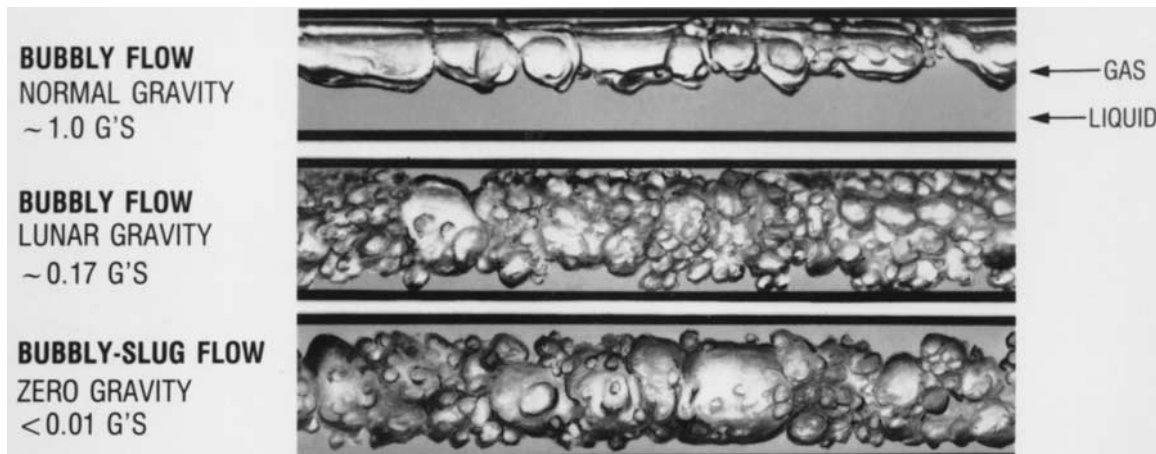


Results of the Workshop on Two-Phase Flow, Fluid Stability and Dynamics: Issues in Power, Propulsion, and Advanced Life Support Systems

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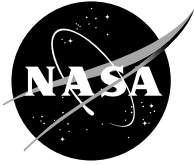
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EXECUTIVE SUMMARY

The Two-phase Flow, Fluid Stability and Dynamics Workshop was held on May 15, 2003 in Cleveland, Ohio to define a coherent scientific research plan and roadmap that addresses the multiphase fluid problems associated with NASA's technology development program. The workshop participants, from academia, industry and government, prioritized various multiphase issues and generated a research plan and roadmap to resolve them. This report presents a prioritization of the various multiphase flow and fluid stability phenomena related primarily to power, propulsion, fluid and thermal management and advanced life support; and a plan to address these issues in a logical and timely fashion using analysis, ground-based and space-flight experiments.

Issues were identified from previous workshops⁷⁻⁹, a NRC study report⁵ and studies on similar topics and some consultations with members of the scientific/technical community. Science and engineering issues were examined from the standpoint of not only trying to build the necessary design and operations tools and methods, but also to bolster the confidence of the technical and program management community by verifying that these systems will function satisfactorily and predictably in space. These issues were prioritized into four categories as "Critical," "Severely-Limiting," "Enhancements," and "Awareness."

A plan to resolve these issues in a logical order, using ISS and other space-based experiment facilities, ground-based facilities and modeling, is proposed.

Issues deemed "critical" are primarily two-phase instability mechanisms that could be substantially different in space than on earth, namely, phase separation distribution and control; parallel flow instability; density wave oscillations; two-phase accumulator behavior; system stability under various gravity environments; critical heat flux under transient flow and heating conditions and recovery from heater dryout; contact line dynamics; thermal fluid management; and scaling both experimental data and analysis to full-scale systems.

Issues deemed "severely-limiting" included spray cooling; steady-state flow boiling critical heat flux; the impact of noncondensable gases; two-phase flow through tees, manifolds, packed bed reactors; filling and emptying containers, including a large mass fluid management experiment; disconnected capillary surfaces; and removing individual bubbles from liquids.

This plan is being provided to the Office of Biological and Physical Research to guide their strategic research initiative subject to review by appropriate advisory committees and the NASA Headquarters management.

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INTRODUCTION

Recently, NASA commissioned two strategic planning exercises. The first exercise was a blue ribbon panel of external scientists to prioritize research aboard the International Space Station (ISS). This panel was chartered by the NASA Advisory Council as the Research Maximization and Prioritization (ReMAP)¹ Task Force. Initially, they were limited to prioritizing ISS research only; however, they later expanded their charter to include prioritizing of all space-flight and ground-based research. Research was prioritized based on whether the research task was either enabling human exploration of space or basic research of intrinsic scientific interest.

The task force designated the following topical areas within the Office of Biological and Physical Research (OBPR) as Priority 1, the top priority. Within the research program for the Advanced Human Support Technology Division, the topics of Advanced Environmental Monitoring and Control and Advanced Life Support were deemed to be critical, especially with regards to enabling human exploration. Within the research program for the Physical Sciences Division, both Fundamental Microgravity Research and Engineering Research Enabling Exploration were designated as critical. These areas have elements of multiphase flow, boiling and capillary phenomena.

In addition to the ReMaP Task force, a group has been chartered by the Space Architect's Office as the NASA Exploration Team (NExT) to study various missions over the next several decades and the technology that will be required to undertake and complete these missions. In one presentation², system requirements were identified based on the technology required to achieve some of these missions. These are listed in the Table 1:

Table 1: Projected Technology Development Goals

Technology Need	Now and 2010	2020	2030
Maximum Single Launch Mass	40 Metric Tons	100 Metric Tons	100+ metric tons
Specific Impulse	> 1000 s	> 3000 s	> 3000 s
Launch Costs			< \$2k/kg
Power Systems Mass	>200w/kg	>500w/kg	Sustainable power systems
Maximum Power Available	75 kW		Multi-mW
Air	Closed Loop	Closed Loop	Closed Loop
Water	Closed Loop	Closed Loop	Closed Loop
Food	Bring your own Lunch	Options to Grow	Sustainable Cycle

Figure 1 depicts the estimated mass savings for a Mars exploration mission in terms of the weight of the International Space Station. The estimated savings from implementing these improvements in total system mass is in excess of 80 %.

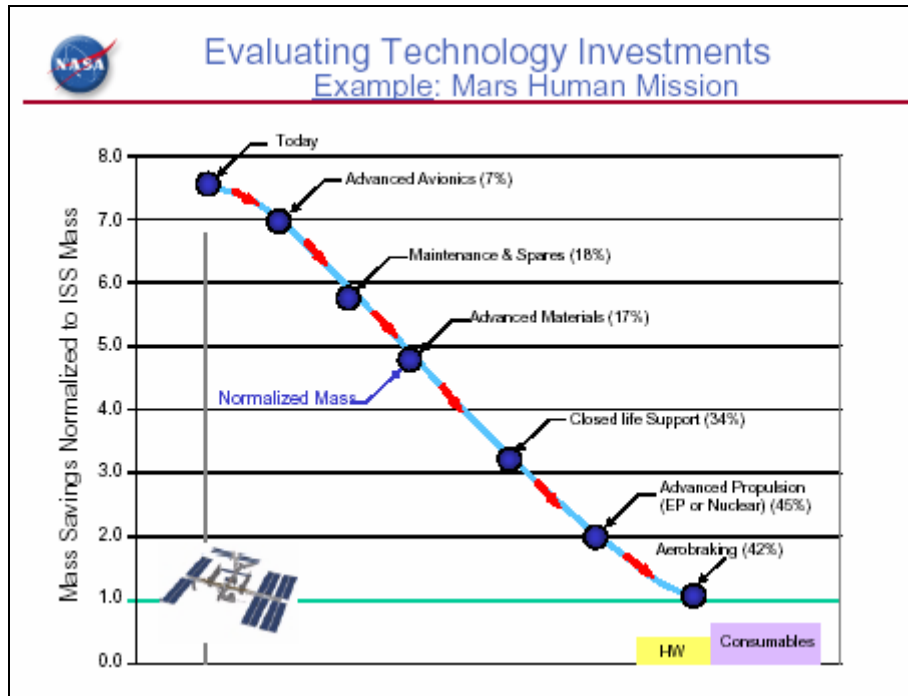


Figure 1: Estimated vehicle mass savings as a function of system improvements.

