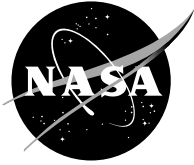


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Workshop on Critical Issues in Microgravity Fluids, Transport, and Reaction Processes in Advanced Human Support Technology Final Report

Francis P. Chiaramonte and Jitendra A. Joshi
NASA Headquarters, Washington, DC

February 2004

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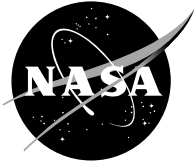
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PREFACE

Workshop on Critical Issues in Microgravity Fluids, Transport and Reaction Processes in Advanced Human Support Technology Final Report

A workshop titled “Critical Issues in Microgravity Fluids, Transport and Reaction Processes in Advanced Human Support Technology” was held in Cleveland, Ohio on August 11–13, 2003. The main objective of the workshop was to initiate a dialogue between the Advanced Human Support Technology (AHST) and the Microgravity Physical Science research communities that will lead to the identification and prioritization of fluids, transport and reaction problems associated with AHST and lay the groundwork for strategic collaborative investigations. The elements of AHST systems and subsystems that are most sensitive to the presence or absence of gravity involve fluids (gas or liquid), transport and chemical processes. Specialists from industry, government and academia participated in the event. The participants spent an evening listening to and discussing presentations from AHST and microgravity fluids and combustion researchers that were intended to provide an overview of typical research in each field. The next day, the morning session focused on particular case studies that highlighted key issues in AHST and key features of fluids and transport behavior in microgravity. Following the introductory sessions, the participants dispersed to four ‘breakout groups’: Air Revitalization, Solid Waste Management, Water Recovery Systems, and Thermal Systems and Phase Change Processors. In each group, discussions focused on known and anticipated problems and open design and operation issues where these fluids and transport processes that are crucial to the successful operation of the system were identified.

The AHST Program in the Bioastronautics Research (BR) Division of the Office of Biological and Physical Research (OBPR) conducts research in order to provide technologies for Advanced Life Support (ALS) systems and Advanced Environmental Monitoring and Control (AEMC), among other things. The ALS project provides life support technologies that significantly reduce life cycle costs, improve operational performance, promote self-sufficiency, and minimize resources for long-duration missions. ALS provides the basic functions that sustain life: controlling pressure, temperature, and humidity; closing the air and water loop in a manner that eliminates expendables while providing usable water and breathable air; supplying food; and managing wastes while maximizing resource recovery from wastes. The AEMC project seeks to provide mature, tested environmental monitoring technologies and control strategies for use in flight systems to monitor the physical, chemical and microbial environment of both the human compartments and life support systems of current and future spacecraft environments and extravehicular activity.

The Microgravity Fluid Physics and Combustion programs, in the Physical Science Research (PSR) Division of OBPR, embrace a broad range of research topics including studies of heat and mass transfer processes, fluid dynamics, complex fluids, the behavior of combustion processes including the development of rational design procedures for maximizing efficiency and minimizing pollution associated with combustion processes on Earth, and the development of novel methods for producing materials and improvement of fire safety in reduced gravity conditions. Both programs either exploit microgravity conditions to perform experiments that

will advance fundamental understanding of earth-based processes, or focus on the microgravity behavior of fluids, transport and combustion processes with a view to establishing a knowledge base for space applications. As a result, NASA has developed expertise in microgravity fluid physics and transport, and chemically reacting systems that are relevant to strategic thrusts in advanced human support technologies. Indeed, fluids, transport and reaction processes are common to many components of NASA's AHST programs in life support, environmental monitoring and control, extravehicular activity, and human factors.

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1 EXECUTIVE SUMMARY

NASA's efforts in AHST are directed toward knowledge and technology that enable human travel, research, and exploration beyond where we have been. The primary long-term challenge for life support systems necessary to sustain crews for extended periods departs from the largely open systems (requiring frequent resupply) of current technology and moves toward a closed-loop system for air, water, and waste. Elements of life support systems typically involve multiphase flows, chemical reactions, and heat and mass transport processes under reduced and microgravity environments. Further advances in the development of these technologies would benefit considerably from the fundamental knowledge base that has been built up by the microgravity research community.

This workshop was designed to bring the experts from the AHST and Microgravity Research communities together to identify the most pressing and fruitful areas of research where success hinges on collaborative research between the two communities. Thus an effort was made to bring together experts in both advanced human support technologies and microgravity fluids, transport and reaction processes. Expertise was drawn from academia, national laboratories and the federal government. The intent was to bring about a thorough exchange of ideas and develop recommendations to address the significant open design and operation issues for human support systems that are affected by fluid physics, transport and reaction processes.

The workshop participants focused on four key AHST areas: Air Revitalization, Solid Waste Management, Water Recovery Systems, and Thermal Systems and Phase Change Processes. The top technical priorities for each area of advanced human support technologies were identified. They include particulate matter measurement, fire signature understanding and packed bed development for air revitalization. Solids transport and processing, three-phase flow and resource recovery are the top priorities for solid waste management. The priorities for the water recovery system are: understanding multiphase flow, obtaining accurate water quantities for monitoring purposes, and modeling biofilm behavior. The development of two-phase thermal control systems is the thermal systems priority. Fouling, phase separation, and liquid degassing were important issues to address for all of the AHST areas.

Several organizational recommendations were also formed based on the workshop discussions, such as the development of a Knowledge Readiness Level (KRL) for characterizing the maturity of the microgravity research analogous to the Technology Readiness Level (TRL). Increased collaboration between the AHST and microgravity research communities needs to be facilitated in order to significantly advance the AHST technologies. Microgravity researchers should participate in developing AHST technologies beginning with the concept development phase through final hardware testing and on-orbit performance verification. Finally, design guidelines should be developed in a format that is readily useful to system designers. Compiling the information into system-specific design guides detailing the fundamental mechanisms and predictive tools (models, equations, correlations) relevant to AHST systems will prove to be an extraordinarily valuable tool for the system designers.

2 RECOMMENDATIONS AND FUTURE DIRECTIONS

2.1 INTRODUCTION

Numerous risks associated with the development of advanced life support systems for long duration space travel exist. Some of these risks involve microgravity issues in fluid systems and reacting flows. A systematic program of investigation is needed that identifies fluids, transport and reaction related issues relevant to AHST to reach the necessary state of knowledge. The following technical priorities and organizational recommendations will be instrumental in developing a cooperative program between the AHST and microgravity communities. The salient findings and recommendations from an organizational, programmatic and research perspective are listed below. Detailed explanations of each technical area can be found in the following sections: Section 2.2.1 Air Revitalization, Section 2.2.2 Solid Waste Management, Section 2.2.3 Water Recovery, and Section 2.2.4 Thermal Systems.

2.2 TECHNICAL PRIORITIES

2.2.1 Air Revitalization

The opportunity exists to leverage off near-term particulate matter measurement experiments to be conducted on board the International Space Station (ISS) to better understand the particulate matter size distribution in a crewed spacecraft cabin in the range below 10 microns. At the same time, a coordinated effort to understand fire signatures must be undertaken to make more reliable, robust fire detection systems for crewed spacecraft. Another important area is the continued development of packed beds for carbon dioxide removal. Issues include fouling, monitoring, solid phase deposition from the reaction and morphology of catalyst fines, and microgravity effects on detection, ventilation and sensor effectiveness. Furthermore, phase separation and liquid degassing is a common thread throughout the Environmental Control and Life Support (ECLS) system. Research in these areas is cross-cutting through several ECLS system design sub-disciplines, e.g., oxygen production by water electrolysis, humidity control and airborne particulates (gas-solid separation).

2.2.2 Solid Waste Management

Current Solid Waste Management (SWM) systems perform only limited waste processing functions and are somewhat insensitive to microgravity conditions. Future SWM systems will likely become substantially more complex and microgravity sensitive, and include the processing functions of volume reduction, stabilization, sanitization, and resource recovery. Both fundamental and applied research is required to address the numerous anticipated SWM microgravity concerns. The areas that will likely require the greatest level of research and development include solids transport and processing. With respect to transport, SWM will likely be dealing with two and three-phase flow, with moisture contents ranging from very low (dried) to very high (slurry) levels. Transport systems may range from simple to complex, and face numerous problematic issues including slug and other non-uniform flow. Processing systems will face similar issues as well as complex interactions between containment, mixing, reaction

processes, and phase separation issues. Additionally, microgravity-compliant monitoring and control systems will be required. A fundamental understanding of these issues is needed to facilitate applied SWM research and technology development. Such research will also likely have beneficial overlap with other elements as well, such as the water recovery and air contaminant treatment systems.

2.2.3 Water Recovery

Since many water recovery systems require an understanding of microgravity fluid physics, the past approach has been to avoid two and three-phase flow. The fluid flow problems in many of the water recovery systems are related to multiphase flow, scale-up, and biofouling. For example, problems in multiphase flow systems include the spatial distribution of phases in the system, solid-liquid transport and handling, gas-liquid transport and handling, and three-phase transport and handling. The applications of multiphase flow include packed bed reactors, multiphase metering and sampling, bioreactors, phase change systems, condensers, laundry systems, gas-liquid separators, solid-liquid separators, and dewatering systems. The ability to use packed bed reactors in water recovery systems in space opens the door for many opportunities to purify and treat the water. Monitoring water quality is relatively easy on Earth; however, obtaining an accurate measure of the quantity of water in microgravity is more difficult. Many water processing reactors require a chemical or biological film on the surface of a tube or bead. Important issues for biofilm reactors include biofilm sloughing and mass transport under microgravity conditions. Well-conceived fundamental and applied research on these topics would provide useful information that could lead to new and better water recovery systems.

2.2.4 Thermal Systems

Currently, many of the thermal subsystems involve single-phase fluid and heat transfer processes; but the need for improved energy-to-mass ratios and the availability of future spacecraft that will generate large quantities of power and waste energy, such as the nuclear-based ones, is urging a shift towards two-phase operations. Consequently, the design of important thermal subsystems for future applications as in boilers, condensers, evaporators, heat exchangers, phase separators, normal and cryogenic fluid storage units, fuel cells, radiators, and heat pipes will all involve complex multiphase fluid flow and transport microgravity issues. Microgravity data and engineering correlations for these applications are very scarce. Therefore, there is a real and immediate need for both basic research and engineering development in this area that can only be accomplished through joint collaboration and cooperation between the microgravity (fluids and reaction processes) and the AHST communities in the government laboratories, academia, and private industries.

2.3 ORGANIZATIONAL RECOMMENDATIONS

Develop a knowledge readiness level characterizing the level of understanding of microgravity behavior of processes and mechanisms that underlie AHST systems.
For the readiness levels please refer to section 5.3.7.

Facilitate increased collaboration between the AHST and microgravity communities.

- Provide additional funding mechanisms for collaborative proposals (e.g., special topics NRA)
- Personnel exchanges
- Hold panels and symposia at respective discipline conferences
- Exposure of personnel to microgravity issues and participate in testing
- Visits to NASA sites (short-term)
- Develop and distribute contact lists of Microgravity/AHST experts
- Develop training tools
- Provide a manual that effectively summarizes pertinent microgravity knowledge
- Provide websites for information exchange
- Develop accessible databases for data exchange
- Proposals directed at applications that will operate in microgravity must, at a minimum, include a subsection that specifically addresses the microgravity issues.
- PI should be in contact with NASA personnel familiar with the pertinent AHST project during execution of the funded proposal to (a) seek input such as technical requirements and experiment definition, (b) help keep NASA updated on technological progress.
- Encourage collaborative technology development through: rapid technology development teams, cooperation with existing NASA technology development projects, and the Small Business Innovative Research (SBIR) program.

Microgravity researchers participate in AHST design reviews.

- Facilitate appropriate personnel involvement during early stages of technology development, feasibility and design reviews.

Develop design guides.

A significant amount of key information that is useful to AHST designs exists; however, it is not in a format that is readily useful to system designers. It is scattered throughout the literature and microgravity research, commercial aerospace, and academic communities. Soon-to-be published and yet-to-be-conducted work will also be useful to designers. Compiling the information into system-specific design guides detailing the mechanisms, behaviors, fundamentals, and physics relevant to AHST systems will prove to be extraordinarily valuable tools for AHST system designers. These design guides should be based upon scaling laws, correlations, previous flight experiments and performance, and theoretical analysis to better assist designers who will build the next generation of AHST systems. Compiling these design guides into a useable format and delivering them to the AHST system design community is a recommended high priority.

3 INTRODUCTION

3.1 MOTIVATION FOR THE WORKSHOP

The Bioastronautics Critical Path Roadmap (CPR), Revision D, identifies seven risks associated with ALS systems for long duration space travel. In order to address many of these questions pertinent to these risks, it is important to develop systems that will mitigate the issues involving fluids systems and reacting flows. It is well known that gravity affects the disposition of single and multiphase fluids and fluid interfaces. As an example, multiphase flows and thermal reactors are known to be particularly sensitive to the orientation and magnitude of the gravity vector. Multiphase flows are poorly understood in microgravity and reduced gravity, and, in many instances, even under terrestrial gravity.

Depending on specific mission goals, human support technologies such as water reclamation or plant growth, will operate in a variety of gravity environments ranging from weightlessness to microgravity to the reduced gravity environment of accessible planetary surfaces. To make crucial design decisions for these technologies, a thorough understanding of the gravitational dependence of fluid and reaction processes will be essential.

