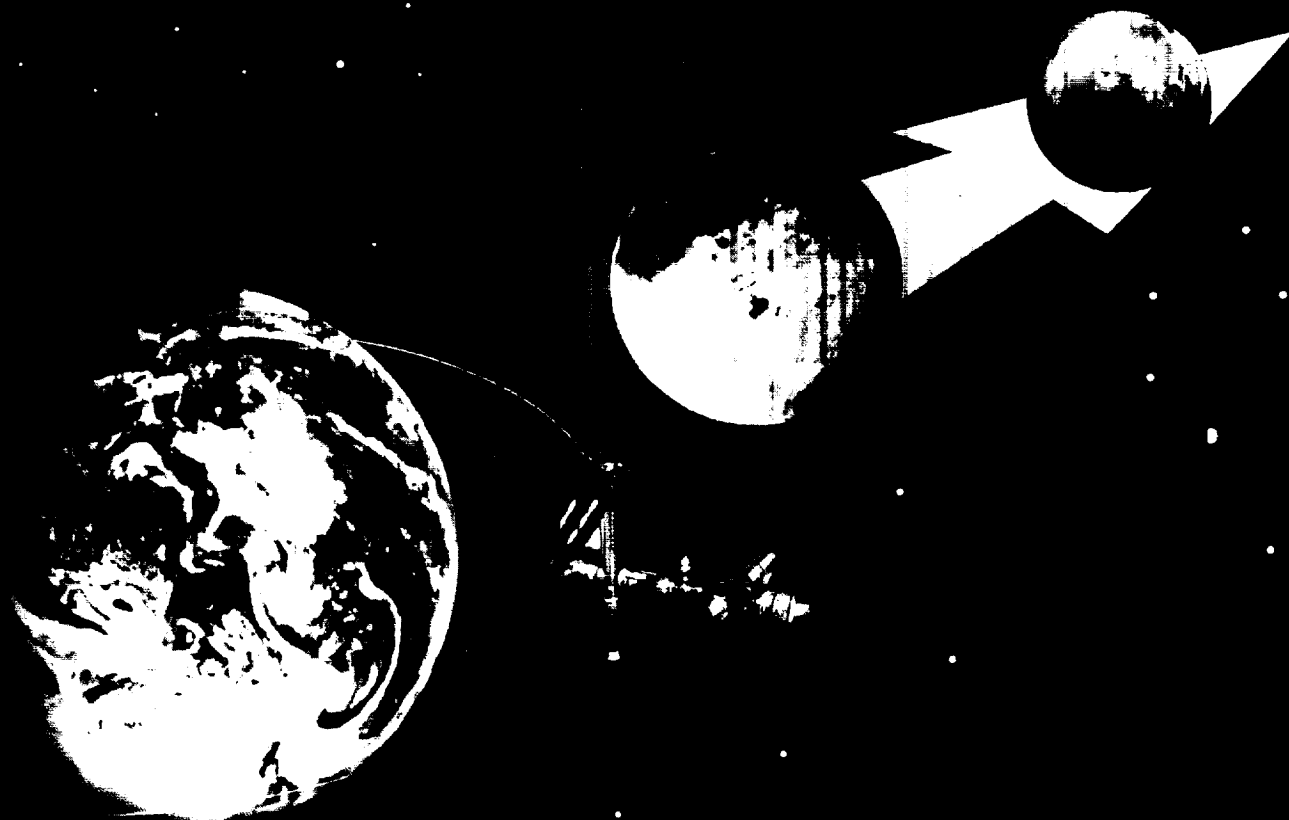
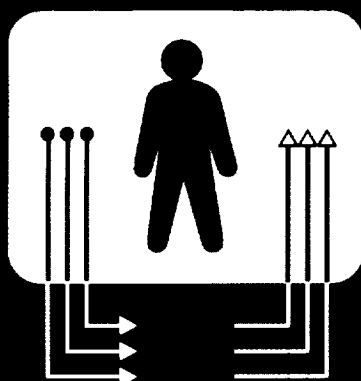