Table 2: Goals for Advanced Power Technologies

Fuel Cells	20,000 hr. life Greater than 400 Whr/kg
Photovoltaics	30% efficiency 300W/kg Large, deployable structures
Energy Conversion	> than 20-percent dynamic conversion > than 15-percent static conversion
Power Management	> than 2,000 V (dc/ac) distribution and control
Reactors	> than 25 W/kg (system level) - 10's of kW > than 100 W/kg (system level) - multi-mW systems

Independent of these two efforts, NASA developed its own technology plan³. It determined that the power requirements may range from 20 kW for a typical lunar exploration base, to 50 kW for a typical Mars surface exploration base, and into the multi-megawatt (MW) range for propulsion systems of interplanetary spacecraft. The multi-megawatt power levels would be required for the “thrust” phase of the mission, while a few hundred kilowatts would be required for the “coast” and “orbital” phase of the mission.

NASA’s long range plan is to use nuclear power for propulsion and power, to explore the outer planets on both manned and unmanned missions. Besides the development of new systems and technologies, there is a need to significantly increase the capability and reliability of existing systems. In order to enable this exploration, Two-phase and capillary flow behavior are integral within both critical and severely limiting technologies required for power, propulsion, life support, and environmental control systems.

WORKSHOP GOALS AND METHODOLOGY

The immediate goal of this workshop was to develop a coherent scientific and technical “roadmap” and research plan for strategic research within the Office of Biological and Physical Research. This roadmap provides guiding principles for the Office of Biological and Physical Research to effectively and efficiently utilize its resources in the development of new hardware, selection of investigations and manifesting opportunities aboard ISS to answer key questions to enable multiphase-based advanced technologies for exploration.

The workshop undertook the following tasks:

1. Review and modify a prioritized listing of the significant open design and operation issues for two-phase flow, fluid stability and dynamics in power, propulsion, thermal and fluid management, and human support systems.
2. Review and modify a road map that identifies the plan of resolution via space-flight experiment, ground-based microgravity testing, normal gravity testing, computer modeling and/or analysis.
3. Assess the Two-Phase Flow Facility (T ϕ FFy) and Contact Line Dynamics Experiment (CLiDE) facility to achieve a significant portion of strategic research identified within this plan.
4. Identify other critical experimental facilities or tests that can not be conducted within the T ϕ FFy and CLiDE.

The ultimate goal is to develop a predictive framework and methodologies for multiphase parameters (e.g., pressure drop, heat transfer coefficients, critical heat flux, proper treatment of capillary-controlled and wettability-controlled interfacial systems, etc.) that would be made available to the designers of the space-based systems in the form of formulas, correlations, or software codes.

Over the last 20 years, there have been several similar workshops, conferences and studies that discussed the challenges facing the development of both existing and new technologies for space exploration. A representative list includes the following:

- The Workshop on the Commercialization of Space Fluid Management⁴,
- Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies⁵,
- Workshop on Two-Phase Fluid Behavior in a Space Environment⁶
- “Microgravity Fluid Management Symposium⁷,” NASA-CP-2465, NASA Lewis Research Center, 1986
- Workshop on Research Needs in Space Thermal Systems and Processes for Human Exploration of Space⁸
- Workshop on Research Needs In Fluids Management for the Human Exploration of Space⁹

Each of these workshops assembled a group of experts including scientists, design engineers, system operators, and customers to accomplish the following:

1. Brainstorm problems and issues that can prevent, inhibit or limit system performance
2. Prioritize problems in terms of criticality of the knowledge needed for safe and reliable system performance
3. Develop a roadmap or plan to thoroughly investigate the impact of these problems on system performance.

These workshops and reports were useful and were effective at the brainstorming, but it was not always possible to prioritize the problems and formulate a detailed plan or roadmap. However, the output of these prior efforts was used as a basis for developing the priorities and roadmap encompassed within this report.

In order to prioritize the vast list of issues, a hardware developer’s perspective was taken. It was determined where there are deficiencies in knowledge that needed to be satisfied, and a timeline was developed to correct these deficiencies.

The engineering and design technology questions were divided into three categories: Functionality, Changes in Operating Conditions, and System Stability. These are detailed further in Table 3.

Table 3: Engineering and Design Technology Questions

Functionality or “Will it Work?”	<ul style="list-style-type: none"> • Over what range of conditions? • What are its advantages over other means?
Changing Operating Conditions or “How does system respond to transients in set points?”	<ul style="list-style-type: none"> • How do I start it on a reliable basis? • How do I safely shut it down so I can restart it later? • How does the system respond to changes in operating conditions and set-points?
System Stability or “What can cause system instability?”	<ul style="list-style-type: none"> • What can cause it? • What sequence of events can cause it? • How do I identify its onset before it becomes severe? • How can the system recover from an unstable state? • What is the effect of the instability? • What sort of damage can result?

Technology issues were then ranked in terms of the following priorities:

- 1. Critical:** These technologies are enabling and if issues are not adequately solved, mitigated or addressed, the program or mission can’t achieve its objectives. As a result, the mission doesn’t go. There are no alternative technologies that can be used.
- 2. Severely Limiting:** This research is considered an enabling technology. There are alternative systems or technologies that can be used, but there is a steep price in terms of safety, reliability, system mass or cost.
- 3. Enhancements:** These are not enabling technologies, and such systems may even already be in use. However, further technology development can provide

significant increases in reliability, extended performance, or savings of mass or cost.

4. **Awareness:** There are design issues for which analyses, models, or other resolution methods already exist; yet, there has not been sufficient communication between research, design and operations communities. Resolution may be readily achievable without any further research.

There are multiple methods of resolution of two-phase flow and fluid dynamics and stability issues in microgravity. A listing of these methods and a short discussion are presented below:

Existing Space-Flight / Ground-Based Data: Despite the various issues with the behavior and control of Two-phases in reduced gravity, there have been several systems that have been built, tested and used in various space systems. These systems were usually built for functionality, not necessarily technology development. Consequently, because of weight and packaging concerns, there was limited instrumentation incorporated onto the space systems. Nonetheless, it may be possible to learn some useful information from such systems.

Analysis/Modeling: Several two-phase flow issues have been thoroughly investigated for their effect on system performance in normal gravity. Some, though not all, have aspects that should be gravity independent. For example, these include stability criteria for the pumped-loop instability and density wave oscillations. Unfortunately, some of these analyses have yet to be applied in the design of existing two-phase flow systems and could provide critical insight into the operation of low pressure drop systems.

Normal Gravity Testing: One tried, but not necessarily true, method is testing in normal gravity. This method is very cost effective when compared to any low-gravity based testing and it is possible to test using either a full-scale facsimile or the actual space flight hardware. Testing these systems at full-scale in normal gravity can generate a high degree of confidence, sometimes incorrectly, that these systems will function well in a variety of gravity levels with no problems. Unfortunately, testing in variety of orientations only changes the direction of the buoyancy force, not the magnitude of the buoyancy force unless other changes are made to the system. While not always applicable, one curious scientific note is that Jawardena et al.¹⁰, shows similarities between low gravity flows and capillary flows in normal gravity, especially in terms of flow regime mapping and definition. Great care must be taken to verify, especially at the system level, when applying normal gravity test results to predict low gravity functionality.

