to support the current program, but should be reassessed as more focused systems technology programs are initiated. The review panel fully endorses the current R&T Base program including the planned 10 to 12 percent annual growth.

Specific Program Observations and Comments

Controls-Structures Interactions (CSI). The CSI technology program, although managed through the OAET Materials and Structures Division, is conducted as an interdisciplinary program involving both structures and controls researchers in an integrated team. The CSI program was reviewed and is fully endorsed by this panel. The CSI effort has a good balance among analytical methods, control concepts and laboratory testing. An aggressive flight experimentation component would be highly beneficial to the overall effort.

Micromachines/Sensors. An important new technology with high potential payoff was briefed to the panel, called micromachines/sensors. The concept is to develop extremely small machines, principally sensors, but also actuators and possibly other machines, using microelectronics fabrication techniques. JPL's Center for Space Microelectronics Technology has invented a position sensor using the electron tunneling concept that gives these micrometer-sized devices adequate sensitivity to make them practical for guidance and control (G&C) as well as other applications. The Center has developed and tested a micro-gravity accelerometer prototype with 10^{-8} sensitivity at 1 kilohertz. In the ITP presented, NASA proposed to wait until fiscal year 1995 to augment the R&T Base program for exploring potential G&C applications of this family of devices. The review panel believes that the potential benefits are important and that a small exploratory activity should be started immediately within the current R&T Base program.

Technology Transfer. The G&C program has produced significant accomplishments at the base level, but lacks major focused elements needed for transfer into high priority transportation systems, spacecraft, and science platforms. Two bridging technology programs exist, funded by OSF to demonstrate OAET developed technology for their applications. These include, LIDAR winds aloft measurement, at KSC, to provide near real-time data at the launch decision point, and electric actuators for space transportation systems. The NASA Office of Safety and Mission Quality (OSMQ) is jointly funding with OAET the development of a flight qualified engineering model of a navigation grade, long life, highly reliable fiber optic rotation sensor that has been under development by OAET for over ten years. These programs are very important but only address a small fraction of the OAET developed G&C technologies with potential benefits in space transportation, spacecraft and platforms.

Technology Coordination. An outstanding process is being used to develop and coordinate the GN&C/Avionics Program for space transportation and space stations through the activities of a Strategic Avionics Technology Working Group (SATWG). The SATWG is comprised of technical representatives from all the NASA Centers, industry, universities and DOD that are involved in establishing requirements and implementing systems as well as the technologists. Technology needs and opportunities are addressed and evaluated from the standpoint of the customer in a total systems concept. A good example is the SATWG's vehicle health management (VHM) panel. The VHM panel is co-chaired by MSFC and LeRC. The panel includes personnel with the total launch system perspective as well as technical specialists in propulsion systems, power systems, G&C systems, sensors and algorithms, launch operations, and automatic checkout and monitoring systems. The recommended avionics portion of the resulting technology plan was structured to support an integrated multi-disciplinary solution to VHM. The panel's assessment is that the SATWG has had a major impact on focusing NASA planning for technology development in this area and proposed augmentations to the highest priority needs on space transportation.

So far the SATWG has concentrated on space transportation and Space Station *Freedom* to a lesser degree. This planning approach should be expanded

to address other spacecraft and operations planning. It is also an excellent model for the other disciplines to follow in their planning processes.

Focused Elements. Eight new proposed focused initiatives in G&C starting in fiscal years 1993 and 1994 were reviewed; five in space transportation (i.e., ETO Vehicle Avionics, Transfer Vehicle Avionics, Commercial Vehicle Avionics, Autonomous Landing, and Autonomous Rendezvous and Docking) and three in space platforms (Earth Orbiting Platform Controls, Deep Space Platform GN&C, and Precision Pointing of instruments and platforms).