Advanced Environmental Monitoring and Control Program

Strategic Plan



Advanced Environmental Monitoring and Control Strategic Plan

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Table of Contents

Introduction..... 1

The NASA Imperative 2

Advanced Environmental Monitoring Program Mission..... 4

Strategic Goals and Objectives 4

Program Inputs, Deliverables, and Customers..... 8

Metrics 9

Conclusions 12

Bibliography..... 13

Figure

1. Advanced Life Support Program 2
 Technology Development Roadmap

Introduction

Human missions in space, from short-duration shuttle missions lasting no more than several days to the medium- to long-duration missions planned for the International Space Station, face a number of hazards which must be understood and mitigated for the mission to be carried out safely. Among these hazards are those posed by the internal environment of the spacecraft itself. Through offgassing of toxic vapors from plastics and other items carried aboard the spacecraft by the astronauts, through failures or off-nominal operations of spacecraft environmental control systems, through accidental exposure to the crew of hazardous compounds used in experiments - all present potential hazards that while small, may accumulate and pose a danger to crew health. The first step toward mitigating the dangers of these hazards is understanding the internal environment of the spacecraft and the compounds contained within it, which is then followed by controlling the environment.

The relentless advance of technology, especially in the area of microminiaturization of a wide variety of instrumentation, has enabled an entirely new approach to the monitoring and control of the spacecraft environment. Whereas only a decade ago, instrumentation to measure volatile organic compounds in spacecraft air would have taken up a large rack of instruments and a correspondingly large amount of power, this instrumentation has been reduced drastically in size for the Space Station and will now fit in a small instrument rack. Further revolutionary reductions in size and power requirements, while maintaining or increasing capabilities, are underway. These changes will enable entirely new approaches to the monitoring and control of spacecraft environments. Future spacecraft will have integrated networks of redundant sensors which will not only inform the crew of hazards but will pinpoint the problem location and, through analysis by intelligent systems, recommend and even implement a course of action to stop the problem. Advanced Life Support systems will also benefit greatly from these sensors and control systems - neural nets will take the inputs of hundreds of microminiaturized sensors, integrate them and provide an optimized process control system with efficiencies impossible to obtain with state of the art systems today. And by using technologies developed by molecular biologists for the study of DNA, specialized detectors will be able to rapidly identify and quantify potentially virulent pathogens in spacecraft air and water.

This strategic plan details strategies to determine NASA's requirements for environmental monitoring and control systems for future spacecraft, and goals and objectives for a program to answer these needs. In keeping with NASA's new operating philosophies, this program is operating efficiently and on a lean budget, but it will nonetheless revolutionize our capabilities in monitoring and control of human-occupied spacecraft.

The NASA Imperative

NASA's foremost mission has always been exploration, from the earliest days of the Mercury program, through the manned lunar landings, the Viking landings on Mars and the robotic exploration of the solar system. With the recent emphasis by Congress and the Administration on producing agency strategic plans for all executive branch agencies, NASA responded by producing a strategic plan divided into "Strategic Enterprises." Amongst those Strategic Enterprises is the "Human Exploration and Development of Space" or HEDS.

HEDS represents a long-term strategy for NASA to lead in the human exploration and development of near-Earth space, the moon and the solar system. Of the goals allowing this exploration, none is more important than supporting human life during the short- and long-range missions envisioned within HEDS. As such, an umbrella program of HEDS Advanced Human Support Technologies has been undertaken, which consists presently of the Advanced Life Support, Space Human Factors Engineering and Advanced Environmental Monitoring and Control programs. All three of these programs support each other and are key to the success of providing support to humans in their exploration of the solar system.

The Human Support program has a 20-year vision aimed towards revolutionizing the maintenance of human life and activities in space through applications of cutting-edge technologies (Figure 1).