Ground-Based Reduced Gravity Testing: The use of drop towers and aircraft flying parabolic trajectories can provide from 2 to 20 seconds of low gravity ranging from 1×10^{-4} to 0.5 g's. While this is insufficient for most system level

tests, it is possible to conduct tests on component behavior and specific scientific phenomena.

Space-Flight Experiment: Long duration, high quality reduced gravity will be required to conduct system level tests. The Office of Biological and Physical Research can provide access to the Microgravity Science Glovebox (MSG), Express Racks and the Fluids Integrated Rack (FIR) on-board the International Space Station. These facilities have telemetry, and on the order of 1 kW of power plus 2 – 3 kW of heat rejection capability. Of course, with planning and coordination, it may be possible to utilize other platforms for conducting tests.

Ultimately, the system needs to be demonstrated and its performance verified under realistic conditions. The system needs to be tested against the full range of anticipated operating conditions and its responses to off-nominal situations needs to be assessed. This is an absolute necessity if any “new” technology is going to be incorporated. Program managers must deliver hardware that performs up to specifications, on budget, on time and will operate with minimal problems over an extended period of time. These managers want a high degree of confidence that the hardware will function with no problems. While scale model testing in microgravity and modeling/analysis can alleviate many concerns, the development of techniques to conduct full-scale normal-gravity testing that effectively mimics the microgravity performance and response of the system is one of the ultimate goals of this roadmap. It should be realized, though, that this is not always possible.

ISSUE PRIORITIZATION

1. Critical Issues

These technologies are enabling and if issues are not adequately solved, mitigated or addressed, the program or mission can’t achieve its objectives and can’t go. There are no alternative technologies that can be used.

1A. Phase Separation, distribution and control

Complete phase separation is not always achieved and distribution to the appropriate outlet and the control of the quality becomes critical. For example, liquid droplets in a vapor or gaseous medium can pit and erode turbine blades while gas bubbles in a liquid can cause similar problems.

Phase separation, distribution and control can be achieved through either “active” or “passive” means. Active separation often involves a centrifuge. The key issue is how the system responds to a condition where very large vapor or liquid slugs flow into the separator and exits in both output streams. Ultimately, it is necessary to determine the largest size and velocity of slug that can be accommodated before the separator is overwhelmed. Initial testing can be done using ground-based facilities.

Passive separation has relative benefits over centrifugal separation in the areas of power consumption, vibration levels, mass and/or volume. These devices also have fewer

moving parts, which should improve reliability. One drawback is that they tend to be susceptible to fouling.

Capillary devices have been used for years to acquire liquid propellant and minimize the amount of gas pressurant entering the system. These devices can be either screens, membranes or interior corners¹¹ and their operational principles should be fully understood and exploited. Furthermore, investigation the effects on alteration in surface wettability is needed.

A rough separation can also be achieved also using inertial forces, such as passive cyclonic devices, tees or manifolds. While the initial separation may not be complete, multiple stages of these or other similar devices with a two-phase recycle should be able to achieve complete separation.

While flow splitters such as tees and manifolds are susceptible to unequal phase distribution (a problem that can generate parallel flow instabilities) they can provide a first-stage separation device.

These techniques also have potential applications for fuel cells, the drainage of condensate in refrigerators and the collection of urine from proposed rat cages. Some of these techniques can be studied and refined using ground-based facilities, but long duration techniques ultimately will be required.

1B. System Stability

Besides knowing whether or not a system will work, it must respond “gracefully” to changes in operating conditions, and it must be able to operate in a stable manner. Because of the lack of data and opportunities to conduct meaningful low-gravity tests, instabilities that can only occur in reduced gravity should be ranked as critical and be thoroughly tested. These can be divided into two classifications: instabilities those occurring during transient operations and those that can occur during steady-state operation.

Transient operations are when the system operator makes a change in the desired operator state of the system, such as turning the systems on or adjusting flowrates. Steady-state instabilities can be defined as those instabilities that occur without the operator initiation or intervention because of problems with a combination of the system design and the governing physics.

System startup and shutdown and set-point changes are examples of critical transient operations. For most power and thermal management systems, sufficient liquid needs to be in both the pump and the evaporator section in order to generate the flow and remove the heat generated during the startup phases. For capillary-based systems, such as CPL’s (capillary pumped loops) and LHP’s (loop heat pipes), the evaporator is the pump, and dryout becomes catastrophic. Shutdown is also critical because the system must be able to restart. For example, in the case of capillary technology, a sufficient amount of liquid must be in the evaporator wick to ensure restart.

The issues with startup and shutdown not only pertain to entire thermal management systems, but also to parallel evaporators. It is crucial that, as components are needed, they are activated and sufficient coolant reaches them to provide adequate cooling without disrupting the conditions within the rest of the system through the diversion of coolant flow.

Changes in set-point operation can also affect the “balance” of a system. Propulsion systems will require power and thermal management systems that can handle megawatts of power during the thrust phase of a mission and hundreds of kilowatts during the coast or orbital phases. As a point of reference, when ISS has been completed, its power system will produce less than 100 kW.

Examples of steady-state instabilities that have significant potential for causing serious problems in microgravity include parallel flow channel instability, density wave oscillations, and phase accumulation.

Parallel channel flow instability has been identified as a problem in normal gravity. As flow enters a splitter, it can be mal-distributed resulting in insufficient flow through one of the parallel legs. For the case of parallel evaporators, insufficient liquid flow into the leg can result in dryout and burnout of that evaporator. Multiple normal gravity studies have shown that the flow and phase distribution are extremely dependent on the orientation of the tee run and sidearm with respect to gravity. Similar tests have been conducted in microgravity¹² and have also demonstrated a phase preference in distribution of the flow. Long-duration microgravity tests are necessary in order to obtain accurate data that will not be perturbed by multiple gravity levels associated with the ground-based facilities.

Density wave oscillations (DWO) are another instability phenomena in multiphase systems. DWO are caused by the transport delay of the void waves passing through adiabatic or diabatic channels, and the feedback-induced inlet velocity perturbations due to the pressure boundary conditions which are applied. Currently, there are no reliable microgravity data on DWO in parallel channel arrays or loops.

Phase accumulation within flow system components is another critical issue. There is concern that there would be a gradual preferential accumulation of either the gas or liquid, followed by a sudden release of that phase. The resulting slugging phenomenon has already been seen in expansions¹³ and in a packed-bed waste water biological reactor during tests conducted using ground-based low-gravity facilities. Because of the gradual phase accumulation, it is necessary to conduct testing using long-duration microgravity facilities, such as the ISS. In addition, manifolds, porous media (e.g., packed beds and soils), and wicking structures were identified as components that can accumulate and preferentially retain one phase over the other. This happens until some critical condition has been met and that phase is suddenly released into the system.

Two-phase flow stability issues will arise for systems operating in multiple gravity environments. For liquid storage, thruster operations can initiate mixing, resulting in changes in temperature profiles around tanks. This can cause significant changes in the evaporation rate and thus increase system pressures and/or alter the flow rates into and out of the tanks. Other transport issues such as Marangoni convection, free surface turbulence, and presence of noncondensable gases all affect the interfacial heat and mass transfer rates and therefore can play intricate and complicating roles.

In addition, launch vehicles encounter multiple gravity environments for “sustained” time periods. Typically, proton-exchange membrane (PEM) fuel cells are used to power the spacecraft and need to operate in normal gravity prior to launch, much greater than normal gravity during launch and/or landing phases of a mission, and microgravity once the vehicle is in space.