A systematic program of investigation is needed that identifies fluids, transport and reaction-related issues relevant to AHST to reach the necessary state of knowledge. It is anticipated that some issues will be common to different AHST systems (independent of system geometry or application) and some will be specific to particular human support technologies. Interdisciplinary approaches to technology development with participants from the physical and biological sciences and engineering will be essential. Furthermore, mission designers, engineers and technologists must be represented in any process that leads to problem identification and prioritization.

3.2 CHARTER TO THE WORKSHOP

Fluids, transport and reaction processes are common to many components of NASA's AHST programs in life support, environmental monitoring and control, and extravehicular activity. The goal of the NASA OBPR workshop on Critical Issues in Microgravity Fluids, Transport and Reaction Processes in AHST is to initiate a dialogue between the AHST and the Microgravity Physical Science research communities that will lead to the identification and prioritization of problems where fluids, transport and reaction processes play a role in AHST and, thus, lay the ground-work for strategic collaborative investigations.

The direct and indirect effects of microgravity will be considered and emphasis will be placed on identifying problems where fluids, transport and reaction processes are crucial to the successful operation of humans support technologies. This workshop will be a first step in a systematic program that involves the identification of fluids transport and reaction related issues relevant to AHST.

4 WORKSHOP STRUCTURE AND FUNCTION

4.1 WORKSHOP PLANNING AND DEVELOPMENT OF PRE-WORKSHOP DOCUMENTS

The organizing committee consisted of representatives from the AHST Program and the Microgravity Fluids, Transport and Reaction Processes Programs. Committee members came from NASA Headquarters (HQ), Glenn Research Center (GRC), Johnson Space Center (JSC), the Jet Propulsion Laboratory (JPL) and the National Center for Microgravity Research (NCMR). Regular teleconferences were held between the organizing committee to develop the purpose and scope of the workshop, as well as compile the background reading material for the participants.

In order to prepare the participants, several documents were provided to them in advance of the workshop. One document summarized background material to better understand the needs of the AHST Program. Another document summarized background material to better understand Microgravity Fluids, Transport and Reaction Processes. At the end of the background material, appropriate references and/or websites were included for participants to further look into and understand the AHST Program and the Microgravity Fluids, Transport and Reaction Processes Programs.

Pre-workshop surveys were also developed for the workshop and were sent to the participants prior to the workshop. The intent was to gather as much information as possible on AHST problem areas related to the presence or absence of gravity that involve fluids (gas or liquid), transport and chemical processes. The completed surveys were used as the basis for breakout group discussions at the workshop.

4.2 PARTICIPANTS

An effort was made to bring together experts in both advanced human support technologies and microgravity fluids, transport and reaction processes, along with current NASA researchers. Expertise was drawn from academia, national laboratories, and the federal government. The intent was threefold: to bring about a thorough exchange of ideas; to draft a document relating the significant open design and operation issues for human support systems that are affected by fluids, transport and reaction processes; and to identify issues that have already been addressed and are no longer of relevance to system designers.

For a complete list of participants refer to Appendix B.

INVITED TALKS

4.2.1 Microgravity Background A: Multiphase and Fine Particulate Flows

Workshop Summary: Multiphase Flow, Fluid Stability and Dynamics in Microgravity, Brian Motil, NASA Glenn Research Center

A summary of the subject workshop hosted by NASA GRC on May 15, 2003, was presented. The participants included academia, industry, and government scientists and engineers from across the country. The goal of the workshop was to assess and prioritize multiphase flow issues associated with space power, propulsion, fluid and thermal management, and advanced life support systems. The problems or issues identified from earlier workshops were reviewed and classified as follows:

- a) **Critical**—Must be resolved to achieve NASA mission.
- b) **Severely Limiting**—Resolution provides significant savings to mission (cost, weight, etc.).
- c) **Enhancement**—Resolution increases reliability or provides moderate savings to mission.
- d) **Awareness**—Better understanding may lead to resolution of higher priority problems.

The critical issues list included: a) phase separation, distribution and control; b) system stability during transient and steady state operations; c) phase change; d) contact line dynamics; e) container thermal/fluid management; f) and the ability to properly scale systems up to full size.

The severely limiting list included: a) several phase change issues not mentioned in the critical list; b) flow through components such as packed bed reactors (porous media), tees, expansions/contractions, valves and bends; c) filling and emptying containers; d) disconnected capillary surfaces (such as those found in packed bed reactors or tanks); e) management of a large mass of fluid (sloshing, etc.).

From this prioritized list, a scientific research plan and a roadmap to address the critical scientific and related technology issues were developed. Finally, the workshop participants were asked to review and comment on a near-term experimental plan to utilize the ISS facilities for a two-phase flow experiment.

The workshop report is available at: <http://www.ncmr.org/events/multiphase/>.

4.2.2 AHST Background A: Water Reclamation and Air Revitalization Technologies

The focus of this talk was to give an understanding of the current research and technology development efforts in water processing and air revitalization technologies for the AHST Program. The rationale for developing technologies based on functional requirements in the absence of missions was discussed during the talk. As we embark on missions beyond Low Earth Orbit (LEO), the re-supply constraints will be more stringent, and it will be an imperative to recycle larger portions of the wastewater stream as well as recycle air while recovering the major constituents, such as oxygen that are currently wasted as carbon dioxide. This should be done at lower mass and power penalties (current systems for carbon dioxide removal are of a low

thermodynamic efficiency). The other area of focus needs to be the development of microgravity compliant technologies especially from the perspective of multi-phase flow.

4.2.3 Microgravity Background B: Chemically Reacting Flows

Chemically Reacting Systems

In this talk research activities associated with chemically reacting systems in microgravity were briefly summarized to give an overview of the capabilities of this research community. Understanding the effects of microgravity on reactive, high temperature systems is a particular strength of this group. Topics discussed during this talk included laminar flames, droplets, flame balls, smoldering, particle formation, smoke detection, flame synthesis, and in-situ diagnostics for chemically reacting flows. Chemically reacting flows in microgravity are often very different from those in normal gravity and the differences are typically not intuitive. For example, the size of particles generated in microgravity can be orders of magnitude larger than flame-generated aerosols in normal gravity. Also, much weaker flames can exist in microgravity than in normal gravity. Furthermore, gaseous radiation, often negligible in normal gravity flames, can have a dominant effect on the temperature of microgravity flames. The absence of buoyancy in microgravity is responsible for much of this behavior, and the lack of free convection in high temperature systems can lead to significant changes in the flow field, which can affect everything from particle formation to the dominate chemistry.

With the extensive experience of this research community in understanding the effects of microgravity on chemically reacting flows, it is believed that AHST would benefit from the expertise of this group. Areas where this interaction may be of value include: particle detection and removal, solid waste incineration, carbon dioxide reduction, trace contaminant removal and food preparation.

Chemically Reacting Systems Exploration Research Roadmap: Closed Loop Life Support, Uday Hegde, National Center for Microgravity Research

The presentation discussed the subject roadmap developed at the Workshop on Gravity Effects on Chemically Reacting Systems for Space Exploration held in Cleveland in April 2003. Sixteen participants from different NASA centers, industry, university (PSR and BR grantees) and the NCMR participated in the two-day workshop.

The research challenge, consistent with OBPR organizing questions, is to depart from the largely open loop systems of the past and present and to move toward closure of the air, water, and waste systems. It was recognized that this effort would clearly be enabled by technologies that allow resource reclamation. Roadmap endpoints for micro- and hypo-gravity compliant physical-chemical systems for air, water, and solid waste processing were identified. Research objectives for meeting these endpoints were identified and include: parallel research efforts on reactor systems with similar objectives (e.g., solid waste processing) in order to conduct effective trade studies, demonstration of ground-based and micro/hypo-gravity compliance, and model development; all leading to on-orbit validation of critical technologies and system components. More information on this workshop can be found at <http://www.ncmr.org/events/gravitational/>.

4.2.4 AHST Background B: Solid Waste, Thermal Management, Monitoring

The focus of this talk was to give an overview of the various efforts in solid waste management, thermal management and environmental monitoring in the AHST Program. Various aspects of solid waste management and the associated technology development efforts in the context of microgravity compliance and issues associated with multi-phase flow were discussed. Also, thermal management from the current perspective and technology thrusts required to reduce the system mass, power and volume were discussed. Of special importance was the issue associated with two-phase flow. The Advanced Environmental Monitoring and Control program element is chartered with development of sensors for the monitoring of the internal spacecraft environment. Fluidics based sensors and other environmental monitors functioning in the aqueous environment will have to overcome two-phase flow problems that are likely to cause sub-optimal functioning of the sensors.

4.2.5 AHST Case Study 1: Water Processor

Advanced Life Support

The ALS project is tasked with developing the next generation in life support technologies for advanced missions. The goal is to reduce the equivalent system mass by a factor of three. This reduction is evaluated within the context of the existing/planned ISS Environmental Closed Life Support System (ECLSS). The ISS ECLSS provides: temperature and humidity control, CO₂ removal, CO₂ reduction (planned), oxygen generation, O₂/N₂ control, potable water procession, urine recovery, waste management, and crew systems (toilet, shower, etc.).

The future ALS system will provide all the capabilities of the ISS ECLSS but will also provide solid waste recycling and eventually food production capabilities as well. The development of such a system will reduce the mass and cost of future human exploration missions. They will also increase self-sufficiency and correspondingly the level of safety of these missions.

One of the key steps in the development of the ALS system is the flight verification of fundamental fluid physics phenomena in microgravity. For example, the next generation transit vehicle water treatment system has a wide range of microgravity issues, which need to be addressed in the near future. Some of the topics are: thermal/physical properties of thin fluid films, two-phase flow in open chambers, splashing in liquid/gas boundaries, centrifugal separations (what occurs during start and stop events), pumping of saturated fluids, surface tension directed flow stability, reaction kinetics in packed beds (effects of channeling and condensation), stability of packed beds during launch, and deterioration of packed beds during operation. Although this list is specific to water treatment technologies, similar lists of microgravity fluid physics issues can be identified for most ALS technologies.

4.2.6 Microgravity Case Study 1: Two-Phase Flow/Interfacial Phenomena

Effect of Reducing Gravity on Gas-Liquid Flows, Mark J. McCreedy, University of Notre Dame

This talk focused on the differences between gas-liquid flows in earth gravity and microgravity. This approach is taken because most data available for the behavior of gas-liquid flows was obtained in earth gravity and essentially all of the textbook generalizations and insights are for this case. However, the influence of gravity is so profound that this information gives a completely invalid picture of microgravity gas-liquid flows. Some comparisons of flow regimes in earth and microgravity from McQuillen's studies are shown as video clips that can be accessed on the following website, <http://www.nd.edu/~mjm/flow.regimes.html>. (Note that the behavior of flows in the absence of gravity is quite different from the behavior of flows in the presence of gravity.)

The physical role that gravity plays in gas-liquid, including in packed beds, is to provide low-pressure drop drainage. Due to the lack of the low-pressure drop drainage, gas-liquid flows in microgravity will have higher liquid holdup and consequently a higher-pressure drop, which results in higher heat and mass transport rates. In packed beds, there will be no "trickle" regime (the one most commonly used for processing) in microgravity. By looking at interfacial stability calculations for gas-liquid flows, it is shown that even if gravity is not present, surface tension does not automatically become a dominant force.

The values of the Capillary number (viscous to surface tension forces) and Weber number (inertial to surface tension forces) will reveal if surface tension will strongly affect flow behavior. These numbers are small for flows in small passages, with slow velocities, and with low viscosities. Because gravity is not normally important in small passages, there is no particular difference between earth gravity and microgravity. Consequently some useful devices, where the flow is only in small tubes or channels, can be tested on earth and operated in microgravity with confidence.

Capillary Phenomena, M.M. Weislogel, Portland State University

An understanding of capillary phenomena is critical to the design of many fluid systems aboard spacecraft including liquid fuels, cryogenics, wastewater collection and recycling, condensate removal, and thermal fluids for power cycles and temperature control systems. Unfortunately, there remain sizable gaps in our abilities to predict system behavior with ample certainty to assure failsafe performance of a given fluid system. As a result of such shortcomings, singular failures occur on-orbit that, though they may add immensely and immediately to our "trial and error" database, have increased our efforts to develop the tools needed to predict such fluid phenomena with greater certainty and to design systems with greater reliability.

Significant design difficulties are encountered for capillary systems where multiple stable interfaces are possible, or large interfaces are in motion, or geometries are complex producing many possible flow scenarios, flow regimes, natural frequencies, stability limits, and damping characteristics. The difficulties faced are physical and mathematical involving moving contact

lines, a wide variety of non-ideal wetting conditions, complex geometries, and the nonlinear normal stress balance at any interface. The designers of fluid systems for spacecraft must be aware of the breadth of fluid responses possible for a given system. In the best situation, the designer must be aware of current advances from the research community while the research community must make the best effort to communicate the applications potential of their research to the former. The best designs will exploit, rather than merely account for, capillary phenomena to increase performance with reliability.

Limitations on the use of KC-135 flights as a microgravity simulation were discussed. The limitations include: (1) the time period of about 20 seconds is much shorter than needed to observe many important phenomena, (2) although the average gravity level is close to zero, fluctuations may be as much as 0.1G, (3) the period of occurrence during parabolic flight of a 2G environment can be confounding.