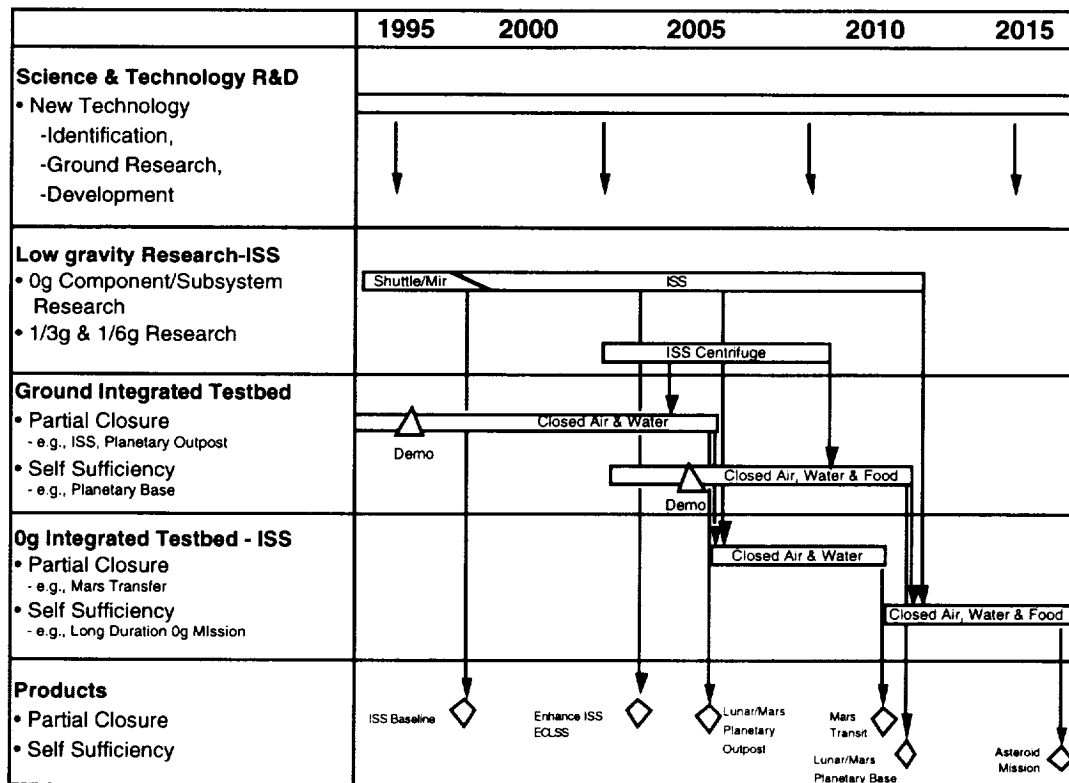


Figure 1. Advanced Life Support Program Technology Development Roadmap

This vision will be implemented through a program of sponsoring technology development projects in industry, academia and NASA field centers and then incorporating and maturing those technologies through the use of testbeds, at first on the ground and then on the International Space Station.

The Advanced Environmental Monitoring and Control program will play a key role in the success of the Human Support program, by providing breakthrough technologies to drastically improve the way spacecraft environments are monitored and controlled. Advanced sensors will provide a detailed knowledge of the spacecraft environment never before possible. Advanced control systems will give future spacecraft increased autonomy, freeing the crew to work on experiments and the actual business of exploration. Robust new technologies will provide increased reliability, freeing the crew from the drudgery of replacing or calibrating sensors. Overall safety will be increased, resulting from early detection and mitigation of problems as well as increased system reliability.

Although the Advanced Environmental Monitoring and Control program is a mandate of the HEDS Strategic Enterprise, there is an important tie with the Technology Strategic Enterprise of the NASA Strategic plan as well. The Environmental Monitoring program will work in concert with the Technology Strategic Enterprise to maximize the technology return of the program.

Advanced Environmental Monitoring and Control Program Mission

Provide future spacecraft with advanced, microminiaturized networks of integrated sensors to monitor environmental health and accurately determine and control the physical, chemical and biological environment of the crew living areas and their environmental control systems.

The overarching mission of the Advanced Environmental Monitoring and Control program sets out a grand strategy to provide new technologies in the area of environmental monitoring and control for the International Space Station and future human exploration missions. It is clear that existing technologies will not meet the needs of future exploration in the area of reduced weight and cost, greatly increased capabilities and greatly reduced overall risk. In addition, the crew time spent in monitoring and controlling the spacecraft environment must be reduced as a component of the overall reduction in overhead tasks, to allow more time for research and exploration-related tasks. The Advanced Environmental Monitoring and Control program brings together related technologies in physical, chemical and biological monitoring and advanced control and ties them synergistically to provide much-needed technologies for the future of human space exploration.

Strategic Goals and Objectives

Goal 1: Determine the Requirements for Environmental Monitoring and Control Systems aboard future human spacecraft

Objective 1.1 Establish and continuously update integrated Environmental Monitoring requirements.

Objective 1.2 Determine the state of the art in environmental technologies in other government agencies, industry and academia in order to maximize efficacy of limited program funds.

Before limited program funds can be allocated to the development of new technologies, it is critical to determine in as great a detail as possible the technical requirements for monitoring the internal environment of future spacecraft. These requirements are varied, from reliability (e.g., as we move to the space station era, sensor systems should be operable and reliable without maintenance for long duration missions) to requirements for sensing a particular compound (e.g., sensor systems should be able to detect formaldehyde in concentrations down to parts per billion). These requirements will draw upon needs stated in the HEDS strategic plan and other pertinent studies of future human spaceflight which have been conducted over many years.