1C. Phase Change

The primary phase change concern is heater surface dryout that can occur during vaporization. The key parameter is the Critical Heat Flux (CHF) which occurs when nucleate boiling evolves into transitional boiling. While CHF can be avoided via design and operation during steady flows, transient and oscillating flows resulting from some other instability elevate CHF to a critical concern. The reason is that CHF is often the last step before failure of that particular leg of the flow loop. Critical heat flux prediction techniques under varying flow rate and heat flux conditions need to be developed and recovery methods need to be explored.

As recovery is attempted, while quenching the hot surface, massive amounts of vapor are generated as the liquid rewets the surface. The expanding vapor can easily entrain liquid and form an effective barrier against the liquid rewetting the hot surface. In normal gravity, buoyancy-driven instabilities can counterbalance the momentum of the vapor generation in rewetting the hot surface. However, in reduced gravity, buoyancy disappears as an effective means of surface rewetting, and rapid vapor generation may, therefore, inhibit significant cooling by the liquid.

Ultimately, the design of gravitationally-insensitive phase change components such as evaporators/condensers should be given a very high priority. The rationale is that if the performance of the component can be predicted and verified in normal gravity, then there is sufficient confidence that this performance can be extended into a low gravity environment.

1D. Contact Line Dynamics

The stability of free-surfaces is critical. It is well-known that free surface system stability is affected by contact line dynamics. However, of lesser certainty, is the ability to predict the proper contact angle at the free surface/solid junction (when the contact line location is not fixed) and to assess this uncertainty on fluid stability. Although it is apparent that the region next to a moving contact line contributes to system dissipation, experimental results often cannot be predicted by existing hydrodynamic theory. Additional complexity is introduced by the evaporation and/or condensation of working fluids.

This phenomenon is not only important to phase stability in accumulators but also in other components such as phase separators and microfluidic devices. Consequently, the effect of dynamic contact line on stability has to be resolved as part of the overall system stability. The times involved in free surface relaxation rule out drop towers; and the vibration levels in the aircraft are incompatible with the controlled g-environment needed for capillary surface studies. Studies on these systems, therefore, require long experiment times and thus long duration periods of microgravity.

Many applications having a lower priority rating in this document still need this critical information as an “input” in order to satisfactorily predict the contact line behavior.

1E. Container Thermal/Fluid Management

Long term storage of subcritical cryogenic fluids with or without venting is needed in order to minimize loss of cryogenic liquids which not only serve as propellant, but also as a volumetrically-efficient means of storing vital fluids for fuel cells and for life support. Tank pressure control can be achieved via thermal vent systems (TVS) and other innovative means such as the synergetic application of cryocoolers and forced mixing jets.

1F. Scaling

Most of the planned facilities for satisfying the issues identified within this plan are severely hampered by the size, mass and power levels available within ISS and the ground-based low gravity platforms. Furthermore, certain working fluids, such as cryogenics and liquid metals, pose significant safety hazards to personnel and difficulties in usage. Predictive capabilities, both computational and analytical, need to be developed to extend relatively small scale experimental results towards practical full-scale systems. These capabilities should be developed for both the component and system level and need to account for size, fluid properties, power levels and the acceleration environment. To validate these models, they need to be verified experimentally and modified, per those experimental results, accordingly.

2. Severely Limiting

This research is considered an enabling technology. There are alternative systems or technologies that can be used, but at a steep price in terms of safety, reliability, system mass or cost.

2A. Phase Change

Almost all of the low gravity boiling studies, especially the long duration studies, have focused on pool boiling. There have been some flow boiling studies on the effect of the direction of the gravity vector on the boiling process, but these studies cannot assess the effect of the lack of buoyancy-driven phase positioning and the effect of shear, especially when compared against the Marangoni convection. Both long-duration space-flight experiments and ground-based low-gravity studies can assist the understanding of these phase change issues. However, limitations exist based on system volume and power availability not only to pump the test fluid, but to heat sub-cooled liquid and initiate the

phase change. These limitations are much more severe for space-flight experiments than for ground-based low-gravity experiments.

Critical heat flux under both pool and steady flow boiling conditions can provide some baseline data for transient flow and heating conditions. Several microgravity pool boiling experiments have already found evidence that the low-gravity CHF value for pool boiling is lower than that in normal gravity. To date, the amount of low gravity flow boiling CHF and heat transfer coefficient data from surfaces, other than perhaps wires, is nonexistent. Yet, many power and thermal management systems are envisioned with flow through evaporators. While there are techniques to enhance the CHF, such as surfactants¹⁴, e-fields, and enhanced surfaces, these techniques have yet to be demonstrated on large-scale thermal management space systems. These techniques should be considered at the enhancement level, not the severely limiting level. Baseline flow boiling data is needed now.

Spray cooling is used in a variety of high-power-density cooling applications for quenching the hot surface. Typically, only 15 -20% of the liquid mass is vaporized. The high liquid mass flux is used to provide sufficient vapor removal from the hot surface. In terrestrial applications, gravity plays a significant role in removal of both the liquid and vapor from the heater surface; therefore, it is anticipated that the conversion of liquid to vapor will be substantially reduced in a microgravity environment. An additional problem with spray cooling is the fluid management after the jet or spray has impacted the hot surface and has “rebounded” off of it. Both the vapor and the liquid must be removed and collected in order to permit additional coolant to impact the heater and to enable recycling of the coolant.

Experiments focusing on condensation, primarily the drainage of liquid condensate films at low shear conditions, should be conducted. Measurement of the condensation heat transfer coefficient is also required.

The presence of noncondensable gases within the two-phase systems can diminish system performance. Noncondensables tend to accumulate in the vapor condensation portion of a power or thermal management system. It can, not only, reduce the condensation heat transfer coefficient by establishing a concentration boundary layer but can periodically surge into the rest of the flow loop and be source of additional system instabilities. While quantification of the effect of noncondensable gases on the system performance still needs to be ascertained, the primary goal should be the isolation and removal of noncondensable gases.

2B. Flow through Components

Understanding of flow through splitting/combining components (e.g. tees), through porous media, and into and out of accumulators has a higher priority than understanding flow through tubes, expansions, contractions, valves, and bends.

Tees and manifolds are used to both split and combine the flow. As mentioned earlier, one critical issue is the channel instability as tees and manifolds distribute the flow to the

parallel channels. Understanding two-phase flow behavior is critical in flow splitting as it cannot be assumed that either flow and phase distributions will be equal among the exit legs. Flow combining is of interest due to the compressibility of the gas or vapor phase. Here, slugging can develop in the exit leg since the gas can be “held back” as the liquid passes into the system.

Multiphase reactors are one of the most widely studied areas of chemical reaction engineering. Currently, there are no chemical reaction data related to mass transfer studies for two-phase systems in microgravity. Most studies have been limited to hydrodynamics or have been hampered by hydrodynamic instabilities. Advanced life support systems require knowledge of the mass transfer from solid wall to the liquid and gas phases. In some instances, the flow is actually three-phase as the solids are suspended within the fluid.

Three-phase (gas-liquid-solid) reactors can provide high throughputs, compact design, operational flexibility, relative simplicity in both design and operation, and minimal power consumption. In almost every analysis or design, the most important parameters, and arguably the most difficult to predict, are related to the hydrodynamic flow of the phases. In fact, reactor classifications are generally based on the hydrodynamics. The many advantages of the packed bed reactor (PBR) make it an excellent candidate in support of long-duration human space activities in reduced or zero gravity. Unfortunately, two of the more common modes of operation (trickle and countercurrent flow) cannot be used in microgravity since, in those modes, the motion of one phase is driven by gravity. Other modes, such as pulse flow, may actually have a higher interaction between phases in low or zero gravity.