4.2.7 ASHT Case Study 2: Major Constituent Analyzer (MCA)

Spacecraft Cabin Atmospheric Monitoring: Overview of the Major Constituent Analyzer, Jay Perry, NASA Marshall Space Flight Center

A brief summary of the ECLSS design was presented to provide the workshop participants with a perspective of the challenges facing ECLSS designers and the approach used by the NASA for a variety of crewed exploration endeavors. The ECLSS system for the ISS was reviewed with particular emphasis upon the Atmosphere Revitalization (AR) subsystem. The AR subsystem is comprised of the Carbon Dioxide Removal Assembly (CDRA), Trace Contaminant Control Subassembly (TCCS), and Major Constituent Analyzer (MCA). The AR subsystem is contained in a single rack located in the ISS's U.S. Segment Laboratory Module. Redundant equipment provides for the similar function in the Russian Segment.

The MCA, a scanning mass spectrometer that is a derivative of the Central Atmospheric Monitoring System (CAMS) used onboard Navy submarines, was the focus for the remainder of the discussion. The MCA monitors six analytes—nitrogen, oxygen, carbon dioxide, methane, hydrogen, and water vapor. In-flight operational experience was discussed. The MCA was activated in February 2001 during the Laboratory Module activation. Operational problems were experienced within two months. Problems with mass spectrometer electrometer saturation and ion pump current spikes were traced to faulty inlet leak design and microgravity sensitivity, respectively. The ion pump current spikes are attributed to the accumulated oxide coating on the ion pump sloughing and then drifting into the ion beam. This problem was not anticipated from ground testing because all development testing was conducted in a horizontal plane perpendicular to the gravity vector.

Other problems have occurred with loss of control synchronization and a leaking verification gas assembly. These problems have been traced to various software bugs and a damaged seal, respectively. Hardware and software replacement and modification have typically resolved most of the problems that the MCA has experienced.

4.2.8 Microgravity Case Study 2: Fluid Phenomena in Microgravity

Summary of NRC Report on “Microgravity Research in Support of HEDS,” Richard Lahey, Rensselaer Polytechnic Institute

This talk presented a summary of a National Research Council (NRC) study that considered NASA's research needs associated with Human Exploration and Development of Space (HEDS).¹⁵ A summary of this report was published in 2000, in which the key mission enabling technology was found to be the use of multiphase systems and processes in microgravity. It was pointed out that multiphase technology will likely be required on all manned deep space missions to satisfy the requirements for energy production and utilization, propulsion and life support. Currently the extensive use of multiphase technology in space is not a viable option for NASA.

The NRC report recommended a research strategy to NASA for the development of multiphase technology for use in reduced gravity environments. It was specifically recommended that NASA develop and qualify a multidimensional Computational Multiphase Fluid Dynamic (CMFD) model for use in spacecraft and habitat design, system/process evaluation, and for the scale-up of appropriate experiments aboard the ISS. Numerous examples were given showing the predictive capabilities of CMFD models for multiphase flows on earth and how these same capabilities might be achieved in space.

4.3 WORKSHOP STRUCTURE AND FUNCTION

The participants were divided into four breakout groups (Air Revitalization, Solid Waste Management, Water Recovery Systems, and Thermal Systems and Phase Change Processors). Each breakout group was led by one AHST lead and one Microgravity lead. The goal was to develop a list, in priority order, of significant open design and operation issues that are affected by fluids, transport and reaction processes for each area discussed. At the end of the workshop each breakout group presented a summary of their findings to the entire workshop.

4.3.1 Breakout Group 1—Air Revitalization

Within the workshop objectives, cabin atmosphere revitalization for crewed spacecraft and habitats was discussed with respect to the primary functions that contribute first to crew survival and second to crew safety. Functions that contribute to crew comfort were also discussed; however, those functions were not considered to be critically limiting and recommendations are not presented for them. These general aspects are fundamental to any artificially produced ecosystem that successfully supports human health and safety in an extreme external environment. This group reviewed the major functions and representative technical solutions for atmosphere revitalization with specific attention given to potential problem areas that may benefit from collaboration between microgravity science and flight systems engineering disciplines. The objective of this review was to establish focus areas for more detailed discussion and to drive out areas where existing or future fundamental research may benefit spacecraft cabin atmosphere revitalization system technological development. The group also recognized that overlaps exist with other environmental control and life support functional disciplines. To this

end, the group expanded its discussions to include fire detection and suppression and humidity control.

4.3.2 Breakout Group 2—Solid Waste Management

The primary goal of this group was to develop a prioritized list of significant open design and operation issues in the realm of solid waste management that are impacted by the gravitational environment. Containment, mixing, transport, reaction processes, and phase separation were considered. In order to accomplish this goal, it was necessary to identify the potential required SWM functions and candidate SWM system components for a wide range of current and future mission scenarios.

4.3.3 Breakout Group 3—Water Recovery Systems

Many research and technology issues affect water recovery systems. The breakout group for water recovery systems focused only on the microgravity fluid physics issues (not biological or chemical issues) related to water recovery.

4.3.4 Breakout Group 4—Thermal Systems and Phase Change Processors

The breakout group for thermal systems and phase change processes focused on issues related to gravitational effects on and microgravity behavior of fluid flow, heat and mass transfer, and phase separation in thermal system components such as boilers, condensers and heat exchangers, fuel cells and heat pipes.

The group discussed the issue of two-phase versus single-phase working fluids and, most importantly, the effects of microgravity on two-phase systems. A prioritized list of future recommendations for research for mission enabling technologies was synthesized from the group's deliberations.

5 RESULTS AND DISCUSSION

5.1 ATMOSPHERE REVITALIZATION BREAKOUT GROUP

5.1.1 Introduction

As crewed space exploration has increased in mission duration and complexity, NASA has developed and implemented a variety of spacecraft life support systems. The technological solutions to safely support human life in the hostile space environment have evolved from those required to support a single astronaut for minutes to hours during Project Mercury to days and ultimately months for crews of three or more during the Apollo, Skylab, Shuttle, and ISS programs. Maintaining a safe, comfortable environment for the crew requires significant resources. Providing for the health, safety, and comfort for a single person is quite a challenge, with more than 30 kg/day of oxygen, water, and food required.¹ Figure 1 summarizes the resources required for a complex mission. Mass savings may be obtained by addressing the absolute need for certain water uses, such as washing dishes and clothing. At an even lower complexity, however, there are basic needs to supply atmospheric gases and remove carbon dioxide from the atmosphere. Controlling the trace chemical contamination levels, relative humidity, and airborne particulate matter loading are imperative to crew comfort and health. The challenge implied by Figure 1 is that the life support system design must provide long-term support for a minimal mass, volume, and power penalty while maximizing crew safety and system reliability and performance. Table 1 summarizes the typical cabin air quality parameters for a crewed spacecraft.²

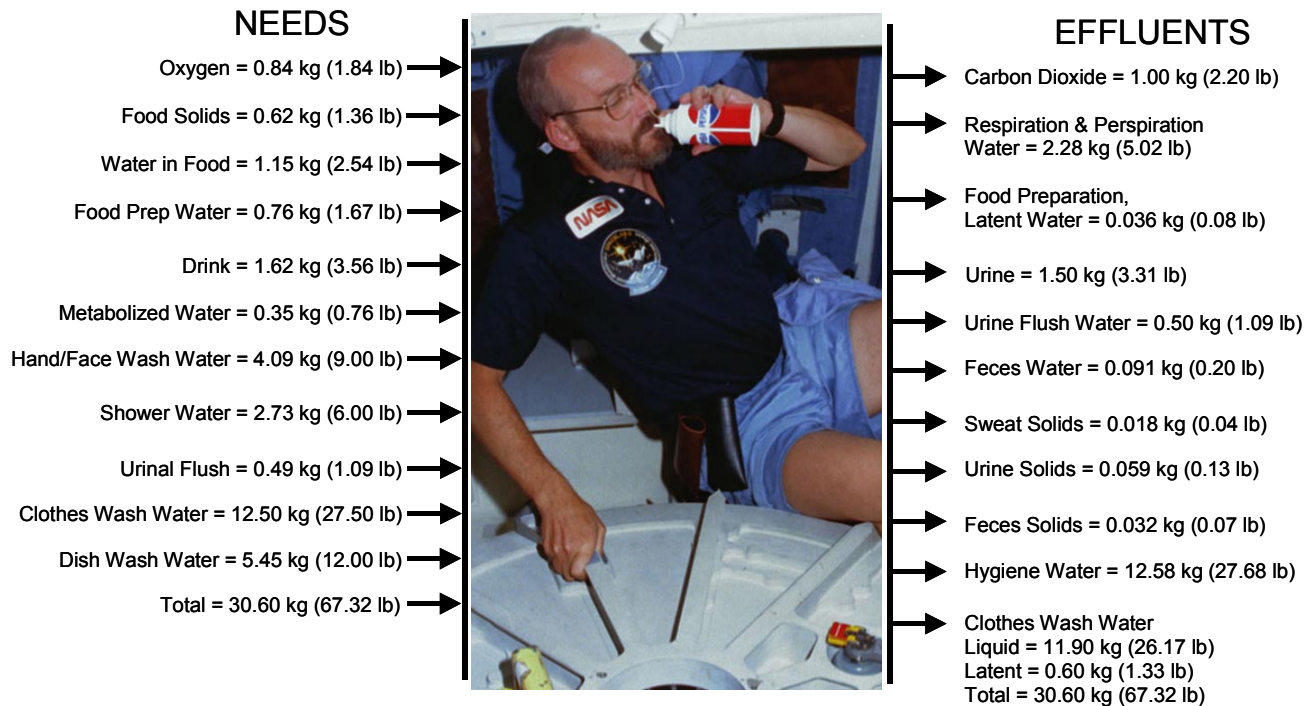


Figure 1.—Daily crew needs and byproducts

TABLE 1.—SPACECRAFT CABIN
AIR QUALITY PARAMETERS

PARAMETER	STANDARD
Carbon dioxide	5.3 mm Hg 24-hour average 7.6 mm Hg maximum
Oxygen	19.5-23 kPa
Water vapor	4.4-15.5°C dewpoint
Trace chemical contaminants	Less than 180-day SMAC*
Particulate matter	0.2 mg/m ³ for 0.5-100 micron
Microbes	500 CFU bacteria/m ³ 100 CFU fungi/m ³

*Spacecraft maximum allowable concentration.

5.1.2 Overview of Pertinent AHST Systems

A spacecraft ECLS system may be defined functionally to aid evaluation of areas for microgravity sensitivity. Figure 2 shows the functional interactions that exist within a typical spacecraft ECLS system, and Figure 3 shows typical sub-functions under each ECLS system design discipline. With respect to atmosphere revitalization, the atmospheric gas supply, CO₂ removal, CO₂ reduction, trace contaminant control, and oxygen generation functions are the primary focus areas. Figure 2 shows interfaces between atmosphere revitalization and other ECLS functions. These include the temperature and humidity control and water processing functions. Fire detection and suppression can also be considered as an interfacial discipline with atmosphere revitalization. Both detecting smoke and suppressing a fire both are influenced by or influence cabin atmospheric quality.

Table 2 summarizes the technological solutions for atmosphere revitalization for NASA crewed space vehicles and space stations.^{3,4,5,6} The early programs, Mercury, Gemini, and Apollo, employed equipment that relied heavily upon physical and chemical adsorption and coarse particulate matter filtration to address these challenges. Skylab, America's first space station, employed a similar approach for cabin air purification with the exception that carbon dioxide partial pressure control was provided by a pressure swing adsorption system. Trace chemical contamination control still relied upon expendable adsorption beds. Likewise, screens provided coarse particulate matter filtration. Little change was realized with the development of the Space Shuttle. Air purification systems used on board the Shuttle Orbiter actually reverted to systems similar to those used before Skylab. Expendable chemical and physical adsorption systems have been the rule for CO₂ and trace chemical contaminant control on board the Shuttle Orbiter. As a result, mission duration is limited to 15 days or less. For three missions, a pressure swing chemisorption process based upon solid amines was demonstrated for carbon dioxide partial pressure control.⁷ However, this system had to use expendable resources to address requirements for redundancy. Recent work has been undertaken to address the redundancy issues.^{8,9} This new system, however, is still in the conceptual design stages. Overall, broad application of regenerable processes for cabin atmospheric quality control was not realized until the

development of the ISS.^{10,11} Even so, some functions, such as particulate matter filtration and trace chemical contaminant control still employ expendable components.