Environmental monitoring is a key component of many industries and a key function of other government agencies. The Environmental Protection Agency, for example, has a need to monitor the air for pollutants and soils for contamination, while the oil industry has a need to monitor its processes and its

external environment for contamination. It can be easily seen that there is a great deal of overlap between NASA's needs and the needs of industry and other government agencies in the area of environmental monitoring and control. In order to maximize the return from the limited NASA budget, it is in NASA's interest to provide a "filter" on the needs developed in the requirements document to determine NASA's unique needs. This will allow NASA to sponsor technology development efforts in areas not currently being addressed by outside groups, while using the best technologies developed in industry, academia and government for the remainder of its needs. In addition, opportunities may exist for shared development of dual-use technologies, which also uses limited program funds to the greatest advantage possible.

As is stated later in this plan, it is vitally important to involve technology users as early as possible in technology development efforts. The immediate users of Advanced Environmental Monitoring and Control technologies reside within the NASA Medical Sciences, Advanced Life Support and Space Station teams. The importance of crew health risks in setting priorities for technology development requirements cannot be overstated, and significant involvement of all three of these teams in requirements development is essential to meet their long-term needs.

Goal 2: Obtain state of the art, revolutionary technologies for spacecraft environmental monitoring and control

Objective 2.1: Sponsor development of high-risk, high potential return environmental sensor and control system technology development.

Objective 2.2: Obtain state of the art technologies to enhance environmental monitoring and control from industry, academia and other government agencies or off the shelf as appropriate for NASA's use.

A wide range of technologies will be needed for monitoring and controlling the environment of future spacecraft. These technologies will not only take the form of actual sensors and systems, but also will consist of software, knowledge bases and control systems such as neural nets. Furthermore, there are technologies which are not environmental monitoring and control per se, but which could significantly enhance or enable environmental monitoring and control, particularly for NASA-unique needs. Such enabling or enhancing technologies include micromachining, microelectronics, optoelectronics, and nonlinear optics. As stated under the previous goal, it is in NASA's interest to infuse technologies developed externally where appropriate. However, it is also clear that the environment of future spacecraft will pose unique challenges to environmental monitoring and control systems, particularly in the areas of extreme long-duration reliability, capabilities for detection of a wider array of contaminants, resistance to contamination, and a host of other challenges. For this reason, coupled with other unique needs in the area of Advanced Life Support system monitoring, it is appropriate for NASA to fund a suite of technology development projects capable of meeting its unique needs.

A significant infrastructure is required for development of advanced technologies appropriate for NASA's Advanced Environmental Monitoring and Control program. Fortunately, this program is able to take advantage of world-class facilities such as the MicroDevices Laboratory at the Jet Propulsion Laboratory as well as others at universities across the country, which were developed to fulfill research and technology development needs well beyond those of environmental monitoring and control. The Advanced Environmental Monitoring and Control program is able to "stand on the shoulders" of organizations such as the Ballistic Missile Defense Organization as well as NASA's Space Science program to achieve technological developments well beyond its own means, through taking full advantage of dual-use technologies and previous investments.

Goal 3: Provide Mature, Tested Environmental Monitoring Technologies for use in flight systems

Objective 3.1 Select environmental monitoring and control technologies whose proof of concept has been demonstrated, for further development in increasingly realistic environments.

Objective 3.2 Provide environmental monitoring and control systems for use in integrated testbeds.

Objective 3.3 Provide advanced, integrated environmental monitoring and control technologies for use in flight systems for the Human Exploration and Development of Space

In the development of advanced, high-risk technologies, it must be acknowledged at the outset that some will fail or at least not advance to the stage where they are useful for flight projects. A key program goal is the establishment of decision points for technology development projects where their suitability for further development is evaluated. A wide range of criteria will be employed in making the decision to terminate some projects, while allowing others to proceed on for further development, amongst the foremost of which will be technical performance, estimated system costs and estimated schedule requirements for maturing the given technology to the point of flight readiness. These criteria will be applied equally to both NASA-developed or sponsored technologies and those developed outside of NASA, in order to give NASA the best possible technologies for use in its flight systems.

As with requirements definition, it is essential to involve the user community in the technology selection process. Methods for accomplishing this process are detailed later in this plan.