Technologies that may use PBR units include extraction of oxygen and hydrogen from lunar or Martian soil; bioprocessing of waste water; gas-liquid catalytic reactors such as the Sabatier reaction used to process methane and water from carbon dioxide and hydrogen; the flow of water and air through soil to sustain plant growth; phase separators; and fuel cell diffusers. The design and scale-up of equipment to carry out these processes requires a fundamental understanding of the transport processes involved.

Relevant experiments should initially be conducted in ground-based low-gravity facilities and focus on mass and heat transfer and preferential flow channeling. Because of the longer time scales involved in porous media (much greater than open media) long-duration reduced gravity experiments should be identified to examine not only long term behavior for heat and mass transfer, but also the effect of the packed bed on system stability.

Accumulators are used to maintain a system at constant pressure by providing volumes to accept or dispense fluid. Changes in density, either associated with temperature or phase change, need to be accommodated. Accumulators may be of fixed or variable volume (e.g., bellows, diaphragms or bladders). They may or may not have wick structures. Temperature control can be one means of setting the accumulator pressure, especially for volatile working fluids.

The chief issue is the placement of the accumulator within the system and its effect on system stability. The orientation of the accumulator with respect to the tee (attached either to the sidearm or run) could play a significant role in determining which phase preferentially fills the accumulator. Finally, many of the microgravity sloshing, phase positioning and mass gauging issues are similar between tanks and accumulators, but the time-scale of input and output of fluids tends to be much shorter for accumulators than tanks.

Multiphase pumps have been baselined for several different systems. Some designers for power, thermal management and various life support systems have incorporated such a pump within their systems. The desired operating parameters, working fluids, system temperatures and pressures, and flow rates, are significantly different from system to system. In some cases, the pumps separate the phases into two outlet streams: one that is mostly, if not all liquid and the other is mostly, if not all, gas. For some systems, the pump is expected to operate as a single phase pump, but be “tolerant” of the presence of the second phase by maintaining prime or recovering easily from prime loss. While most constant displacement pumps can be considered to be multiphase pumps, the pump weight and power consumption must be reduced while the reliability and lifetime is increased.

2C. Filling and Emptying Containers

There is a need for an overall enhancement of filling efficiencies and expulsion rates for transferring fluids into and out of storage tanks, containers and accumulators.

For liquid flows exiting tanks, it is necessary to preclude gas ingestion in liquid acquisition ports. Liquid Acquisition Devices (LAD's) use capillary forces to provide liquid outlets and have been used reliably for years. While there are efforts to reduce the mass of both LAD's and a startup bucket within propellant tanks, one focus should also be to increase the flow rates through the LAD. There are some applications though, whereby it is not possible to use LAD technology due to tank configuration, materials problems, etc. Also LAD's can prevent the complete emptying of supply tanks by retaining a residual amount of the fluid.

As tanks are filled, it is also necessary to either prevent or control flash evaporation. Evaporation of the storage fluid can significantly increase the tank back pressure thus slowing the filling process. It is necessary to minimize the venting so that the fluid/liquid loss is reduced.

Mass gauging is required to determine the mass of fluid present in a container in space. Currently differences in the forces required to achieve different satellite rotation rates are used to calculate the mass of the spacecraft, and thus the liquid within the spacecraft. This method requires the additional expenditure of propellant. Mass gauging information via another means is crucial for efficient and safe maneuvering of the spacecraft.

2D. Disconnected Capillary Surfaces

Stability dynamics of disconnected capillary surfaces: a singly connected fluid body may contain disconnected fluid-fluid interfaces, as in the case of a tank with two separate orifices open to the air. Recent work has shown that the stability conditions for multiple, disconnected free surfaces attached to a single fluid body are markedly different from the conventional, 1-free-surface case and is the source of the phase accumulation problem within PBR.

2E. Phase Separation: Bubble Removal

For several specific applications, an active technique is required to remove bubbles from a liquid. This is crucial for example in a tissue growth bioreactor where gas bubbles will literally kill the tissue culture and stop the usefulness of the experiment. Bubble positioning and removal are necessary if there are no means to prevent the bubble from being introduced into the medium in the first place.

2F. Large Mass Fluid Management

In order to utilize the large-mass spacecraft needed for long duration missions, a full-scale experiment is required to examine the issues of fluid sloshing. While contact line dynamics have been successfully applied to smaller scale tanks and experiments, there has been no experimental verification of the behavior on a large scale.

3. Enhancements

These are not enabling technologies, and such systems may even already be in use. However, further technology development can provide significant increases in reliability, extended performance, or savings of mass or cost.

3A. Capillary System Instabilities

Much work has been done already for the microgravity tanking problems of sloshing. More work still can be done in the area of dynamic control of phase distributions and liquid placement through application of external forces such as magnetic and electric fields. The effects of these external fields on contact line dynamics are not well understood and require further clarification. Very little has been done regarding vibrations on two-phase accumulators where contact with the wall by the two-phase mixture may result in pressure surges and temperature swings as liquid contacts hot, dry walls. Contact line dynamics appears in these problems; however the relevant regimes have not received attention in the past.

Slow capillary driven flow (i.e. wicking) are strictly two-phase flows at low Capillary and Reynolds number, Essentially, a train of gas-liquid slugs moves slowly through a small capillary tube, or is slow two-phase flow distributed through a porous medium. It is expected that the flow is not substantially different in normal or microgravity, however, distribution effects of fluid into and out of such a component may be affected.

3B. Phase Change

Interfacial area and the flow adjacent to that area is affected by the free surface turbulence, which in turn, affects the interfacial heat and mass transfer. In microgravity, the lack of buoyancy-driven shear has been found to promote coalescence and could alter the behavior anticipated for pressure control within storage tanks and accumulators.

Models should account for thermal stratification and convection in heat pipes and containers.

Overboard dump lines must perform reliably under wide ranges of thermal environments. Due to the Joule-Thompson effect, fluid dumped overboard to space may freeze and halt the continued flow. Current methods involve preheating the effluent stream to reduce the mass that is frozen; however, more efficient means can possibly be developed.

3C. Sloshing & Vibration

Further investigation of the possibility of affecting fluid motion through surface wettability alterations is needed. It is also necessary to extend the parametric range of liquid spreading models for the dynamic contact angle beyond the current steady, zero-inertia, low-Capillary number limit.

For near-term applications these issues are enhancements. However, for the large-mass spacecraft needed for long-duration missions, these issues become severely-limiting

3D. Liquid Positioning

In addition to liquid acquisition devices (LAD's), impulsive and magnetic methods can be developed as a non-intrusive means to position liquid in a manner to minimize gas entrainment while expelling liquid from a tank.

3E. Long-Term Material Property Evolution

The change of material properties of solids and fluids over long periods of time can change the wetting and other transport characteristics within the system. These property changes should be characterized over long periods of time, so that predictive modeling of system performance is successful.

4. Awareness

There are design issues for which analyses, models, or other resolution methods already exist; yet, there has not been sufficient communication between research, design and operations communities. Resolution may be readily achievable without any further research.

4A. Normal gravity instability issues applicable to microgravity

There are several normal gravity instabilities that are problematic to systems that operate in reduced gravity. For the most part, the analyses, and the mechanisms, of these problems appear to be gravity independent. Thus, these problems are solvable through analysis and awareness.