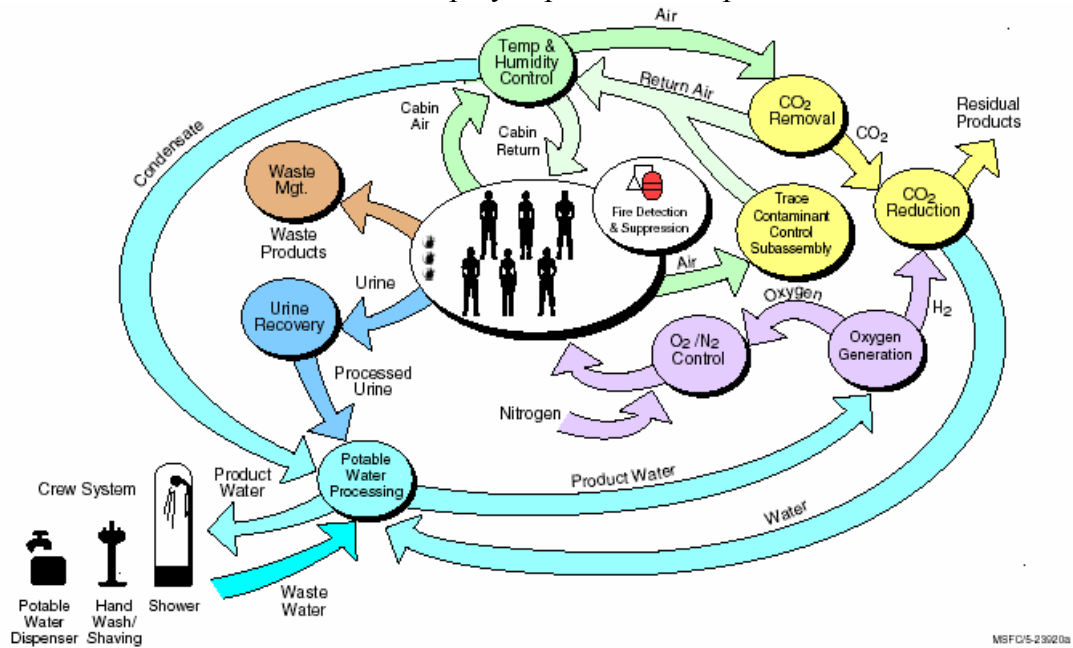


Figure 2.—A nearly closed environmental control and life support system

Control Atmosphere Pressure	Condition Atmosphere	Respond to Emergency Conditions	Control Internal CO ₂ & Contaminants	Provide Water	Prepare for EVA Operations
<ul style="list-style-type: none"> • O₂/N₂ Pressure Control Assemblies (USO/RS) • Positive & Negative Pressure Relief (USOS-Transport) • O₂/N₂ Storage (USOS, RS, Progress) • O₂ Generation Assembly, O₂ Solid Chemicals (RS) • Major Constituent Analyzer (USOS) (Share) • Gas Analyzer (RS) (Shared) 	<ul style="list-style-type: none"> • Cabin Air Temperature & Humidity Control Assemblies (All) • Ventilation Fans (USOS, RS, MPLM) • Air Particulate Filters (All) • Intermodule Ventilation Fans & Valves (All) • Ducting (All) 	<ul style="list-style-type: none"> • Smoke Detectors (All) • Portable Fire Extinguishers (All) • Fire Indicators and Fire Suppression Ports (All) • Portable Breathing Apparatus and Masks (All) • O₂/N₂ Pressure Control Assemblies (USOS) (Shared) 	<ul style="list-style-type: none"> • CO₂ Removal Assembly (USOS/RS) • CO₂ Vent (USOS/RS) • Trace Contaminant Control Assembly (USOS/RS) • Major Constituent Analyzer (USOS) • CO₂ Reduction Assembly (RS) • CO₂ LIOH Removal (RS) • Manual Sampling Equipment (USOS) • Gas Analyzer (RS) 	<ul style="list-style-type: none"> • Potable Water Processor (USOS/RS) • Urine Processor (USOS/RS) • Process Control Water Quality Monitor (USOS) • Condensate Storage (USOS/RS) • Fuel Cell Water Storage (USOS) • Waste Water Distribution (USOS) • Hygiene Water Processor (RS) 	<ul style="list-style-type: none"> • O₂/N₂ Pressure Control Assemblies (USOS) • O₂/N₂ Distribution (USOS) • O₂/N₂ Storage (USOS) • Major Constituent Analyzer (USOS) (Shared)
Atmosphere Control & Supply (ACS) & AR	Temperature Humidity Control	Fire Detection & Suppression & ACS	Atmosphere Revitalization (AR)	Water Recovery & Mgmt/ Waste Mgmt	ACS & AR

Figure 3.—Functional summary of environmental control and life support

TABLE 2.—SUMMARY OF SPACECRAFT CABIN ATMOSPHERE
SUPPLY AND REVITALIZATION TECHNOLOGIES

PROJECT	MISSION DURATION	CABIN VOLUME (m ³)	CREW SIZE	ATMOSPHERE CONTROL TECHNOLOGIES
Mercury	34 hours	1.56	1	Atmosphere: 100% O ₂ at 34.5 kPa Atmosphere supply: Gas at 51.7 MPa CO ₂ removal: LiOH Trace contaminants: activated carbon
Gemini	14 days	2.26	2	Atmosphere: 100% O ₂ at 34.5 kPa Atmosphere supply: Supercritical storage at 5.86 MPa CO ₂ removal: LiOH Trace contaminants: activated carbon
Apollo	14 days	5.9	3	Atmosphere: 100% O ₂ at 34.5 kPa Atmosphere supply: Supercritical storage at 6.2 MPa CO ₂ removal: LiOH Trace contaminants: activated carbon
Skylab	84 days	361	3	Atmosphere: 74% O ₂ /26% N ₂ at 34.5 kPa Atmosphere supply: Gas at 20.7 MPa CO ₂ removal: Type 13X and 5A molecular sieves regenerated by vacuum swing Trace contaminants: activated carbon
Shuttle	14 days	74	7	Atmosphere: 21.7% O ₂ /78.3% N ₂ at 101 kPa Atmosphere supply: Gas at 22.8 MPa CO ₂ removal: LiOH Trace contaminants: activated carbon with ambient temperature CO catalytic oxidation
Space Station	180 days	Up to 600	3 to 6	Atmosphere: 21.7% O ₂ /78.3% N ₂ at 101 kPa Atmosphere supply: Gas at 20.7 MPa/water electrolysis CO ₂ removal: Silica gel with type 13X and 5A molecular sieves regenerated by vacuum/temperature swing CO ₂ reduction: Sabatier reactor (planned) Trace contaminants: activated carbon with thermal catalytic oxidation Monitoring: Mass spectrometer for major constituents

5.1.3 Major Activities

Evaluation of the major ECLS system functions summarized in Figure 2 and Figure 3 identified two major classifications—those that provide for basic crew survival and those that provide for and maintain crew health and safety. Oxygen supply and CO₂ removal are classified within the functions that are critical for crew survival. Functions that provide for and maintain crew health and safety include fire detection and suppression, atmospheric humidity control, suspended particulate matter removal and disposal, trace chemical contaminant removal, and suspended microbe removal. A third classification, ECLS functions that enhance ECLS system performance was also considered, and carbon dioxide reduction and various monitoring technologies.

Representative examples of ECLS system equipment were considered for each classification. A major portion of the team's focus centered upon smoke detection, the issues surrounding smoke particle agglomeration in microgravity, and the potential impacts on the ability to actually detect smoke. All other atmosphere revitalization-related functions were discussed with particulate matter control and phase separation being common threads to the discussion. Adsorption- and catalytic reactor-based systems were not thought to have significant microgravity issues associated with them beyond the behavior of particulate fines generated from bed packing size attrition. Data quantifying fines generation in packed beds used in ECLS systems is not readily available. Many ECLS atmosphere revitalization systems include either pre- or post-processing unit operations that employ some phase separation. The most prevalent is gas-liquid separation using inertial techniques, usually centrifugal separators.

Microgravity effects upon mass transfer in some atmosphere revitalization systems were discussed briefly. Evidence for microgravity effects on mass transfer of trace chemical components of the cabin atmosphere from bulk gas phase into liquid films with humidity control systems has been observed in flight. Ground testing developed correlating equations for trace chemical component transfer into humidity condensate. When these equations are used to correlate flight data, predictions for the gas phase concentration typically differ by a factor of three. This evidence indicates that the effective surface area for mass transfer is described best by an annular geometry through the heat exchanger channels indicative of annular rather than stratified flow. While expected, this evidence may have implications for biofilters where aqueous-phase reactions and mass transport from the gas phase into an adsorbed liquid phase may be affected.

5.1.4 Issues and Problems

Issues relating to the discussion centered primarily upon the lack of background data on spacecraft cabin suspended particulate matter size distribution. This issue is common to understanding the effects of microgravity in smoke detection and aerosol behavior and control. To understand the effects of agglomeration and transport, the particulate matter background and particulate matter signature of various materials must be investigated.

Similarly, data is not available on reactive systems that result in solid phase deposition. The Bosch CO₂ reduction reaction and the post-processing unit operation for the Sabatier CO₂ reduction reaction, a carbon formation process, both deposit carbon as a final product. Scale-up testing conducted on prototype Bosch reactors indicated that the selection of catalyst and size of the reactor can influence the deposited carbon density and morphology. Carbon packing density, which is driven by morphology, is critical to reactor sizing and the overall process economics of a carbon dioxide reduction system based upon the Bosch reaction. Low carbon packing density was instrumental in selecting the Sabatier process over the Bosch process for development for the ISS. It is not known what carbon morphology and packing density may be achieved in a microgravity environment. Further, it is not known whether a carbon formation post-processing stage for a Sabatier-based CO₂ reduction system would suffer from similar challenges. Better understanding of this aspect of CO₂ reduction is needed to understand the true process economics associated with moving toward a more complete oxygen loop closure for a physico-chemical ECLS system.

Membrane transport was discussed with a variety of issues in mind. These encompass mass transport across membranes in an aqueous system and phase separation. The phase separation challenge involves removing dissolved gases from the liquid phase. Applications to Extra-Vehicular Activity (EVA) operations where high-pressure O₂ generation is necessary were discussed. The challenges to a lower pressure oxygen generation system most likely will be that much greater for a system delivering O₂ at higher pressures.

Also, data from in-flight experiments concerning inter-phase transport from the cabin atmosphere and condensed liquid phases are not available. Correlations from ground testing are presently adjusted by further correlating them to flight air quality and humidity condensate loading data. Investigation of inter-phase transport and microgravity effects on the mass transfer coefficient in co-current two-phase flow streams, such as those found in condensing heat exchangers, and potentially in biofilters are necessary to best understand the phenomena and develop more reliable predictive techniques to support design and flight operations.

5.1.5 Recommendations

The group established recommendations for each major atmosphere revitalization functional category. The functional categories and potential research areas are the following:

1. Oxygen Production by Water Electrolysis
 - a. Mass transport across membranes in aqueous systems
 - b. Separation of dissolved gases from water
 - c. Investigate new systems, including all unit operations, separations, and reactions, capable of producing high pressure O₂

2. CO₂ Removal
 - a. Fines generation in a heated, packed bed—fouling, monitoring, and deposit morphology
 - b. Regeneration cycles—effects on energy transport to packed beds
 - c. Microgravity effects on detection, ventilation, and sensor effectiveness

3. Fire Detection and Suppression
 - a. Particulate size distribution background (baseline)
 - b. Gaseous and aerosol combustion product signatures
 - c. Smoke particle agglomeration (for detection, sensors development/specification - unique low-g reaction products and particle behavior)
 - d. Fire suppression, type and amount, dispersion agents
 - e. Partial-G for all of the above
 - f. Consequences of fire, combustion product deposition, and ramifications for other systems
 - g. Smoke/particulate matter migration and evolution in complex geometries—CFD and particle/aerosol dynamics, boundary conditions with the cabin environment
4. Humidity Control
 - a. Gas-liquid separation in a fouling environment- particulate matter, contaminants, biofilms, and deposits
 - b. Effects of dryout, rewetting, and restarting events
 - c. Two-phase slug flow of liquid water/water vapor-air systems
5. Airborne Particulates (Aerosols)
 - a. Gas-solid separations
 - b. Dust deposition
 - c. Multi-scale particles interaction and agglomeration (low-G unique particle agglomeration)
 - d. Partial-gravity environment
6. Trace Components
 - a. Fines generation in heated packed bed, fouling, and monitoring
 - b. Trace molecular species (SMAC species)
7. Gas-liquid interfacial transport Airborne Microbes Type and amount
 - b. Background (baseline)
 - c. Suppression
 - d. Consequences: deposition, adhesion, growth, and ramifications to other systems
 - e. Microbe migration and evolution in complex geometries—CFD and particle/aerosol dynamics, boundary conditions with cabin environment

Of these, ECLS system engineers identified phase separation as a challenge during the early development stages of the ISS. The earlier study did not consider particulate matter issues. Carbon formation processes were identified as difficult to understand; however, only intuitive considerations were addressed with no recommendation for further research. Mass transfer limited processes, such as adsorption and catalytic oxidation, were considered to be insensitive to microgravity effects.¹²

It is interesting that the workshop attendees identified many of the same challenges when evaluating the ECLS system functions from a different viewpoint—that of microgravity researcher. The group also identified additional areas of interest and concern that the earlier effort did not. These are the areas for priority research. The challenges identified were discussed

with respect to their criticality and benefit from research that may foster development. Recommendations for research are classified in two priority categories—high priority and priority.

5.1.5.1 High Priority

High priority recommendations for research are the following:

1. Monitor particulate and microbial background environment (size, morphology, composition). Establish background(s) for given crewed environment.
2. Gaseous and aerosol combustion product signatures.
3. Develop and compile system-specific design guides for mechanisms, behaviors, fundamentals, and physics based upon scaling laws, correlations, previous flight experiments and performance, and theory.

5.1.5.2 Priority

Priority recommendations for research are the following:

1. Develop robust packed bed technology, particularly monolithic substrates or other non-particulate bed morphology for catalyst and adsorbent media supports.
2. Develop new devices/systems for phase separations. Exploit recent developments in capillary devices/systems where possible or employ capillary systems to enhance functional reliability.
3. Investigate chemical systems for humidity control.
4. Sensor and electronics systems miniaturization including distributed systems.
5. Investigate alternative degassing techniques (e.g., ultrasonics).

5.1.6 Conclusion

Atmosphere revitalization functions and crosscutting functions within an ECLS system were discussed. Areas for research were identified and areas for priority research were defined.