The primary motivation for the first three initiatives is lower space transportation costs. One of the proposed key technologies to reduce avionics systems and operational costs is advanced avionics systems technology that provide an open architecture, modular elements and fault tolerance. The approach is to develop: (1) an adaptable concept that can be applied across several transportation systems to allow increase production runs and fewer spares; and, (2) an increased systems level fault tolerance to allow use of lower cost parts and launching with failed parts to eliminate delays on the pad. A key technology proposed to reduce prelaunch, launch and turnaround costs is vehicle health management (VHM) avionics. VHM is a total transportation system technology concept that considers all subsystems and includes an integrated VHM avionics architecture and ground mission control elements. The G&C proposed initiative only includes the avionics systems and VHM architecture technologies. Companion elements for the various subsystems, such as propulsion and power systems, etc., are proposed in the other elements of the ITP. The proposed new initiative offers potential reductions in operational costs of many vehicle systems, not just avionics.

Autonomous rendezvous and docking (AR&D) and autonomous navigation and landing (AN&L) are enabling technologies for the unpiloted vehicle operations planned in the SSF and SEI programs. Technology development and demonstration programs will be needed before these programs could commit to such unpiloted operations. For example, the SSF would not commit to AR&D for an unpiloted cargo vehicle without a prior demonstration of the capability. In the late 1970's, one of the Viking landers came within 10 meters of hitting a boulder large enough to have upset the vehicle upon landing. The onboard landing systems could neither detect nor avoid that hazard. Technology does not currently exist to autonomously navigate and land an unpiloted Mars explorer vehicle in a safe and desired location with a high probability of success.

NASA has done an excellent job of responding to user requirements. For example, OSF ranked VHM among the highest of their priorities, and this technology figures prominently in OAET's ITP. The panel endorses the proposed G&C elements in the strategic plan. The SATWG should be used to help set priorities among the elements of the new initiatives in case cutbacks are required.

The panel supports the requirements for the proposed two new spacecraft/platform G&C initiatives. However, we recommend that additional efforts be made to obtain OSSA endorsement and definition of their needs for these technologies for the future programs. The programs include: multi-integrated controls for increased pointing accuracy of platforms and payloads; GN&C technologies for increased lifetime and performance of deep space platforms; interactive controls for simultaneous multi-instrument operations on GEO platforms; and precision pointing systems for future telescopes and interferometers.

Recommendations

Overall, the review panel endorses and recommends funding the strategic technology plan as presented. If reductions from the strategic plan levels are necessary, the panel recommends that priorities at the initiative level and elements within each initiative be established that consider: (1) responsiveness to customer requirements; (2) focus on technology transfer (define finite duration programs with specific deliverables; and, (3) use metric to structure the programs (e.g., relative cost, reliability and performance improvements). The panel recommends that the SATWG be used in the process of setting priorities. The R&T Base should not be sacrificed for the proposed new focused programs.

The panel recommends that the current R&T Base program be restructured, if necessary, in order to start the micromachine/sensor research this year and to be augmented in fiscal year 1993 to fully explore its potential. The panel recommends an expanded use of the SATWG concept including continued avionics technology planning and transfer process development. This process should be expanded to include OSSA and OSO requirements and participation. Lastly, the panel recommends that OAET work with OSF and OSSA to develop more detailed technology insertion roadmaps.

D.10 Aerothermodynamics Panel Report

Background

The Aerothermodynamics Base Research and Technology (R&T) Program focuses on advancing our understanding and capabilities to address the issues associated with high temperature gas effects as they impact the aerodynamics and heating encounters by vehicles and spacecraft for both Earth and planetary mission. Consequently, a primary concern is with problems of flight at high Mach numbers that encompass the continuum, transitional, and free molecular flow regimes. For the Earth to Orbit (ETO) class of vehicles which encounters Mach numbers as great as 25, a significant amount of dissociation and chemical nonequilibrium exists at the high altitudes (i.e., above 50 kilometers - km). In addition, because many ETO concepts must also return to Earth for landing, the relationship between high speed aerothermodynamic efficiency and low speed flight performance must be investigated for each configuration. For more energetic missions that may involve probes or aeroassist space transfer vehicles (ASTV's), flight Mach numbers as large as 50 are encountered where ionization, radiation, and thermochemical nonequilibrium can be significant.

The small NASA group involved in this research area has carried out extensive experimental and computational work. They have developed a world class expertise in developing the experimental data base and computational tools for vehicle design at extreme speed. The computational tools include not only computational fluid dynamic tools but also computational chemistry which provides a unique capability for calculating high temperature gas properties. In addition, the vehicle synthesis engineering tools that have been developed are becoming the industry standard for preliminary design and analysis.