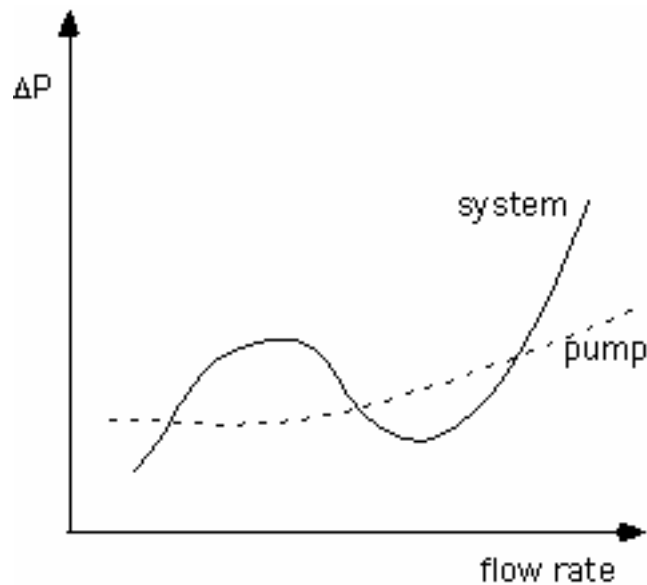


Figure 2: Mass Flow Rate for a Two-Phase System vs. Pressure Drop with Pump Curve Overlays

- The flow excursion or “Ledinegg” type instability occurs because of the nature of the pump curve and the two-phase system’s pressure drop. The system’s pressure drop is generated by the flow through the system’s components such as valves, bends, boilers, straight tubing and other fittings. In Figure 2, the pressure drop vs. the mass flow rate is plotted.
- Pressure drop instabilities result from an accumulator’s response to control pressure fluctuations at a pump’s exit. Depending on the timeliness of the accumulator’s response, this may cause an undershoot or overshoot of the system pressure loss vs. mass flow rate curve.

4B. G-jitter issues

CFD analysis has been used to assess the effect of g-jitter on phase distributions in propellant storage tanks and should be applied to accumulators. Within this context, more robust two-phase CFD codes and efficient numerical algorithms capable of predicting phase locations and phase distributions under variety of environmental conditions and applied external forces are needed. .

4C. Flow through Specific Components

Most scientific studies have limited the study of two-phase flow to flow through straight conduit and generic changes in conduit geometry such as bends, expansions, contractions, and tees. Specific components, e.g., valves, have not been examined because of the wide variety of configurations. One concern is the pressure drop across the valve. The real problem involves high-pressure-drop induced problems such as flashing and/or cavitation, and the opening and shutting of these valves. The valve tortuosity, orifice size; and flow coefficient can be well-defined for single-phase flows and can be translated into acceptable performance characteristics for two-phase flows.

There is also a wide variety of mechanical pump types. Most single-phase pumps should not generally have two-phase flow problems; however, centrifugal pumps can deprime due to cavitation. In reduced gravity, there is no hydrostatic head, so relying on the pump being at the lowest level to re-establish priming is meaningless. Some pumps, such as positive displacement pumps, can better tolerate the presence of two-phases.

RESEARCH PLAN

Based on the prioritization and the availability and appropriateness of the various low-gravity facilities, a plan was developed for extensive flight and ground-based experimentation and associated modeling that supports fundamental engineering (not necessarily science). In addition to the strategic research, OBPR plans to continue ongoing and additional fundamental science driven research in this area. The latter is expected to provide synergistic support for the strategic research. The integrated strategic, fundamental, experimental and modeling approaches will provide a cost-effective and expedient way to meet the needs of the exploration technology developers in a timely manner.

For example, analyses have already been developed for Ledinegg type instability, which is known to exist in normal gravity and most likely in reduced gravity as well. These analyses can be applied both to avert potential problems in design of new hardware and applied to alleviate or control problems in existing systems. It may be possible to apply some of these analyses to CPL's and LHP's that are currently being used in thermal management systems. This can be accomplished by teaming researchers with hardware people to investigate currently operating systems and possibly allow researchers to add limited instrumentation to future systems to further some of these studies. Admittedly, the mass of proposed instrumentation, data bandwidth, the number of data acquisition system channels, and the program manager's desire to operate at normal conditions will limit the amount of research that can be accomplished.

This plan utilizes both existing or planned ISS and ground-based facilities as appropriate for experimental testing.

Objectives

The overall intent of this plan is as follows:

- Development of a “generic” two-phase database and predictive/simulation tools that can be used by space system designers. It would be worthwhile to develop a software package that assists in the design and evaluation of these systems. However, the code would need to be maintained and updated in the long-term. This would need a long-term commitment of resources.
- Methods for testing systems in normal gravity need to be identified, evaluated and developed with a high degree of confidence that these systems will function properly in a variety of gravity levels with no problems.

The OBPR’s strategic plan has been tailored to address several “guiding” questions that are related to the NASA mission. Among these questions are the following:

- “What technology must we create to enable the next explorers to go beyond where we have been?”
- “What new opportunities can our research bring to expand understanding of the laws of nature and enrich lives on Earth?”

To address the first question regarding research oriented towards the exploration of space, the specific objectives are:

- Improve performance and reliability of advanced life support system using two-phase technology. Two-phase technology is required for many life support systems including the management and processing of drinking and hygienic water; collection, processing and recovery of waste water; food management including production and storage; and environmental control such as temperature and humidity.
- Improve performance of gas/liquid/solid separation and mixing technologies for space and terrestrial applications.
- Enable efficient Packed Bed Reactors (PBR) operation in a micro- and hypo-gravity environment. PBR technology is used in many common chemical and biological processes such as the Sabatier reaction to produce oxygen and in the treatment of wastewater.
- Enable development of reliable power systems for space power and nuclear electric propulsion through improved understanding of reduced gravity effects on phase change and on multiphase systems. Two-phase technology is required in relatively low power production (portable fuel cells) as well as very large systems (nuclear-electric propulsion).
- Reduce mass and increase reliability of storage and management of propellant and other liquids (including cryogenic) in low-g.

The strategic research in power and propulsion for travel beyond LEO has the potential to provide significant return benefits to Earth. The advanced power systems developed can be used to provide reliable fuel cells. An improved understanding of two-phase systems for advanced life support can provide the additional benefits of increased productivity and efficiencies in chemical and biological process systems on earth. Examples include geothermal energy exploration, enhanced oil recovery, chemical and drying processes, and water and wastewater treatment.

Proposed Space Flight Experiment Hardware

The primary thrust for this plan is to develop design tools and fundamental understanding that are timely and consistent with the goal of the various exploration initiatives. The plan will utilize ISS facilities, such as the Fluids Integrated Rack (FIR) and the Microgravity Science Glovebox (MSG). A preliminary flow schematic of Two-Phase Flow Facility (T ϕ FFy) which would utilize FIR is shown in Figure 3. MSG can be utilized to use the Boiling eXperiment Facility (BXF) and Contact Line Dynamics Experiment (CLiDE) Facility (see Figure 4).

The T ϕ FFy system would have multiple test sections whereby different configurations of heat exchangers could be used to study boiling and condensation phenomena. The test