As technologies mature and progress on to further levels of development, it becomes increasingly important to test them in interaction with other systems. For environmental monitoring and control technologies in particular, interaction of these technologies with spacecraft environmental control and life support systems is critical, and system interaction with astronaut operators is also of high importance. For this reason, integrated, human-in-the-loop testbeds are under

development which will uncover system-level interactions and bring to light problems which may not have surfaced at earlier levels of development. This environment will no doubt prove challenging in the maturation of environmental monitoring technologies. After success of environmental monitoring and control technologies is demonstrated in integrated ground testbeds, flight testing will proceed prior to incorporation of the technologies in flight systems.

Goal 4: Provide the benefits of NASA-developed environmental monitoring and control technologies to United States industry and for improving human welfare.

Objective 4.1 Establish criteria in announcements of research opportunity and subsequent progress reviews encouraging early technology transfer.

Objective 4.2 Establish partnerships and Memoranda of Understanding with industry, academia and government organizations to use NASA-developed environmental monitoring and control technologies for the economic benefit of the United States and for improving human welfare.

Technology transfer has always been a key part of the NASA Mission, since the Space Act was signed by Congress in 1958. Recently, increased emphasis has been placed on technology transfer by the Administration. As stated in "Technology for America's Economic Growth, A New Direction to Build Economic Strength" (1993), "All laboratories managed by... NASA... that can make a productive contribution to the civilian economy will be reviewed with the aim of devoting at least 10-20% of their budgets to R&D partnerships with industry." The NASA Administrator has also directed the preparation of plans to "push technology transfer to the top of your agendas" in a 1992 letter to his directors.

Advanced Environmental Monitoring and Control systems under development by NASA will provide many opportunities for technology transfer and partnerships with industry. As stated earlier, a great deal of development of these technologies is going on outside of NASA, which will lead to many natural flows of technology both into and out of NASA.

Program Inputs, Deliverables, and Customers

The Environmental Monitoring program has a long-term mission structured towards delivering key environmental monitoring and control technologies starting in the Space Station era and aiming towards human missions into the solar system beyond Earth's orbit. As noted earlier, the program is requirements-driven, with inputs from the HEDS strategic plan and other studies which have been conducted concerning future human exploration of the solar system.

Requirements for environmental monitoring to assure human health will be obtained from the Aerospace Medicine division at NASA HQ and the Medical Sciences Division at JSC. The JSC Medical Sciences Division has the responsibility to work with the National Research Council to define Spacecraft Maximum Allowable Concentrations (SMACs) of chemical contaminants in the atmosphere and in drinking water for various length missions. These SMACs will be used to determine threshold limit, sensitivity and accuracy requirements for environmental sensor systems. In addition, the program will work with the Office of Space Flight in determining likely future environmental control systems, which will interface with environmental monitoring and control systems developed under this program. The program will also work with the Advanced Life Support program to determine specific sensor and control technology needs particular to individual ALS system elements, such as nutrient sensors for plant nutrient delivery systems.

Near-term customers for products developed within the Environmental Monitoring program shall include the ALS program, the JSC toxicology group and the Office of Space Flight. In addition, members of industry, academia, and government benefitting from technology transfer accomplished under the Environmental Monitoring program should be considered customers.

Top-level deliverables of the Environmental Monitoring program follow:

- | | |
|------------------|--|
| <i>1995-2000</i> | <ul style="list-style-type: none">• Breadboard-demonstrated sensor systems capable of monitoring a wide variety of atmospheric contaminants• Initial demonstration of microbial sensor systems• Breadboard-demonstrated water contamination sensor systems• Initial demonstration of advanced integrated control systems for advanced life support systems• Flight demonstration of selected air monitoring technologies |
| <i>2000-2005</i> | <ul style="list-style-type: none">• Integrated monitoring and control systems demonstrated in ground testbeds. Initial integration of microbial sensors achieved.• Initial testing of sensor and control systems onboard ISS (rack-level) |

- Continuing development of advanced environmental monitoring and control technologies
- 2005-2010*
- Fully integrated monitoring and control systems demonstrated in high-fidelity ground testbeds with humans in the loop. Full autonomous control of Advanced Life Support systems achieved.
 - Integrated monitoring and control systems demonstrated aboard ISS.
 - Continuing development of advanced environmental monitoring and control technologies
- 2010-2015*
- Integrated environmental monitoring and control of Space Station achieved.
 - Delivery of technologies suitable for environmental monitoring and control on lunar and planetary missions.

Metrics

It is highly important to measure the progress of the Advanced Environmental Monitoring and Control program in meeting its stated goals, objectives and deliverables. This progress may only be measured through the use of metrics that reflect the strategic goals of the program. The metrics must be easily applied, comprehensive, sensitive to improvements in program technologies, and well-aligned with program needs. Metrics, once defined, will drive the program.