The importance of the technology being developed in the base R&T program is clearly acknowledged in the focused Transportation Technology program where the technology push-pull is evident in the ETO, Space Transportation, and Technology Flight Experiments areas. For example, the Office of Space Flight (OSF) references their reliance on the base capability for performing system and aerothermodynamic analyses for advanced transportation system concept development. Enhancement and application of the aerothermodynamics technology to vehicle design will result in reduced flight environment uncertainty, optimized configurations, and improved performance margins. Furthermore, the SEI Directorate in OAET having identified aerobraking as a Category 1 technology, requires the products of both the base program and the focused Aeroassist Program to enhance/enable transportation systems. One of the major flight experiments is the Aeroassist Flight Experiment (AFE) which has evolved from the research conducted in the base Aerothermodynamics program, bringing an element of basic research to a major flight demonstration (i.e., the Aerobrake concept). The program, at its successful completion, will provide the first set of flight data for the validation of the extensive calculations of this demanding flight regime, and bring the concept to a "demonstration in flight" state for application to many space problems.

Status

The review panel observed significant changes in the program including contacts, outlook, organization, and coordination of the OAET research center personnel with potential flight program users and other centers with complementary interests and capabilities. There was considerable increased appreciation of potential mission applications through contacts and the system and configuration analysis activities, specifically where the vehicle thrusts matched NASA's future plans. Some remaining concerns include, for example, the absence of an expanded and transferred activity of the excellent and unique computational chemistry capability that has been developed at the Ames Research Center (ARC) to other NASA centers or to other government agencies, universities, and industry.

Key Technology Applications

The focus of the ITP in the area of aerothermodynamics was on the aerobrake concept for space transportation and vehicle studies for ETO transportation. The aerobrake research has expanded the basic aerothermodynamic studies to include systems, thermal protection, material and structures, and guidance, navigation and control (GN&C). Aerobraking is a technology which, when combined with any propulsion system, provides a technique for the use of planetary atmospheres to enhance space missions. It provides possibilities for the control of re-entry into the atmosphere, lower gravity loads for human entries, and better control of final Earth contact. In addition, aerobraking provides a unique capability to provide orbital plane change and orbital insertion choices using only a small amount of

propulsion in combination with dips into the upper atmosphere.

ETO vehicle studies apply the aerothermodynamics base capabilities to provide improved flight environment definition and more optimized overall performance through configuration assessments. Credible early phase vehicle development will greatly influence the viability and affordability of all future space transportation systems (e.g., Assured Crew Return Vehicles-ACRV, Personal Launch Systems-PLS, National Launch Systems-NLS, and Advanced Manned Launch Systems-AMLS). These are examples of mission requirements for which multiple configuration must be assessed.

Potential Payoffs

In the framework of NASA's long range goals of space exploration, aerobraking provides a unique capability, while symbiotically interacting with the main propulsion system, to considerably enhance the performance of all planetary entry systems. For example, a specific lunar mission using aerobraking on return can reduce the mass required in low Earth orbit (LEO) by 25 to 35 percent. Aerobraking also provides a solution to the challenges of very high speed returns to Earth from deep space exploration missions. It also has other specific systems applications that are valid for any planetary atmosphere (i.e., especially for plane changes from one orbit to another using aerodynamics maneuvers in the upper atmosphere). In addition to NASA's use of aerobraking, the DOD has indicated interest in utilizing aerobraking for the purpose of rapidly precisely placing C^3I assets in times of need such as the Persian Gulf crisis.

In a similar manner, the vehicle studies focusing on configuration design and assessment will produce flight system enhancement resulting in reduced design conservation, reduced weight and complexity, and reduced cost. The OAET aerothermodynamics capability adequately applied to the broad range of options will benefit NASA and the Nation.

Consequences of No Action

Basic aerothermodynamic technology has advanced to the point that a major flight test is currently planned (i.e., the Aeroassist Flight Experiment — AFE). This flight test must be supported to its full conclusion or the investment of years of research efforts to develop this unique capability will not be exploited. The review panel believes that the impact of aerobraking on planetary exploration and Earth re-entry is very significant, and that the inability of mission designers to use such systems in optimized mission planning will have a critical effect on future space exploration.