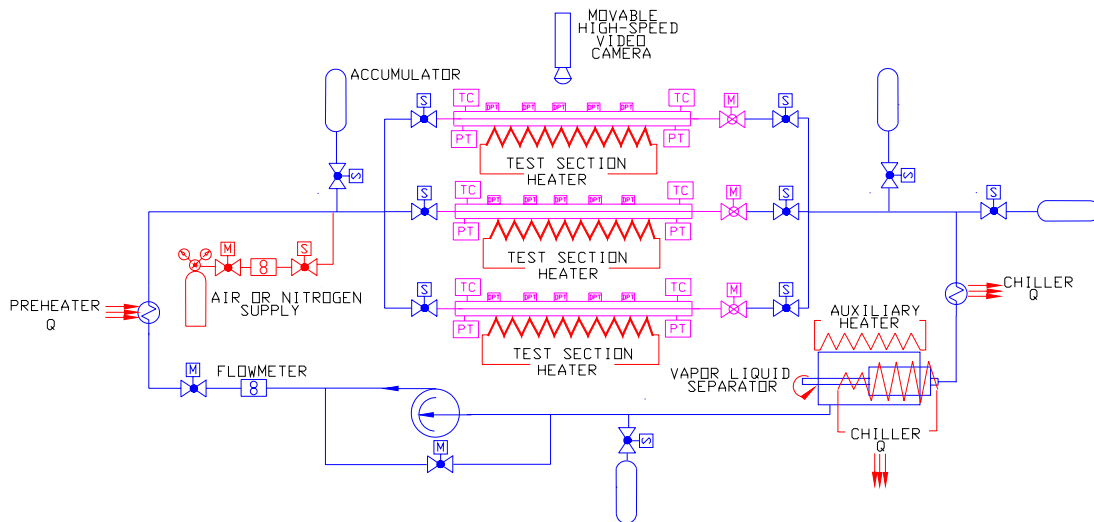


Figure 3: Proposed Flow Schematic for ISS Two-Phase Flow Experiment

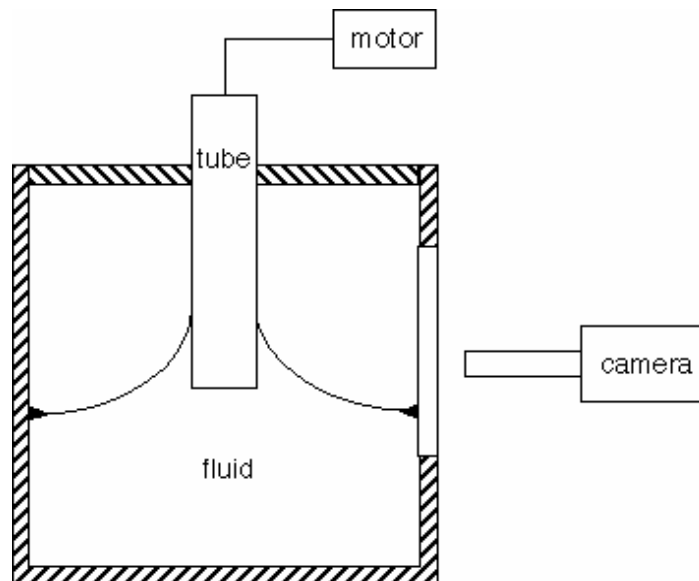


Figure 4: Schematic of Contact Line Dynamics Experiment (CLiDE) Facility

sections would be instrumented for pressure drop, void fraction, heat fluxes, temperatures, high-speed imaging and other diagnostics. Besides a high-speed data acquisition system with a large data storage capability, telemetry could be used to update control and test parameters and download limited amounts of data. In addition, there would be multiple accumulators that could be used to investigate system stability and fluid management issues. The system could accommodate adiabatic tests through either the space station nitrogen supply or have an experiment-specific compressor to pressurize a sufficient amount of air or other non-condensable gas for reuse as the supply bottle is depleted.

The general purpose CLiDE facility would allow for studies of effects of contact line dynamics on real systems of strategic importance. It would consist of a square cell with viewing windows. An axisymmetric fluid interface will form between a central cylinder (with a surface finish appropriate to the application) and a circular pin lip fitted to the walls. The cylinder may move into or out of the fluid to provide limited controlled dynamics. Temperature control of both the fluid and central tube will permit examination of evaporative and condensation effects on moving contact lines. A video camera (with microscope if needed) will capture the interface dynamics. Possible candidate systems include (but are not limited to) unsteady contact lines with significant inertia.(see Figure 4). This hardware requires minimal controls besides indexing the cylinder to the appropriate position in the fluid and filling the cell with the test liquid.

The following limitations would be imposed upon any space station experiment:

- ISS power availability is ~ 3kW, 2kW for rack system support and 1kW for pumping, separating and heating fluid.
- ISS heat rejection availability is about 3 kW for the rack, is single phase, with an inlet coolant temperature of about 20 deg C
- ISS volume constraints are about 1 x 1 x 0.5 m.
- Acceleration and vibration levels range from the micro (10^{-6}) to milligravity(10^{-3}) range.
- Fluid needs to be non-toxic
- Fluid needs to be triple-contained. Flow loop would count as only the first level of containment.
- ISS manifesting opportunities.

At least two flow loops would be constructed. One flow loop would be for testing aboard ISS. The second flow loop would be “similar” to the ISS experiment loop in terms of test sections and components but would have special modifications that would enable normal gravity and ground-based low-g testing, perhaps with either components, or the entire loop, at a variety of different orientations relative to gravity. This feature would allow for the development of normal gravity testing techniques that would build limited confidence in determining how the system and components might behave in reduced gravity.

Similarly, a ground-based CLiDE Facility of appropriate dimensions should be available for drop tower tests of limited scope.

Because of the limitations listed above, namely the volume and power constraints and the manifesting opportunities, the ground-based facilities can also provide answers to some of the previously-identified issues. These facilities can also provide a short-term intermediate low gravity environment (from 0.01 to 1.0 g's).

Since these exploration missions will be to planetary bodies other than earth, or normal, gravity, it will be necessary to conduct tests in long-duration partial gravity facilities. Other than the 2.5 m research centrifuge planned primarily for life science research aboard the ISS, there are no current plans for such a facility.

While modeling and scaled-down experiments can provide sufficient insight into the performance of space power and propulsion systems, it is necessary to conduct larger-scale and full-scale tests with the actual working fluids in order to boost the confidence in the predictive tools that have been developed. For example, a full-scale experiment on fluid management principles in reduced gravity using liquid cryogenes needs to be conducted in tanks of at 1 m³ of volume. Because of safety considerations, some of these experiments will require an expendable launch vehicle.

ROADMAP

Timeframe 2003-2008

Space Flight

- Design and build multi-user two-phase test facility for ISS to conduct experiments on:
 - Phase Change
 - Boiling-related research would focus on measuring the two phase heat transfer coefficients, and Critical Heat Flux (CHF), not only in the steady state flow and heating conditions, but also during transients. As part of the CHF research, study quenching/rewetting of dried out surfaces. Spray-cooling research for high heat flux applications should also be conducted.
 - Condensation-related research should be on the drainage of the liquid condensate, especially in low vapor-shear applications.
 - Two-phase instability phenomena
 - Experiments on parallel flow channels would focus on flow through multiple evaporating channels. The primary objective of these tests would be to study two-phase flow through some splitting manifold into the parallel channels. The “preheater” in Figure 2 would be expected to have sufficient capability to generate boiling, into at least the slug flow regime. The parallel channels could focus on different aspects of boiling.
 - Density wave oscillations (DWO) experiments would utilize control valves placed within the flow loop in order to induce and

respond to the passage of vapor and liquid slugs through the system.

- Phase accumulation experiments with regards to the behavior of accumulator with regards to its orientation to tees and other components.
- Long duration experiments on two-phase flow through components and porous media.
- Phase distribution, separation and control to assess the effectiveness vs. the design and operating parameters for both active and passive separation techniques. One type of experiments would include an assessment of the effect of slugging phenomena on at least one active separation device
- Begin scoping experiments aimed at determining suitability of surface modifications for optimizing damping in interface oscillations.
- Design and build multi-user facility to conduct experiments on contact line dynamics.
- Conduct the Microheater Array Boiling Experiment (MABE) and the Nucleate Pool Boiling Experiment (NPBX) in the Boiling eXperiment Facility (BXF)
- Conduct flight experiments to investigate pressure control in vented or unvented storage tanks..