Metrics for the Advanced Environmental Monitoring and Control Program may be put into two general categories: cost and performance. Within cost-related metrics are the mass index and system cost, and within performance-related metrics are system reliability, knowledge of spacecraft environment and technology maturity. It should be noted that system-level metrics are difficult to ascertain with exploratory technologies due to incomplete system knowledge, but as technologies mature these system metrics become more refined.

Mass Index - This metric is given by the relation:

$$\text{Mass Index} = M/hD$$

Where M = total mass of the environmental monitoring and control system (all consumables included), h = the number of crew members and D = mission duration. This mass index will decrease as miniaturized, distributed sensors and intelligent control systems are developed and refined.

System Cost - Within the new external environment in which NASA operates, lifetime cost has become the dominant factor in determining the viability of space systems. Future environmental monitoring and control systems must be designed and operate within tight budgets. Technologies for these systems must thus be designed to minimize the overall system cost, which includes costs for consumables, operations, and maintenance.

System Reliability - Environmental monitoring and control systems for future spacecraft must have a high system reliability equal to or exceeding that of current and past spacecraft. This metric is a composite metric and may be determined through a bottom-up reliability analysis of proposed environmental monitoring and control systems, or a measure of the reliability may be obtained through a top-down Failure Modes and Effects Analysis. Although impossible to define for component-level technologies, this metric will become increasingly important as systems progress through higher technology readiness levels and the interaction between system components becomes apparent. It is obvious that simple, redundant systems will in general have a higher system reliability than more complex systems. Technologies for future exploration must thus be driven to be as simple and robust as possible.

Knowledge of Spacecraft Environment - As capabilities increase for monitoring the internal environment of the spacecraft, the amount of data on various parts of the spacecraft or habitat will increase, and the data will become less granular. This will result in an improved ability to localize problem sources (e.g., sources of contamination) and input this knowledge into the spacecraft or habitat control system for an early solution. This increased knowledge will also take the form of a greater variety of monitored contaminants, and redundant systems for backup coupled with intelligent fault-prediction systems. A metric entitled "Knowledge of Spacecraft Environment" will thus be a high-level metric comprised of the number of contaminants and primary constituents monitored (in both air and water) as well as the granularity of the monitoring, coupled with the ability of advanced software systems to predict the state of the environment of the spacecraft or habitat. As technologies improve and result in smaller sensors with greater capabilities, the granularity of the detection systems will decrease while the number of monitored contaminants will increase.

Risk Mitigation - Lowered Crew Health risks is a paramount goal of the Advanced Environmental Monitoring and Control program. Increased knowledge of the Spacecraft Environment will feed into this metric and allow lower total risk through early knowledge of those spacecraft contaminants posing the greatest risk to the health of the astronauts.

Technology Maturity - A "Technology Maturity" metric has been developed to allow evaluation of individual technologies for their suitability for further development or use in flight environmental monitoring and control systems. This metric takes into account sensor performance in normal and anomalous conditions, reliability and maintainability and certifiability for flight. The equation to calculate this metric is shown in the Advanced Environmental Monitoring and Control Program Technology Development Requirements document (see bibliography).

It is apparent that all of the metrics described above are related; for example, an increased system reliability or a decreased Mass Index may force an increase in system cost. Lower-level metrics will be set in individual program and project plans to evaluate specific technologies under development by the Advanced Life

Support, Advanced Environmental Monitoring and Control, and Space Human Factors programs. Continuous program management oversight will monitor these metrics to ensure that the program stays on track.

Conclusions

Advanced technologies and new approaches must be developed to achieve success in the Human Exploration and Development of Space. These technologies and approaches must further be directed towards well-defined goals and objectives, in order to produce first-class results without excessive costs. Nonetheless, the goals of HEDS are far-reaching enough that technologies far beyond our current capabilities must be realized. Risks must be taken in developing these technologies; some will undoubtedly fail and prove themselves unsuitable for human space exploration. However, the rewards of pursuing high-risk avenues are well worth the potential pitfalls, and will produce new approaches to revolutionize human space exploration.

This strategic plan has laid out goals and objectives to revolutionize the way environmental monitoring and control will be done on future spacecraft. With the path that has been shown in this plan, technologies will be developed that will provide robust, safe and highly capable flight systems for environmental monitoring and control in the future of human space exploration.

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