5.1.7 Recommendation to NASA on Future Direction

In the future, the atmosphere revitalization group recommends research projects to address the issues and problems cited. For the high priority research, the opportunity exists to leverage off near-term particulate matter measurement experiments to be conducted on board the ISS to better understand the particulate matter size distribution in a crewed spacecraft cabin in the range below 10 microns. This opportunity must not be missed. Collaboration with researchers at NASA GRC and designating a responsible individual for the effort within the ISS Program Office must take priority for this opportunity to yield much-needed data. At the same time, a coordinated effort to understand fire signatures must be undertaken to make more reliable, robust fire detection systems for crewed spacecraft. The group considered the present state of fire detection onboard spacecraft a major safety issue and a significant area that is uniquely microgravity related that must be addressed and, therefore, it rates as the highest priority.

A significant amount of key information that is useful to the ECLS design exists; however, it is not in a format that is readily useful to system designers. It is scattered throughout the literature and microgravity research, commercial aerospace, and academic communities. Soon-to-be published and yet-to-be-conducted work would also be useful to designers. Compiling the information into system-specific design guides detailing the mechanisms, behaviors, fundamentals, and physics relevant to ECLS systems will prove to be extraordinarily valuable tools for ECLS system designers. These design guides should be based upon scaling laws, correlations, previous flight experiments and performance, and theoretical analysis to better assist designers who will build the next generation of ECLS systems. Compiling these design guides into a useable format and delivering them to the ECLS system design community is a recommended high priority.

Work needs to be conducted to develop monolithic substrates for catalyst and adsorbent substrates. These substrates may enhance mass and energy transport as well as minimize particulate fine generation. Efforts already underway within NASA should be supported and expanded to understand their full benefit to advanced ECLS system design and process economics. Presently, NASA is testing advanced monolithic substrates for application to catalytic processes.¹³ This substrate technology is also being investigated as an adsorbent support substrate for trace contaminant and CO₂ removal processes.¹⁴ Other technologies that improve energy and mass transfer should be pursued in addition to these.

Phase separation and liquid degassing is a common thread throughout the ECLS system. Research in these areas is crosscutting through several ECLS system design sub-disciplines. Continued effort to understand and develop alternate phase separation and liquid degassing techniques as well as to obtain a better understanding of microgravity influences on trace component mass transfer will be vital to future ECLS system design and reliability.

5.2 SOLID WASTE MANAGEMENT BREAKOUT GROUP

5.2.1 Introduction

Identification of microgravity fluids, transport, and reaction issues in the area of SWM involves two distinct categories. The first regards those of current SWM operations (typically simple), while the second involves issues pertinent to future missions (potentially complex). Current and historical spaceflight SWM operations have mainly relied on simple, manual segregation and storage techniques, most of which are minimally impacted by reduced gravity. The major exception is human waste (feces and wipes) collection and storage, which in certain flight systems utilize drying (vacuum to space) or bagging with subsequent compaction. Regardless, even this level of processing is comparatively simplistic and is not exceedingly hindered by microgravity environments.

Although existing SWM techniques have sufficed to date, numerous improvements are indicated for current missions. Advancements would likely involve enhanced storage and containment techniques, including improved compaction of wastes to decrease habitat volume needs. Also, given the current ISS water shortage, water recovery through drying might also be warranted. Drying can also confer conditional stability to the wastes, as desiccated material resists microbial

degradation and subsequent gas production. Such near term advances are relatively minor as compared to issues likely to be encountered in future missions, where more demanding requirements (e.g., resource recovery) will make SWM a more integrated and critical element for mission success.

Delineating the effects of microgravity in SWM operations for future missions is inherently more speculative and challenging than those of current missions. First, it must be noted that SWM requirements are highly sensitive to overall system requirements of future mission scenarios. Principal mission-dependent requirements stem from factors such as processing needs, crew safety, planetary protection, integration with other sub-systems and mission cost. Because future missions are not currently well defined, it is unclear what functions, and their associated performance specifications, will be mandated. However, for long duration manned missions, it is essential to move towards materials closure in human life support systems in order to decrease the equivalent system mass at launch and to reduce resupply needs. Thus, while past missions have not required extensive processing, future long duration missions will likely need to transition to more complex operations, including extensive processing to reduce volume and mass, stabilize and sanitize wastes, and recover various resources.

Therefore, to effectively examine the issues of microgravity on SWM systems (particularly future missions), the full array of SWM functions must be considered. SWM systems have five top-level classes of functional operations, including the following:

- Collection/Segregation
- Transport
- Processing, (including pre-and post-processing)
- Storage
- Disposal

Each of these individual operations may vary dramatically depending upon the overall SWM system. For example, transport may simply involve moving dry trash from the point of generation to a plastic bag for storage, or involve the regulated transfer of a three-phase slurry from a storage tank to a reactor. Likewise, processing can range from simple manual compaction to complete oxidation with recovery of water, carbon dioxide and plant nutrients. See the Solid Waste Processing and Resource Recovery Workshop (SWPRRW) Final Report CTSD-ADV-474 for greater detail.

Complex SWM systems will typically involve all five functional operations. As it is difficult to completely isolate these functions from the system they are associated with, the approach taken is to examine complex SWM systems that are being evaluated for future utilization. While there is no assurance that the systems selected for evaluation will be employed in future missions, these systems will likely encompass the vast majority of common functions needed by other technologies as well, and therefore serve as relevant illustrative models.

5.2.2 Overview of Pertinent AHST Systems

Predominate current spaceflight solid wastes include; human waste (feces/wipes), paper, air filters, food wastes, packaging, medical wastes, oxygen candles, spent clothing, tape, and payload wastes (Maxwell and Drysdale, 2001). Predicted future waste models also include these waste types, with the potential for large quantities of inedible biomass from food production systems (SWPRRW Report, 2001). The SWM systems designed to manage these wastes are based on numerous mission-dependent requirements as discussed previously. Prominent features of historical and current spaceflight SWM systems are presented below.

The early missions of Mercury, Gemini and Apollo spacecraft were of relatively short duration and utilized rudimentary waste management techniques. No commodes were utilized in these missions. Instead, single-use plastic bags were taped to the skin and used to collect human fecal material. After use, the bag was sealed, and an included packet of biocide was ruptured and mixed with the feces. This procedure prevented excessive microbial gas production. All non-fecal solid wastes were contained and stored (Weiland, 1994).

To provide convenience during the extended Skylab missions, a commode system was developed. Single use bags were utilized, with an airflow design (vacuum) that ensured that feces was drawn into the bag and retained until the bag was automatically sealed. Used bags were placed in a processor that exposed the feces to space vacuum. This simultaneously dried the material and substantially decreased volume (Weiland, 1994). All non-fecal solid wastes were bagged, passed through a mechanical air-lock system, and stored in an emptied external fuel tank (79 m³) (Maxwell and Drysdale, 2001).

The current Space Transportation System (STS) orbiter commode system also utilizes negative pressure airflow (via fan separators) to transport feces into a receiving chamber where it is then sealed in a porous hydrophobic bag, and exposed to space vacuum (Eckart, 1996). Non-fecal wet and dry wastes are segregated and stored separately in the orbiter middeck, with any overflow volume being stored in the airlock (Maxwell and Drysdale, 2001).

The United States commode design baselined for installation in the ISS is similar to the STS system, except the bags are mechanically compacted into an underlying canister with no exposure to space vacuum. When full, the canister is removed and replaced with an empty canister. Non-fecal solid wastes are bagged and stored. Both the STS orbiter and the Russian Progress vehicle accept all solid wastes for either return to Earth (STS) or incineration during re-entry (Progress).

Research is currently being performed to address both current and future SWM needs.

Though few systems have been developed to high Technology Readiness Levels (TRLs) or utilized in spaceflight, a number of physicochemical and biological technologies have undergone investigation. An abbreviated list includes; storage, compaction, drying, dry/wet size reduction, incineration, pyrolysis, Super Critical Water Oxidation (SCWO), wet oxidation, electrochemical oxidation, chemical treatment, aerobic/anaerobic composting, and biological aqueous slurry reactors. A wide variety of associated pre- and post-processing technologies also exist. Examples

include; separation, drying, compaction, pelletization, size reduction (wet/dry), transport and conveyance, mixing (liquid/solid, solid/solid), and phase separation (SWPRRW Final Report, 2001). Given the breadth of these technologies, and the numerous specific manifestations that can be envisioned for each, it is evident that microgravity issues will be both numerous and difficult to predict.

5.2.3 Major Activities

The breakout group activities first centered on delineating the scope of the SWM issues for spaceflight. As discussed previously, the vast majority of issues appear to be relevant to future missions, particularly those that require extensive processing/resource recovery of waste streams. In order to fully understand the scope of the issues, the five major SWM functions were discussed at length. General issues for each function were preliminarily identified, and it was decided that the most effective manner to approach a detailed analysis was to hypothetically construct a SWM technology suite that managed the waste from the point of generation to the point of disposal. Within this exercise, it was also decided that it would be fruitful to select two distinctive, yet generalized, processing technologies in order to generate a wider array of specific microgravity issues.

To this end, a list was presented that summarizes currently relevant processing technologies. From this list, combustion (e.g., incineration) and aerobic biological processing (e.g., composting/slurry reactor) were selected. Both of these choices are envisioned to encompass a wide variety of issues and provide for significant overlap with numerous different processing technologies. The examination of these two processes indicated that there is a high level of correlation of needed process steps as shown in Table 3. This is entirely consistent with the view expressed earlier that complex SWM systems will likely encompass the majority of common functions.

TABLE 3.—A COMPARISON OF MAJOR FUNCTIONS ASSOCIATED WITH COMBUSTION AND AEROBIC BIOREACTOR PROCESSING TECHNOLOGIES

<u>Combustion</u>	<u>Aerobic bioreactor</u>
<ul style="list-style-type: none"> • Drying • Size Reduction and Classification • Preheat • Mixing • Feed Mechanism Into Combustor • Reaction Bed • Gas Removal • Ash Buildup and Removal • Air Contaminant Cleanup • Water Condensation 	<ul style="list-style-type: none"> • Drying • Size Reduction and Classification • Mixing • Feed Mechanism Into Reactor - Solid, Liquid, Gas Feeding System • Reaction • Residual Separation • Air Contaminant Cleanup • Water Condensation

The remainder of the work involved a detailed examination of these two options with the specific goal of identifying and addressing potential microgravity issues. A detailed description of these issues is given in the following sections.

5.2.4 Issues and Problems

Microgravity issues were identified for each of the major SWM functions including collection/transport (combined), processing, storage and disposal. These issues are discussed separately below.

Collection and Transport – The collection and transport of solid wastes are inherently interconnected, as collection requires transport to a unit. For example, collecting feces in a commode typically utilizes air entrainment to transport solids to the area of accumulation. Because of this tight interrelationship, collection and transport issues will be presented simultaneously.

From the moment of generation, solid wastes will undergo various types of transfer. For instance, waste will need to be transported to initial storage containers, then to pre-processors, processors, post-processors and finally to storage or disposal systems. During this overall process, the solids may be compacted, dried, size reduced (e.g., shredded), pulped, formed into a slurry, or become a residue (e.g., ash). Additionally, air and water may be used in various means to control/facilitate these processes. Therefore, variable dry/moist/wet solids flows, with and without gas phase incorporation will have to be physically moved from one site to another, sometimes with highly controlled flow rates. Transport may involve moving material from one process to another or internally within a single processor.

Potential issues regarding transport include the following:

The poor understanding of multiphase flow under microgravity is the basis for many of the potential collection and transport issues which include the following:

- Pneumatic transport of dry solids, liquid waste and slurries
- Transport of liquid-solid slurries with or without gas entrainment
- Material containment during transfer to storage systems

Storage – Storage techniques have been employed extensively for SWM in current and historical missions. These techniques have been relatively simple, often involving placing solid wastes into plastic bags and sealing. Used food packaging is often rolled tightly into “footballs” that are held together with duct tape.

While these operations adequately address microgravity influences, future systems will employ more numerous and complex storage systems. For example, due to downstream processing requirements, a greater level of material segregation might be necessary, with each fraction requiring its own storage vessel. Likewise, numerous intermediate storage vessels may be needed within a processing sequence. These may require temporary storage of solids in a dried, moist or slurry form. Flow into and out of these storage facilities may require precise control and phase positioning, particularly when “feeding” a processor. Additionally, more sophisticated means of

transport may be associated with storage units, including pneumatic, ram and screw conveyer systems, thereby requiring more complex interfacing.

Some major issues identified for storage in microgravity include the following:

- Uniform packing and distribution within storage vessels
- Uniform flow through, and emptying from, temporary storage vessels to avoid “no-flow” zones
- Phase positioning within tanks with respect to feed line to reactor and filling port
- Gas movement to accommodate volume changes during filling and emptying process

Processing – SWM processing systems, particularly those for future long-duration missions, will likely face numerous obstacles imposed by microgravity environments. The nature of the issue will be highly dependent upon the component function and character. The working group identified numerous issues impacted by gravity related to the identified processing functions associated with the two example technologies, and are listed below.

Drying

- Water removal
 - Vaporization (application of heat directly or via warmed air) can result in solid entrainment in the vapor stream, requiring gas-solid separation
- Water condensation
 - Water removal/drainage from cold plates, etc., requiring gas-liquid separation

Size reduction and classification

- Pretreatment of biomass, paper, plastic
 - Grinding/cutting
 - Size classification (e.g., screens)
 - Transport of material
 - Gas-solid separation
 - Solid-solid separation for size classification
- Dust explosion hazards

Solid, Liquid, Gas Feeding Systems

- Must be actively fed - cannot be gravity-fed system
- Liquid/solid slurry feed
 - Binding within pumps
 - Liquid dryout at gas port resulting in solid plug formation
- Gas-solid slurry
 - Need to avoid backflow of solids
- Ability to avoid slug flows – to minimize pressure fluctuations - this requires a dilute solids flow.