There has been, to the review panel's knowledge, no consideration of a possible second vehicle in the AFE Program. The possibilities of failure or incomplete results from a single AFE flight test have not been considered. The panel believes that it would be prudent to have some contingency plan and possibly a second vehicle, considering the potential value of this technology on future NASA and government space operations.

Specific Recommendations and Comments

Aeroassist Flight Experiment. The panel recommends full support for the AFE program at the highest level possible for successful completion of flight program and full analysis of the resulting data.

Comments: Considering the usefulness, uniqueness, and potential impact on NASA's future missions, this program requires special attention to provide the capability for application. The specific connection with the Marshall Space Flight Center (MSFC), which has experience with major flight programs, enhances the transfer of this technology to application. The review panel is very concerned about the apparent lack of back-up planning for this critical, but high-risk and single-shot, experiment. The panel believes that a small fraction of the total investment is required to insure the future since this test is critical to computational fluid dynamics (CFD) code validation, system and ground facility development activities, and applications to space exploration systems.

CFD Validation. The review panel strongly supports CFD validation efforts using ground and flight tests.

Comments. The successful AFE flight test is a critical element for CFD and ground test validation. Aerobraking technology cannot be transferred to systems because of the lack of adequate ground test facilities and the reliance on not yet validated CFD codes. The panel believes that CFD is key to the future of this technology, systems analysis, performance estimation, and vehicle design. It must be validated in the regions of flight most critical to applications.

Ground Facilities. The review panel strongly supports facility research and construction to support aerothermodynamics R&T.

Comments. The present ground test facilities are totally inadequate for providing data for CFD

validation, flow field, and chemistry modeling and design. Facility research and concept studies are needed to determine future ground test possibilities. Partial simulation would be valuable for specific testing of CFD validation. Increasing the present arcjet test capability is required for advanced materials testing and should be implemented as soon as possible. It is a pacing item in materials and structural concepts testing. Ground facilities will enhance the value of future flight tests by providing a tool for instrumentation development, aid in instrumentation analysis, and provide an important near-term aid to the analysis of flight test results from AFE. Facilities development must include extensive sensor and instrumentation development to provide the full benefit of generating the extreme flight conditions, either fully or partially.

Configuration Assessment. The review panel supports expansion of configuration and systems studies.

Comments. In addition to the configuration and system studies which provide a very important focus of the base R&T effort, configuration assessment includes the evaluation of aerothermodynamic performance using detailed computational tools and experimental capabilities of the base program (i.e., as per the request of OSF). Consequently, validated CFD and ground based experiments are essential capabilities for this activity. This requires unique facilities, some of which are available in the base program, to optimize the important contributions of aerothermodynamics technology to NASA's goals.

General Comments. The new organizational framework is not supported by a base R&T program at a level commensurate with potential contributions, and the program is not balanced in the experimental vs. CFD activity. The review panel recommends extended sensitivity analyses of the aerobraking concept, at least on the basis of presentations made during this review of the ITP. Such analyses will help focus an established priority at the R&T level. The recommendations noted require a significant increase over the current and proposed strategic program outlined in the Fiscal Year 1993 investment strategy. Timing, ramp-up, and balance must be carefully examined to optimize the program.

Priorities

In the review panel's deliberations on key priorities, one stands out - the successful completion of the AFE test and full analysis of results. The recommendations which have been noted were specifically directed because of the panel's belief that Aerobraking technology is critical to the success of the future systems and missions which are NASA's goals. Essential to that success is a viable Aerothermodynamics Base R&T Program to advance and apply critical capabilities and technologies.

D.10 Space Test Program Panel Report

In-space technology research and technology demonstrations in the space actual environment are key components in the process of technology maturation. A family of programs for in-space testing — both in the R&T Base and in CSTI — were presented to the review team. Mission drivers are evident for most of the proposed program, including potential products for commercial participants.