Reaction

- Containing material in reaction bed
- Agglomeration of bed
- Waste accumulation
 - Variability in feed
 - Batch vs. continuous
- Multiphase (solid, gas) heating
- Mixing/distribution of reactants/chemical species
 - Uniformity of blend
 - Mixing in reaction zone
 - Maintaining correct stoichiometry
 - Performance due to diffusion vs. convection
- Controlling material residence time

Ash Separation

- Gas-solid separation- and removal/transport

Air Contaminant Cleanup

- Issues to be addressed by Air Revitalization group

Condensing Heat Exchanger and Removal of Water

- (See Drying)

Monitoring and Control

- Gas compressibility - system stability problems

Disposal – Disposal of wastes differs from storage in that when a material is disposed of, it is assumed that no further handling or access to the material is required. Disposal may or may not incorporate storage systems. For example, a transit mission to Mars might utilize jettisoning of certain wastes as the dominant SWM method. With this technique, the principal microgravity issue regards the forcible ejection of wastes in a manner that does not impose undue potential to cause damage/harm. In contrast, certain wastes may be selected to remain stored within the spacecraft. In this case, storage issues (discussed previously) prevail.

5.2.5 Recommendations

Because of the wide breadth of potential SWM functions and associated technologies, and the uncertainty of future mission requirements, the recommendations generated from the analysis were developed to provide general guidance for microgravity factor identification and resolution. Issues were prioritized based on the perceived complexity of resolution and the frequency an issue was encountered. These prioritized research and development recommendations are listed below.

5.2.5.1 High Priority

Research issues considered to be of highest priority include:

- Three-Phase Flow - This principally involves the transport of moisture-bearing solids with associated gases both external to and within the reactor.
- Solids Containment
 - Reaction bed
 - Size reduction
 - Drying
- Mixing/distribution of chemical species and phases in reactor
- Multiphase separations
 - Gas-Solid
 - Gas-Liquid (especially condensing heat exchangers)
 - Solid-Liquid
 - Three Phase

5.2.5.2 Moderate Priority

Research issues considered to be of moderate priority include:

- Dry solids feed mechanism
- Monitoring and control related to two-phase instability issues
- Monitoring and control related to process control
- Dust explosion hazards

5.2.6 Conclusion

Although the exact nature of future SWM systems remains uncertain, it is clear that numerous system components will be required to work in unison to meet mission requirements. The areas that will likely require the greatest level of research and development include the solids transport and processing. With respect to transport, SWM will likely be dealing with three-phase flow, with moisture contents ranging from very low (dried) to very high (slurry) levels. Transport systems may range from simple to complex, and face numerous problematic issues including slug and other non-uniform flow. Processing systems will face similar issues as well as complex containment, mixing, reaction process, and phase separation issues.

Because specific SWM systems are not yet baselined for utilization with future missions, it may be prudent to conceptualize generalized solids transport processes and examine them on a fundamental level rather than on a case-by-case basis. This requires a thorough surveying of likely SWM system component candidates and a systematic identification of inherent fluid reaction/transport/storage issues. In this manner, areas that appear to be the most common and/or difficult can be selected for further study.

It must also be noted that the need for more complex solid waste processing systems will often stem from mission scenarios involving large amounts of waste production and/or resource recovery for materials closure and self-sustainability. The principal scenario that exemplifies this issue regards the generation of large quantities of inedible biomass from food production

operations. It is almost certain that such operations will exist only on lunar or planetary bases, where substantial gravitational forces exist. Because systems that operate well in microgravity may not operate adequately in reduced (planetary/lunar) gravity environments and vice-versa, SWM requirements must be viewed from various levels of gravitational influence, ranging from microgravity to approximately 1/3 G (i.e., Mars).

5.2.7 Recommendation to NASA on Future Direction

A broad range of issues needs to be addressed to expedite progress in SWM. One of the first actions is to more thoroughly and formally define SWM system requirements for relevant mission scenarios. This will aid in the design of overall SWM systems that are capable of satisfying these requirements. The identification of systems and their respective components will subsequently allow greater definition of specific microgravity issues.

Currently, it appears that both fundamental and applied research is required to address the numerous SWM microgravity concerns. For example, understanding two- and three-phase flow, mixing and reaction, and separation at the fundamental level will facilitate applied research and technology development. Such research will also likely have beneficial overlap with other elements as well, such as the water recovery, and air contaminant treatment system.

In order for AHST to meet overall and SWM program objectives, increased collaboration will be required between AHST and Microgravity researchers. A bi-directional flow of information is needed. First, ALS technology developers need to convey technology/system issues to microgravity experts in order to guide fundamental research. Conversely, relevant fundamental microgravity information should be available to, and used by, technology developers in the preliminary stages of their technology conceptualization, rather than later attempting to adapt a thoroughly developed process for use in microgravity. Potential mechanisms to facilitate increased collaboration include:

Increased Collaboration Mechanisms

- Provide additional funding mechanisms for collaborative proposals
- Personnel exchanges
- Exposure of personnel to microgravity/participate in testing
- Visits to NASA sites (short-term)
- Develop and distribute contact lists of Microgravity/AHST experts
- Develop training tools
- Provide a manual that effectively summarizes pertinent microgravity knowledge
- Provide websites for information exchange
- Develop accessible databases for data exchange

Microgravity Participation in Design Reviews

- Facilitate appropriate personnel involvement during early stages of technology development, feasibility and design reviews

5.3 WATER RECOVERY SYSTEMS BREAKOUT GROUP

5.3.1 Introduction

For long-term space flight, providing a safe supply of potable water is critical for human life support. Since resupply is unlikely to be practical, the recovery and reuse of wastewater is necessary. A number of physico-chemical and bioregenerative processes are available to process wastewater, which is made up of humidity condensate, urine, hygiene, and wash water, for reuse as potable water. A number of processes have been considered for purifying the water including Vapor Compression Distillation (VCD), thermoelectric integrated membrane evaporation, vapor phase catalytic ammonia removal, air evaporation, multifiltration, reverse osmosis, and electrodialysis.

Although significant progress has been made to develop systems to recover wastewater in space, the water processing system is a limiting factor for the number of crewmembers that can be supported for long-term missions, including ISS. The baseline system for ISS uses a single system to produce water for hygiene and consumption by the crew. Urine is pretreated and processed in an ambient-temperature VCD system. The distillate from the VCD is delivered to the wastewater network, which also receives humidity condensate and hygiene return water. The wastewater network delivers water to the water processor, which uses multifiltration technology and a volatiles removal assembly. Multifiltration technology requires little power and provides 100 percent recovery efficiency but relies on expendable beds. Therefore, it is subject to storage and resupply constraints. Current vapor compression technology has moving parts and provides about 85 percent recovery efficiency. Power consumption is fairly low, and resupply requirements are negligible. However, with the current technology, some resupply or special storage reserves are necessary to make up for the losses will continue to be necessary for long-duration space missions.

In spite of the apparent success of current systems, many issues need to be addressed in water recovery and management. These include in-flight maintenance, reliability, the disposal or recycling of brine, as well as the potential for microbial contamination and the accumulation of toxins in long-term water processing, storage, and distribution systems. To this end, many alternatives, both physico-chemical and bioregenerative, may provide opportunities to significantly improve the recovery of potable water from wastewater and the quality of the recovered water.

5.3.2 Overview of Pertinent AHST Systems

The water recovery and management system includes many subsystems. The major components, applicable to most subsystems are as follows:

- Systems that collect water
 - Condensing heat exchangers collect humidity from the cabin air
 - Urine collection and flush systems
 - Systems to collect hygiene and wash water

- Systems that use water and produce wastewater
 - Clothes washer
 - Dish washer
 - Hygiene wash station
- Systems that process wastewater
 - Distillation systems
 - Evaporation systems
 - Multifiltration systems
 - Bioregenerative systems
 - Packed bed systems
 - Reverse osmosis systems
 - Electrodialysis systems
- Systems that store and distribute water and wastewater
 - Storage tanks
 - Pipes
 - Pumps

5.3.3 Major Activities

The participants of the breakout group identified key components in the water recovery system and then examined ways in which microgravity fluid physics may play a role in limiting or enhancing specific technologies that are currently used or could be used in the future. The process involved developing a matrix to elucidate the key functions of the technologies and the associated microgravity physical processes that might influence them. Finally, difficulty of addressing the impact of the physical processes on the components was evaluated in order to identify pertinent research issues.

5.3.4 Issues and Problems

With regard to microgravity issues in water recovery, the approach in the past has been to avoid two-phase and three-phase flow. Gravity (or lack thereof) plays an easily predictable role in single-phase flow, so using single-phase systems usually avoids design problems related to gravity. Of course, some systems are inherently multiphase in nature. For instance, a condensing heat exchanger used to extract water from the cabin air is inherently a two-phase (gas-liquid) process.

However, avoiding multiphase flow severely limits the nature of the systems that can be used for water recovery. For example, consider a fixed packed bed system for water purification, which consists of a column filled with solid packing material over which the water flows. Biologically or chemically active agents on the packing material are used to treat the water. The packing material stays in place due to gravity on Earth, so that the flow is essentially a single-phase fluid moving over a complex (but fixed) bed. However, in microgravity, the packing material can move more freely even if it is constrained in the column by screens or perforated plates. Thus, the flow is two-phase in character. A small amount of motion can result in a grinding action, which can generate fine particulate material that can wash downstream of the column and plug or

foul other components. Furthermore, there are situations in which the presence of a gas phase is required as either a reactant or product of the chemical or biological process along with the liquid and solid phases. But the motion, coalescence, and break-up of bubbles in microgravity are quite different from those under Earth's gravitational field. As a result of these complications in fixed packed bed systems due to the influence of gravity, it is quite challenging to devise effective water recovery systems based on this technological approach even though it may be quite beneficial in other ways.

There are many other systems for water recovery in which a poor understanding of the underlying physical processes in microgravity limits the application of these processes. As a result, there is great potential for valuable advances in systems for water recovery if some of these physical processes are better understood. Furthermore, there may be situations where the lack of gravity may be exploited to design systems that operate more efficiently in space than similar systems used in normal gravity.

5.3.5 Recommendations

Three key themes are apparent in how a better understanding of microgravity fluid physics could be used to provide the necessary knowledge for the development of water recovery systems.

1. **Influence of Microgravity on Multiphase Flow:** As noted in the example of the fixed packed bed reactor described above, multiphase flow is currently avoided in the design of water recovery systems. Yet, being able to implement multiphase flow systems under microgravity conditions could permit the use of technologies for water recovery that have not been considered before. This could result in valuable advances in the technology for water recovery. Thus, a key area of fundamental microgravity fluid physics research that is necessary is related to multiphase flow. This includes issues related to bubble coalescence and break-up, channeling in solid-liquid flows, mixing, bubble injection, preferential phase distribution, flow stability, flow regimes for microgravity multiphase flow, microgravity heat and mass transfer, contact angles and wetting, gas-liquid separation, solid-liquid separation, dewatering, phase management, fluidization, capillarity, droplets, and many others.
2. **Scale-up from Earth Testing to Microgravity Conditions:** Water recovery systems are relatively large in size and must be operated over long-term durations. As a result, testing is fairly difficult. It is necessary to scale up the results from small-scale, short-term experiments in microgravity to large-scale, long-life functional systems. It is also necessary to scale-up experiments performed in Earth's gravity (which are relatively easy for large-scale, long-term testing) to account for microgravity. The issue is that microgravity experiments in a drop tower or parabolic flight aircraft are small-scale and of short duration. Long-term experiments at full-scale must be done on Earth. The challenge is to combine the results from both of these types of tests to provide reasonable predictions of the operation of full-scale systems in space.
3. **Influence of Microgravity on Biofouling:** A major problem in any water system is biofouling, where a layer of biologically active material grows on surfaces in contact with the water. Often the biofouling depends on the nature of the flow as well as the material in contact with

the water. The biofilm layer (slime) can greatly reduce the effectiveness of many physical processes that involve heat and mass transfer. In addition, biofouling can reduce the sensitivity of sensors, clog lines, and contaminate the water. Biofouling is notoriously difficult to control on Earth. Various mechanical and chemical processes (biocides, surfactants, chelating agents, and enzymes) are used to remove the biofilm. Of course, it is difficult to employ many of these techniques onboard a spacecraft for potable water. Even though biofouling is a major concern, it is not clear how biofouling will occur and can be prevented in microgravity. Biofouling is often affected by the flow of the water, which is affected by microgravity. Thus, a better understanding of how fluid flow affects biofouling, particularly under microgravity conditions, is critical in all water recovery systems.

5.3.5.1 High Priority

In many cases, an understanding of flow under microgravity or low gravity conditions is critical to developing new technological solutions or is at least severely limiting in the development of these systems.

- **Multiphase Flow and Separation (Critical):** As alluded to earlier, problems in multiphase flow systems include the spatial distribution of phases in system, solid-liquid transport and handling, gas-liquid transport and handling, and three-phase transport and handling. Issues in multiphase flow systems include interfacial force issues (surface tension, contact angle, bubbles, droplets, coalescence, break-up), the effect of the gravitational field on flow and transport (particularly in microgravity conditions), design and support tools (such as computational fluid dynamics, theory, and fundamental experiments), and scaling laws. The applications of multiphase flow include many of the specific systems noted below including packed bed reactors, multiphase metering/sampling, bioreactors, phase change systems, condensers, laundry systems, gas-liquid separators, solid-liquid separators, and dewatering systems.
- **Packed Bed Reactors (Critical):** The ability to use packed bed reactors in water recovery systems in space opens the door for many opportunities to purify and treat wastewater. Yet there are many concerns related to packed bed reactors operating under microgravity conditions including biofouling, pressure drop, flow stability, flow regimes, physico-chemical degradation, scale-up, and heat and mass transfer.
- **Multiphase Metering/Sampling (Severely Limiting):** Monitoring water requires accurate sampling and metering. On Earth gravity makes it relatively easy to obtain an accurate water sample (bubbles rise to the top of the container). But in microgravity, obtaining an accurate measure of the quantity of water in the sample is much more difficult. Without a precise measurement of the quantity of water, the chemical analysis cannot be accurate.
- **Fixed Film Reactors (Severely Limiting):** Many water-processing reactors require a chemical or biological film on the surface of a tube or bead. Important issues for biofilm reactors include biofilm sloughing and mass transport under microgravity conditions.
- **Other Bioreactors (Severely Limiting):** Several different bioreactor systems, which are used on Earth, such as continuously stirred tank reactors, could find application in water recovery systems. However, the operational issues and performance of these systems under microgravity conditions is not clear.

- Phase Change/Evaporation Systems (Severely Limiting): Many life support systems (not necessarily all related to water recovery) currently involve phase changes or could benefit from the use of components that involve phase changes. Thus, a better understanding of thin film boiling, thin film stability, and wicking under microgravity conditions could lead to new technologies for water recovery.

5.3.5.2 Moderate Priority

In some cases, a better understanding of flow under microgravity or low gravity conditions may enhance the development of certain systems or may provide an awareness that could contribute to a better understanding of the flow physics in the following water recovery systems.

- Condensing Heat Exchanger (Enhance): The condensing heat exchanger is used on ISS to recover humidity from the cabin air. Fluid physics issues that need to be better understood include condensation processes, aerosols, and biofilm formation.
- Laundry Systems (Enhance): While laundry systems are not currently used, they may be necessary for long space flights. Multiphase mixing, multiphase separation, and wetting are important fluid physics issues related to this area.
- Gas-Liquid and Solid-Liquid Separators (Enhance): Phase separation is important in many water use and recovery systems including bioreactors, condensers, and laundry systems. Microgravity enabled technologies need further development.
- Dewatering Sludge (Enhance): The complete reuse of water will require advances in dewatering to recover water from biomass.
- Membrane Processes (Enhance): Membrane processes are typically single-phase during normal operation, but issues related to multiphase flow can occur under some circumstances. In addition, biofouling is a problem that needs to be resolved.
- Fluidized Bed Reactors (Awareness): While fluidized bed reactors are designed specifically to take advantage of gravity, it may be possible to develop microgravity analogs that are independent of gravity.

5.3.6 Conclusion

Many water recovery systems require an understanding of microgravity fluid physics. The fluid flow problems in many of the water recovery systems are related to multiphase flow, scale-up, and biofouling. Well-conceived fundamental research on these topics would provide useful information that could lead to new and better water recovery systems. More applied research related to fluid physics questions for specific water recovery systems could enhance the functionality of those systems.

5.3.7 Recommendation to NASA on Future Direction

Future requests for proposals from the NASA Fluid Physics Program should emphasize the need for research related to specific fluid physics issues pertinent to water recovery. It may even be worthwhile to set aside a certain fraction of the funding or have a separate request for proposals that addresses fluid flow issues directly related to water recovery. These proposals would need to address specific fluid physics issues described above and how the proposed research would

directly impact water recovery systems. In addition, the proposers could be required to indicate specific NASA personnel with whom they have discussed the proposed research.

There are also many situations related to water recovery systems in which the knowledge of the fluid physics at microgravity is well-developed but needs to be transferred to the technology developers. To this end, NASA could develop a “Knowledge Readiness Level” or KRL, along the same lines as the Technology Readiness Level (TRL). In some cases, all that is needed to determine the impact of microgravity on a particular system is a transfer of information from the microgravity fluid physics specialist to the technology developer—a simple phone call. At the other extreme is a fundamental research question that has not been resolved—this might require a multiyear research program. To this end, a KRL system as follows might be useful:

1. General engineering knowledge; information transfer is needed.
2. Physical process is well understood; application to AHST issue is needed.
3. Physical process is understood quantitatively; applied research is needed to adapt the knowledge to an AHST issue.
4. Fundamental physical processes are poorly understood or only qualitatively understood; fundamental research is needed to quantify the knowledge so it can be applied to an AHST issue.
5. Fundamental physical processes are not understood; fundamental research is needed to develop an understanding of the underlying physical processes.

Clearly, some fluid physics issues can be readily addressed by having the right people in contact with one another (KRL 1 and 2). Other issues require applied or fundamental research (KRL 3, 4, and 5). Issues at low KRL's require a mechanism for technology developers to obtain expert advice from fluid physics researchers. Issues at higher KRL's require funded research directed toward the specific issue by fluid physics researchers with input from technology developers. Note that the cost of the "answer" is related to the KRL. Low KRL's are relatively inexpensive, while high KRL's require substantial research funding.

5.4 THERMAL SYSTEMS AND PHASE CHANGE PROCESSORS BREAKOUT GROUP

5.4.1 Introduction

Future missions for exploration of the solar system will require enabling technologies for efficient and reliable energy generation, storage and transfer. Integration of several different engineering subsystems and strategies are envisioned. For example, energy generation may be provided by a combination of nuclear, chemical, or solar sources. Energy storage may be accomplished by rechargeable batteries, regenerative fuel cells, flywheels, or latent heat phase change processes, and energy transfer issues might range from large scale, as in cabin thermal control, to small scale, as in space suit temperature regulation. In most of these cases, design of the thermal subsystems becomes an important consideration.

Currently, most of the subsystems involve single-phase fluid and thermal processes; only a small number involve multiphase fluid and thermal processes. But the need for improved energy-to-mass ratios suggests replacing some of the single-phase operations in favor of two-phase

systems. Thus, the future design of important thermal subsystems for space applications as in boilers, condensers, evaporators, heat exchangers, normal and cryogenic fluid storage units, fuel cells, radiators, and heat pipes will all involve complex multiphase fluid flow and transport issues.

Fluid flow, heat and mass transfer, and phase separation are all affected by gravity. Unfortunately, there is a scarcity of reliable and pertinent reduced-gravity two-phase flow data. Therefore, a full understanding of both single and multiphase transport phenomena associated with the operation of the thermal and phase change subsystems in microgravity is needed for both the design of the units and their safe and efficient operation in space.

Several previous workshops such as, *Workshop on Research Needs in Space Thermal Systems and Processes for Human Exploration of Space* and *Workshop on Research Needs in Fluids Management for the Human Exploration of Space* and a comprehensive NRC report entitled, *Microgravity Research Support of Technologies for Human Exploration and Development of Space and Planetary Bodies* have documented many of the relevant research and engineering issues associated with the operation of thermal subsystems mostly for power and propulsion applications. Thus in this workshop, only the thermal/phase-change subsystems that are relevant to AHST were considered. Naturally, there is an overlap between the problems and issues associated with the different applications and for a general discussion the NRC report provides valuable and comprehensive information and a global perspective.

5.4.2 Overview of Pertinent AHST Systems

Thermal subsystems are critical in several areas of advanced human support technologies for long duration microgravity and planetary missions. This includes cabin temperature and humidity control, space suit thermal and humidity regulation, two-phase and single-phase energy-conversion/power-cycles, refrigeration systems, thermal storage systems, and normal and cryogenic fluid storage tanks.

Temperature and Humidity Control

Control of temperature and humidity within tolerable limits involves physical processes of heat exchange, multiphase flow, phase change and phase separation that are all greatly affected by gravity. This is true for both cabin temperature and humidity control and thermal regulation of space suits, although different length scales are involved in each case.

The system most responsible for maintaining the desired ambient conditions in the cabin is a condensing heat exchanger. Cooling water is used to bring the incoming air to a temperature below the dew point, forming a condensate that must be separated from the air stream. Phase separation can be accomplished either actively or passively through the use of slurper bars and/or inertial and membrane separators. Naturally, gravity is a key parameter to be considered in phase separation.

The astronaut's safety and comfort depends to a large extent on the performance of the space suit thermal and humidity management system. This system will probably rely on an active or passive ventilation system and a miniature two-phase loop that is tailored for heating and

cooling. Optimization of these systems will require resolution of many small-scale single- and two-phase transport issues.

Power Generation Cycles

A generic closed-loop dynamic space power system is composed of a heat source (nuclear or solar), a heat sink (radiation to deep space), and an element that converts thermal energy into useful work (mechanical or electrical energy). For a Brayton cycle, the gaseous working fluid is pressurized in a compressor, heat from the heat source is added to the working fluid via a heat exchanger, the working fluid expands through a turbine producing power and the excess heat is rejected to the space via radiators where the working fluid is cooled before entering the compressor. For a Rankine cycle, a pump pressurizes the working fluid in liquid phase, heat from the heat source is added through a boiler where the working fluid is boiled, and the vapor expands through a turbine producing power. The vapor enters the condenser where excess heat is rejected to space via space-radiator where the working fluid turns into the liquid phase. A liquid-vapor phase separator is required to ensure that liquid entering the pump is completely free of vapor or non-condensable gases. The Rankine cycle is quite efficient for electric power generation and has a higher power-to-weight ratio than the Brayton cycle. However, the Rankine cycle has components such as a boiler, condenser and a phase separator in all of which the working fluid has both liquid and vapor phases and therefore its operation will be greatly affected by gravity. The current single-phase systems are capable of efficiently functioning for the near term missions. But for future long-duration missions, especially, if spacecraft that generate large quantities of power and waste heat such as the nuclear-based ones are developed, implementation of two-phase thermal loops will be imperative.

Thermal Storage Systems

The intermittent nature of energy availability in planetary orbit (as with solar energy for example) presents a special challenge for space power management. An alternative to battery storage is a latent heat thermal energy storage unit. In this system heat is stored in the Phase Change Material (PCM) while it melts during the charging cycle. The stored latent heat is then released as the material solidifies during the discharge cycle. The melting solidification process is affected by natural convection and, therefore, gravity is an important parameter.

Fluid Storage Tanks

Storage systems are needed for preserving both normal and cryogenic fluids for life support systems. For missions beyond low earth orbit both microgravity and on-surface storage is needed. Ventless storage is emerging as a promising strategy for reducing mass but requires an intricate active/passive pressure control mechanism. While, passive pressure control strategy relies mainly on the use of Multi-Layer Insulation (MLI) systems, a combination of forced jet mixers, Liquid Acquisition Devices (LADs) and cryocoolers are proposed for most active pressure control strategies. For optimized and synergetic design and implementation of active ventless pressure control, a series of two-phase transport issues that are all affected by gravity must be examined.

5.4.3 Major Activities

The breakout group first examined key areas of life support where thermal subsystems play a crucial role. As mentioned above, these included: temperature and humidity control; power

generation loops; energy storage systems; and fluid storage tanks. Next, key thermal and phase change components of each system were identified, and the ways in which microgravity fluid physics and transport phenomena may affect specific aspects of these technologies as they are currently used or may be used in the future were also examined. The process involved developing a matrix of the key functions of the thermal and phase change components and then relating them to the microgravity physical processes that might influence them. Finally, the impact of resolving the pertinent transport issues associated with the physical processes for each technology was evaluated in order to identify, recommend, and prioritize the pertinent research issues.

5.4.4 Issues and Problems

The breakout group found that the problems and issues associated with heat transport loops and energy cycles were of critical importance to the future missions. Most of the issues arise due to the desire for two-phase operation in microgravity. Two-phase flow, boiling and condensation heat transfer, flow separation, and phase distribution and separation phenomena can be quite different in microgravity from their 1G (Earth gravity), and reduced-gravity counterparts. Microgravity empirical data, theoretical models, and numerical codes are needed to help the engineers in their future design efforts. The microgravity empirical data must encompass complex flow geometries and different variable gravity flow regimes. The data must be obtained in a systematic fashion in order to aid validation and verification of numerical codes and development of scaling laws.

Since numerous thermal subcomponents such as condensers, evaporators, separators, radiators, accumulators, cold plates, pumps, filters, flow meters, and other instrumentation devices are involved, both their operation individually and collectively is of interest. The operation of thermal subcomponents needs to be addressed as well as the collective operation of those components in the entire system. For example, the affects of microgravity on the following processes and components need to be understood, such as pressure, temperature and volume control in accumulator, heat transfer in miniature high heat flux cold plates or evaporators, and heat transfer in two-phase space radiators. But from a system perspective, identifying the overall limits to system stability when several of these units are interacting in microgravity becomes crucial. Finally, both in order to collect data and control system performance, reliable and accurate instrumentation, especially for monitoring flow and phase distributions/void fractions are needed.