The space test portion of the space R&T program could be particularly important to "space qualify" concepts and hardware. However, it is limited at present in the number of possible experiments due to high cost of flying on the Space Shuttle. Where flight experiment schedules are extended by funding problems, the technology to be demonstrated can be outpaced by mission need dates. To respond to this problem, individual experiments should either be accelerated on a priority basis or canceled. In addition, Space Shuttle established requirements should should be streamlined to be as short as possible in order to encourage application oriented technology experiments, university developed experiments, and to minimize overall space test program costs.

Moreover, as is the case with commercially oriented experiments, the potential user of the technology to be space tested should be involved in the experiment review and design process. The Announcement of Opportunity (AO) process for awarding experiments should be changed to identify the technology area of priority to NASA needs in order to be consistent with the OAET plan based on mission technology drivers and overall program priorities.

Finally, future technology flight experiments should try to utilize Space Station *Freedom* wherever possible to take advantage of longer duration in space and the man-in-the-loop advantage in experiment flexibility and operations.

Enhancing the Competitiveness of the U.S. Commercial Space Industry

Introduction

The U.S. commercial space industry is suffering significant erosion of its formerly commanding lead over international competitors. Alarming evidence of this problem accumulates. As an example, consider the keystone component of the commercial space industry: the geosynchronous communications satellite. During the decade of the 1970's, 100 percent of the world market was manufactured and sold by U.S. firms. The decade of the 1980's saw U.S. market share drop to 70 percent with the entry of serious European, Canadian, and Japanese competition. The early 1990's show a continuing decline of this market share to 60 percent. This erosion can be expected to continue as foreign governments provide their space industries with favorable growth environments and as the once formidable technology of the U.S. declines.

This significant decline in the competitive performance of the U.S. space industry is damaging to the Nation's balance of payments, to our defense posture, to national pride, and to NASA's ability to cost-effectively carry out its mission. NASA can and should move to alleviate this situation. Providing assistance to the U.S. space industry would be in conformance with President Bush's National Space Policy, in recognition of the recommendations of the 1990 Advisory Committee on the Future of the U.S. Space Program, and in response to industry's appeal for help.

The critical question arises: in an era of constrained federal budgets, how can NASA proceed to help the U.S. commercial space industry in the most cost-effective way? A broad spectrum of disparate approaches have been proposed and discussed, ranging from modified procurement approaches to development of industry standards. The most cost-effective approach, however, has been long-practiced and proven by NASA: sponsorship of the development of new, leveraged technologies. Accelerated technology development in several key areas can yield highly cost-effective enhancements in the competitive posture of the U.S. commercial space industry.

These key technology areas include:

- Functionally-dense, radiation-tolerant semiconductors
- Advanced baseband processing architectures
- Distributed network architectures
- Electronically pointed phased-array antennas
- Efficient solid state high power transmitters and low noise receivers
- Bandwidth-efficient high data rate modulations, multiplexing and multiple access methods and systems
- Comprehensive methods of modeling communications channels and advanced telecommunications architectures
- Low cost, expendable launch vehicles (ELVs)
- Advanced passive radiometric sensors
- Advanced data/signal processing and distribution.

More detailed discussion of several of these key technology areas is provided in the paragraphs which follow.

Selected Key Technology Areas

Functionally-dense, radiation-tolerant semiconductors. High density semiconductors for both baseband and radio frequency analog and digital processing applications are extremely important. Very large scale integration (VLSI) and monolithic microwave integrated circuit (MMIC) developments have varying importance, depending on the application, but are critical to being cost-competitive in most advanced communications systems.

Electronically pointed phased-array antennas. Electronically pointing, phased-array antennas represent the communication subsystem technology that would benefit most from further development. The systems architectures and their hardware implementation for this applications have been studied for decades. This technology is vital to the successful implementation of the agile, smart transmitter/receiver. The principles underlying the performance of this class of hardware have been successfully demonstrated in numerous applications. The successful deployment of these developments have, however, been hindered by cost-effective mechanization and manufacturing of the hardware. A properly funded and management development of RF transmit-receiver (Tx/Rx) elements could benefit numerous uses in two way fixed and mobile communications and broadcast applications. The

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basic element design, if cost-effectively realized, would benefit both commercial and military applications which may require from only a few to thousands of elements as part of an integrated application. Pragmatic applications dictate minimal cost design and manufacturing while retaining high reliability and adequate performance — together with mechanical and thermal integrity. To achieve this, substantial additional work in the area of thermal and mechanical design of the Tx/RX element must be carried out. This requires supplemental funding and broad engineering management which could be effectively directed by NASA.

Efficient solid state high power transmitters and low noise receivers. In order to achieve maximum performance and efficiency for communications satellite payloads, discrete components are used often for performance setting portions of low noise receivers and transmitter power amplifiers. In recent years, it has become necessary to procure these discrete devices (typically field effect transistors — FETs) from offshore suppliers. As foreign competition for the devices increases, it will become increasingly difficult to get devices with required performance on a timely basis. Further, as international competitors move from providing components to providing systems, market pressure may make it impossible to obtain these critical devices from foreign competitors.

Low cost, expendable launch vehicles (ELVs). Based on industrial experience, it costs about $30,000 to insert one pound of spacecraft weight into a geosynchronous Earth orbit (GEO). Despite industry's considerable effort to miniaturize and reduce the weight and power requirements of spacecraft payloads, structures, power and control systems, a considerable gap exists today in available low cost launch vehicles suitable for satellites in the 3 to 10 thousand pound class. There is a need for NASA to exploit and advance higher specific impulse (greater than 400 seconds) capabilities of cryogenic engine technologies, examine the dual use of spacecraft guidance and control systems to control upper stage orbit insertion and apply them to the development of a low cost expendable launch vehicle (ELV) in the 3,000-10,000 pound payload class. A goal of $ 10,000 to $ 12,000 per pound into GEO would leverage the space and electronics industries to exploit the rapid improvements in payload technologies (electronics, sensors, signal and data processing). These industries could then continue to offer improved performance and functionality for communications, Earth observations, and planetary missions at competitive and affordable costs to the consumer or the U.S. taxpayer.

Advanced passive radiometric sensors. The current vision of NASA's EOS program defined several sensors to meet several measurement objectives. These include: visual and infrared imaging, passive microwave sensing and active microwave sensing from platforms in different orbits. Some of the major global and regional environmental issues associated with the Global Change Research Program (GCRP) include global warming, ozone depletion, oil spill detection and monitoring, and atmospheric pollution monitoring. The latter requires continuous *in situ* or remote measurement. Because continuous in situ or airborne measurement is expensive, remote sensing from orbital platforms is indicated. A constellation of low Earth orbit (LEO) platforms is also expensive if 21 hour regional coverage is required. A possible lower cost solution is the use of aperture synthesis techniques to develop synchronous orbit passive radiometers at selected microwave frequencies to detect the signatures associated with changes in pollutant species (e.g., NO_x, SO_2 and CO_2 due to coal fired power plan emissions). The potential for low cost passive aperture synthesis radiometers is based on the assertion that with current technology it is cheaper to build systems with increased processing power than it is to build systems with large antenna apertures in orbit.

Advanced data/signal processing and distribution. Modern space-based communications and remote sensing systems are characterized by increasing speeds (several Gigabits per second) and large, real-time data bases (several terabytes) accessed by a diverse user community via multi-speed networks. The burgeoning costs for these systems are raising questions of affordability by both private and government sectors. There is a strong need to identify near and long term technologies to mitigate these costs while providing the needed information extraction and distribution functions. Technology advances are needed for both space and ground segments.

Space. Some of the technologies and techniques that show promise to reduce the raw data rate at the source in space are: single chip data compression, neural networks, expert systems, data fusion, low power optoelectronics processing and switching, and light-weight high-density storage media.

Ground. From ground use, the same technologies and techniques that could be used for space applications are applicable (some may be commercially available) with the addition of robust

network topologies and architectures (distributed and centralized control of networks and data bases), and intelligent nodes.

Summary

NASA has a long and proud history of leading the Nation's civil space efforts. The U.S. commercial space industry has always been intimately interconnected with NASA and has relied on the Agency for the development of many key technologies. These past and continuing technology development successes have proven the cost-effectiveness of that approach. Now, changing conditions in the world commercial space marketplace make NASA's support of technology advancements even more important. These changing conditions call for a significant increase in NASA sponsorship of the development of leveraged technologies to enhance the competitiveness of the U.S. space industry and to maintain U.S. preeminence in commercial space activities.

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