The problems and issues associated with the cabin and space suit, thermal and humidity control were deemed to be of a severely limiting nature by the panel. Basic and applied engineering research is needed for heat exchangers equipped with both inertial and non-inertial (passive) phase separators. Air entrainment, condensation in presence of non-condensable gases, and fouling due to suspended particulates and/or biological organisms were found to be important phenomena affecting the operation of both inertial and membrane condensing heat exchangers. Development of efficient gas traps and filters are necessary to increase the reliability of existing condensing heat exchangers and the effects of contact angle, capillarity, and wicking must be understood and exploited in design of future passive separators.

Adequate in-flight data for separation and transport from the cabin atmosphere is not available. Thus presently, correlations from ground testing are being extended for microgravity analysis through use of limited and inadequate flight air quality and humidity condensate loading data. Knowledge of multiphase transport and microgravity effects on the mass transfer coefficient in two-phase flow streams of condensing heat exchangers is necessary to understand the phenomena and develop more reliable predictive computational tools to aid the engineers in the future design and flight operations.

Astronaut thermal management will require development and optimization of efficient miniature two-phase flow loops and micro encapsulated thermal phase change foam material to provide a tailored heating and cooling capability that is integrated with the overall garment ventilation system. Thus data and analysis for two-phase flow in micro- channels and conduits with complicated geometries may be needed.

The problems and issues associated with normal and cryogenic liquid storage systems and accumulators were also judged to be severely limiting in nature. In this area system stability, effect of gravity on ventless pressure control systems, phase change, phase separation, and phase positioning through application of external forces such as magnetic fields is of prime interest and, again, in need of both basic and applied research.

Finally, latent heat thermal energy storage units will still be an attractive means for space energy storage. The effect of gravity and natural convection on the melting/solidification process is well understood. Existing numerical models can be used to optimize the variable gravity performances. But degradation of performance due to continuous cycling is a main concern.

5.4.5 Recommendations

A number of interesting and intricate scientific and engineering issues need to be addressed in order to accelerate the rate of progress in the design and development of thermal and phase change subsystems for future advanced human support technologies. However, precise and detailed definition of research topics and definitive prioritization of the research areas is not an easy task. This is mainly due to lack of concrete mission scenarios, multiplicity of technology choices, and vagueness of system requirements. Thus, the breakout group spent a good portion of its time prioritizing the research areas based on how they will aid the implementation of overall engineering strategies and how they might satisfy generalized and top-level system requirements. In the future, more precise identification of the engineering systems and their respective components will undoubtedly allow for a greater definition and a more precise prioritization of the specific microgravity issues.

5.4.5.1 High Priority (Critical and Severely Limiting Issues)

- Attainment of phenomenological understanding and accumulation of empirical data for: two-phase flow in complicated micro- and macro- geometries; boiling and condensation heat transfer; and phase-distribution and phase-transition phenomena, in microgravity.

- Development of empirical correlations, theoretical models, scaling laws, and comprehensive CFD codes for: two-phase flow in complicated geometries; boiling and condensation heat transfer; and phase distribution and phase transition phenomena in microgravity.
- Development of stability criteria for two-phase heat transfer loops in microgravity.
- Development of advanced, efficient, reliable, low cost, and compact gas-liquid, solid-liquid, and solid-gas phase separation technologies for operation in variable gravity.
 - Microgravity and variable gravity experiments
 - CFD models
- Development of advanced, efficient, and reliable vapor compression heat pump technology.
- Investigation of gravitational effects and transport mechanisms for two-phase flow in porous media.
 - Suction effects in shear-driven films
 - Shear-Driven flow of droplets
 - Wetting/Contact effects
- Development of reliable and low cost ventless dynamic pressure control mechanisms for liquid storage tanks and design of stable two-phase accumulators.

5.4.5.2 Moderate Priority (Limiting and Enhancements Issues)

- Transport phenomena and surface effects controlling biological and particulate fouling in microgravity
- Wicking and capillary flows
- Cryocoolers
- Liquid acquisition devices
- Phase positioning and phase management through external fields
- Heat transfer in miniature high heat flux cold plates or evaporators
- Heat transfer in two-phase space radiators
- Variable gravity latent heat thermal storage performance
- Gas traps and filters

5.4.6 Conclusion

Future missions for exploration of the solar system will require enabling technologies for efficient and reliable energy generation, storage, and transfer that involve integration of several different engineering subsystems depending on mission definitions and mission strategies. Currently, many of the thermal subsystems involve single-phase fluid and heat transfer processes; but the need for improved energy-to-mass ratios and the availability of spacecraft in future that will generate large quantities of power and waste energy such as the nuclear-based ones is urging a shift towards two-phase operations. Consequently, the design of important thermal subsystems for future applications as in boilers, condensers, evaporators, heat exchangers, phase separators, normal and cryogenic fluid storage units, fuel cells, radiators, and heat pipes will all involve complex multiphase fluid flow and transport issues. Microgravity data and engineering correlations for these applications are very scarce. Therefore, there is a real and immediate need for both basic research and engineering development in this area that can only be accomplished through joint and intimate collaboration and cooperation between the

microgravity and the AHST communities in the government laboratories, academia, and private industries. Precise and detailed definition of the pertinent research topics and definitive prioritization of the research areas is not an easy task because of lack of concrete mission scenarios, multiplicity of technology choices, and unclear system requirements. Consequently, definition and prioritization of the research topics described above evolved during the course of the workshop based on the breakout group's current understanding of the future mission scenarios.

5.4.7 Recommendation to NASA on Future Direction

The envisioned future collaborations between the microgravity science community and their AHST counterparts can be classified into three categories:

1. Basic Research- three to four year research effort to lay the scientific foundation for future state-of-the-art engineering work.
2. Problem Solving- one to six month projects to trouble-shoot an existing engineering problem or obstacle.
3. Advising- one to six day service on technology panels, workshops, etc.

In the first category, the scientist serves as a basic researcher, in the second as an engineering consultant, and in the third as a technical advisor. While the issues and requirements for collaborative work in the second and third categories are clear, specific, and well defined, the issues and requirements for the first category are hard to pinpoint. A great deal of the scarce and valuable time of every workshop is spent trying to identify the pertinent engineering areas for future basic research. This is mainly because distant engineering goals and requirements are vague and unclear at the onset of the workshop due to: uncertainties in the future missions and technologies, lack of industry representation in areas of technical expertise, and lack of NASA technical expertise and input to guide the identification and prioritization process.

The group members were of the opinion that the situation can be greatly improved if there is continuous and systematic cross-fertilization between different members of the two communities before and after the workshops. Various forums can be used to connect the AHST /Microgravity communities and the NASA/Academic/Industry groups. Some of the recommendations are as follows:

- Maintain directories of scientists and engineers, their contact information, disciplines and specialty areas, current research and publications, Task Book reference number, websites etc.
- Hold panels and symposia at respective discipline conferences.
 - Involve the microgravity community early in technology development, such as concept development, Phase A/B reviews and Preliminary Design Reviews (PDRs).
 - Stimulate new areas of application-oriented scientific inquiry and collaboration between the AHST and microgravity communities in identifying future technological needs.
- Conduct periodic follow-on teleconferences, meetings, and workshops.
- Provide collaborative NASA Research Announcement (NRA) programs.
- Instigate and encourage collaborative technology development:
 - Rapid Technology Development Teams
 - Collaboration with technology development projects at HQ and Field Centers
 - SBIR subtopics
- Initiate AHST Flight Programs (KC-135 opportunities with other flight experiments)

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APPENDIX A ACRONYM LIST

AEMC	Advanced Environmental Monitoring and Control
AHST	Advanced Human Support Technology
ALS	Advanced Life Support
AR	Atmosphere Revitalization
BR	Bioastronautics Research
CAMS	Central Atmospheric Monitoring System
CDRA	Carbon Dioxide Removal Assembly
CFD	Computational Fluid Dynamics
CMFD	Computational Multiphase Fluid Dynamic
CO ₂	Carbon Dioxide
CPR	Critical Path Roadmap
CTSD	Crew and Thermal Systems Division
ECLS	Environmental Control and Life Support
ECLSS	Environmental Control and Life Support System
EVA	Extra-Vehicular Activity
G	Gravity
GRC	Glenn Research Center
HEDS	Human Exploration and Development of Space
HQ	NASA Headquarters
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KRL	Knowledge Readiness Level
LAD	Liquid Acquisition Device
LEO	Low Earth Orbit
MCA	Major Constituent Analyzer
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
NCMR	National Center for Microgravity Research
NRA	NASA Research Announcement
NRC	National Research Council

APPENDIX A
ACRONYM LIST (CONTINUED)

O ₂	Oxygen
OBPR	Office of Biological and Physical Research
PCM	Phase Change Material
PDR	Preliminary Design Review
PSR	Physical Science Research
SBIR	Small Business Innovative Research
SCWO	Super Critical water Oxidation
SMAC	Spacecraft Maximum Allowable Concentrations
STS	Space Transportation System
SWM	Solid Waste Management
SWPRRW	Solid Waste Processing and Resource Recovery Workshop
TCCS	Trace Contaminant Control Subassembly
TRL	Technology Readiness Level
VCD	Vapor Compression Distillation

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APPENDIX C BREAKOUT GROUPS

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Kathleen Stebe

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**APPENDIX D
WORKSHOP AGENDA**

Monday, August 11, 2003

Ballroom BC, Sheraton Cleveland Airport Hotel			
4:30 PM	5:50 PM	Registration	
5:00 PM	5:55 PM	<i>Dinner</i>	
6:00 PM	6:05 PM	Welcome, Objectives of Workshop	Bhim Singh, Darrell Jan
6:05 PM	6:15 PM	Vision and Charter	Jitendra Joshi, Iwan Alexander
6:15 PM	6:45 PM	Microgravity Background A: Multiphase and Fine Particulate Flows	Brian Motil, Masami Nakagawa
6:45 PM	7:15 PM	AHST Background A: Water Reclamation and Air Revitalization Technologies	Jitendra Joshi
7:15 PM	7:45 PM	Microgravity Background B: Chemically Reacting Flows	Richard Axelbaum, Uday Hegde
7:45 PM	8:15 PM	AHST Background B: Solid Waste, Thermal Management, Monitoring	Dan Barta, Darrell Jan
8:15 PM	8:40 PM	Wrap up comments for Monday	Bhim Singh, Darrell Jan

**APPENDIX D
WORKSHOP AGENDA (CONTINUED)**

Tuesday, August 12, 2003

Ballroom BC, Sheraton Cleveland Airport Hotel			
8:15 AM	8:20 AM	<i>Logistics - NPRS</i>	Pauline Burgess
8:20 AM	8:50 AM	Case Studies: AHST 1: Water Processor	Michael Flynn
8:50 AM	9:20 AM	MicroG 1: Two-Phase Flow/Interfacial Phenomena	Mark McCreedy, Mark Weislogel
9:20 AM	9:35 AM	----- Break -----	
9:35 AM	10:05 AM	Case Studies: AHST 2: Major Constituent Analyzer (MCA)	Jay Perry
10:05 AM	10:35 AM	MicroG 2: Fluid Phenomena in MicroG	Richard Lahey
10:35 AM	11:05 AM	Panel Discussion	All
11:05 AM	11:35 AM	Charge to group, assignment to breakout groups	Jitendra Joshi
11:35 AM	12:35 PM	----- Lunch ----- Time Out Sports Bar	All
12:35 PM	2:35 PM	Breakout group meetings	All
Group #1: Air Revitalization Group #2: Solid Waste Management Group #3: Water Recovery Systems Group #4: Thermal Systems, Phase Change Processors			Stapleton LaGuardia O'Hare Dulles
2:35 PM	2:50 PM	----- Break -----	
2:50 PM	4:50 PM	Continue breakout groups	Darrell Jan, Bhim Singh, All
4:50 PM	5:05 PM	Assessment of status	Darrell Jan, Bhim Singh, All

**APPENDIX D
WORKSHOP AGENDA (CONTINUED)**

Wednesday, August 13, 2003

Ballroom BC, Sheraton Cleveland Airport Hotel			
8:30 AM	8:35 AM	LOGISTICS AND SURVEY - NPRS	Pauline Burgess
Group #1: Air Revitalization Group #2: Solid Waste Management Group #3: Water Recovery Systems Group #4: Thermal Systems, Phase Change Processors			Stapleton LaGuardia O'Hare Dulles
8:35 AM	10:05 AM	Breakout discussions continue	All
10:05 AM	10:20 AM	----- Break -----	
10:20 AM	11:50 AM	Breakouts prepare presentations	All
11:50 AM	12:50 PM	----- Lunch ----- Time Out Sports Bar	
Ballroom BC, Sheraton Cleveland Airport Hotel			
12:50 PM	1:15 PM	Breakout Presentation #1	Group #1
1:15 PM	1:40 PM	Breakout Presentation #2	Group #2
1:40 PM	2:05 PM	Breakout Presentation #3	Group #3
2:05 PM	2:25 PM	----- Break -----	
2:25 PM	2:50 PM	Breakout Presentation #4	Group #4
2:50 PM	3:50 PM	Conclusions	Darrell Jan, All

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13. ABSTRACT <i>(Maximum 200 words)</i> This workshop was designed to bring the experts from the Advanced Human Support Technologies communities together to identify the most pressing and fruitful areas of research where success hinges on collaborative research between the two communities. Thus an effort was made to bring together experts in both advanced human support technologies and microgravity fluids, transport and reaction processes. Expertise was drawn from academia, national laboratories, and the federal government. The intent was to bring about a thorough exchange of ideas and develop recommendations to address the significant open design and operation issues for human support systems that are affected by fluid physics, transport and reaction processes. This report provides a summary of key discussions, findings, and recommendations.			
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