Ground based

- Conduct ground-based low-g testing of a variety of components. These should include splitting and mixing tees and manifolds to determine their effects on phase distribution and in support of space-flight experiment on parallel channels.
- For phase change related phenomena:
 - Conduct appropriate ground based testing for rewetting/quenching of hot surfaces
 - Investigate the effects of wetting characteristics of a condensing surface on its heat transfer performance and determine how control of wetting properties can lead to enhanced heat transfer
 - Investigate the effectiveness of techniques to enhance heat transfer performance (heat transfer coefficient and CHF) using acoustic, electric field, surfactants and surface enhancement for 1-g and low-g
- For passive two-phase flow separation techniques:
 - Drainage of condensate with refrigerators from their "cold plates. "
 - Drainage of waste water, including urine from rat cages
 - Continue current investigation of bubble removal schemes for the tissue-growth bioreactor and other bubble/drop positioning techniques.
- Conduct ground-based 1-g and low-g hydro-dynamic and mass transfer experiments to provide flow characteristics of two-phase liquid-gas flow in Packed Bed Reactors over an extended range of conditions.

Other

- Modeling and scaling in the development of a two phase design and operator's manual

- Develop 3-D CFD predictive capabilities and verify the accuracy against existing reduced gravity data.
- Extend the 3-D CFD model to other flow regimes of interest in low gravity based on appropriate direct numerical simulations. Results will be used for the development of suitable closure laws for the CFD model.
- Develop predictive and mechanistic models for nucleate pool and flow boiling in low-g for the realistic parameter space of proposed space power systems (e.g., Rankine Cycle).
 - Including contributions of nucleation, bubble growth, bubble departure and rewetting in low-g
 - Use data from “designed” heater experiments on ISS using the Boiling eXperiment Facility (BXF) in MSG to validate the mechanistic models for boiling and heat transfer at the single bubble level
 - Evaluate the effectiveness of selected strategies (additives) in enhancing boiling and capillary performance to attain significant enhancement in heat transfer performance
- Evaluate current two-phase system designs for known and appropriate normal gravity instability mechanisms
- Extend predictive modeling capability for dynamic contact angle.
- Extend predictive models for tracking phase fronts and phase distributions and for interface and phase management through application of external fields.
- Develop rational correlations or models of contact line motion at higher Suratman, Reynolds and Capillary numbers with steady or unsteady motion (e.g., interface reorientation in large tanks)
- Implement proper dynamic contact line boundary conditions in conventional CFD formulations, and validate with experiments.
- Normal gravity testing
 - Design a suitably scaled test loop and characterize it during parametric experiments on earth in conjunction with ISS test loop.
 - Use the test loop to verify two-phase elements of the Rankine cycle with scalability to liquid metal conditions.
- Design and build a suitably scaled cell to study systematically interface reorientation upon a sudden g-change, in drop tower. Begin the experimental program..
- Develop passive capillary controlled low-mass tank configuration to control liquid-vapor interface position and maintain continuous liquid supply at the outlet (without gas ingestion) in low-g environments.
- Conduct ground-based experiments to determine wetting characteristics of solid-liquid combinations and strategies (additives) to modify/control the wetting and spreading
- Develop techniques for mass gauging (inventory management) for low-g

Timeframe 2009-2015

Space Flight

- Conduct experiments and test predictive tools on multi-user two-phase test facility on ISS for:
 - Parallel channel instability tests with parallel test sections that would be designed for a wide range of differences in flow rates.
 - Phase change experiments for various heater surfaces and configurations
 - CHF
 - Quenching
 - Spray cooling
 - Phase change experiments on condensation to determine condensation heat transfer coefficient in microgravity
 - Liquid-gas flows through porous media.
- Conduct research on liquid handling techniques and pressure control within accumulators and tanks to validate predictive models of contact line motion for higher Reynolds (Re) and Capillary (Ca) Numbers coupled with unsteady motion (sloshing in tanks), See next item.
- Acquire data for microscale motion near a contact line in low gravity to validate predictive models for parametric regimes of practical importance.
- Conduct a full scale experiment to test fluid management principles using liquid cryogenics in tanks of at 1 m³ of volume. This experiment will utilize an expendable launch vehicle.
- Define flight experiments for advanced phase separators concepts

Ground based

- Conduct advanced phase separator tests for a wide variety of concepts, including passive methods.
- Conduct scaled experiments using “exotic” materials and fluids such as those required for cryogenic and nuclear power applications.
- Electrical and electroacoustic manipulation of interfaces and fluids
- Conduct further low-g experiments to expand the applicable range and refine predictive models for boiling heat transfer and CHF validated over expected operating range to support the design of
 - Rankine cycle based power system for Nuclear Electric Propulsion.
 - Two-phase advanced thermal management technologies.
- Use bubble level analyses to develop a comprehensive analytical foundation for
 - positioning bubbles in normal and low-g and conduct microgravity experiments to validate the model
 - designing two phase separators and conduct microgravity tests to validate the model
- Conduct experiments for pool and flow boiling and CHF from surfaces of specified characteristics for low-g and normal-g to examine the effect of boiling enhancement techniques.

- Conduct experiments and extend predictive model capabilities to determine the effect of free surface turbulence and presence of noncondensable gases on phase change (evaporation and condensation).

Other

- Modeling and scaling in the development of a two phase design and operator's manual
 - Perform pretest predictions using the 3-D CFD code for experiments to be performed on the ISS.
 - Extend predictive models for pool and flow boiling and CHF from surfaces of specified characteristics for low-g and normal-g
 - Develop predictive models for contact line behavior in the presence of evaporation and condensation
 - Modify the 3-D CFD code, as required, to produce a combined comprehensive modeling effort for multiphase heat transfer and flow leading to user design code.
 - Perform a detailed verification and validation of the user design code.
 - Complete development of generalized models for design of propellant and liquid storage tanks for low-g operation
- Provide results from ISS experiments on liquid-gas flows in packed beds to closed loop ECLSS and ISRU designers
- Perform trade study of requirements vs. hardware design and performance for phase separation.
- Complete development of accurate fluid quantity gauging and liquid inventory management techniques/sensors for low-g operation

Timeframe 2016+

Space Flight

- Conduct large scale system technology demonstrations at relevant pressures, temperatures, and complex geometries to verify robustness of predictive techniques, tools, and scaling.

Ground based

- Conduct experiments for advanced phase separator operations concepts in a wide range of gravity levels including “microgravity,” lunar, Martian, normal and transitional that would be associated either the start of thrusting operations or the end of thrusting operations.

Other

- Thoroughly verify comprehensive computational techniques and incorporate them into either existing or new software packages.
- Use the new predictive framework for pool and flow boiling heat transfer coefficient and CHF and condensation heat transfer to design more efficient heat transfer equipment for terrestrial and space applications

- Provide rational design rules for systems control by wetting
- Provide validated dynamic contact line boundary conditions for higher Re and Ca , steady and unsteady flows, for use in computational modeling of realistic industrial and space-based processes
- Assemble results into two-phase design and operations manuals for space exploration and look into potential for software package development, either as a standalone package or as tools for existing packages.

PROGRAMMATIC RECOMMENDATIONS

Several participants were very concerned about the selection process for strategic research. While the scientific peer-review process has worked well in advancing the fundamental understanding of interfacial phenomena and multiphase flow, these participants felt that the focus of strategic research should be on development and specific technology needs rather than more general phenomenological topics. The research selection processes instituted by the Office of Naval Research Lab was mentioned as an example of outcome or technology-driven proposal selection.

APPENDIX A: WORKSHOP PRESENTATION: CHARGE TO THE PANELS

Why are we here?

- We have provided you a “strawman” Research Plan and Roadmap
- Review Priorities and Roadmap
- Provide Feedback
 - Does the plan make sense? If not, then let us change it so it does.
 - Will the proposed space-flight experimental facilities adequately address significant questions?
 - What other facilities & tests are needed to address critical and severely-limiting issues?
 - Are there any other elements missing in the plan?

12-May-2003

Overview - McQuillen

12

APPENDIX B: WORKSHOP PRESENTATION: REPORT ON MULTIPHASE FLOW PANEL

Discussion of Priorities

13-May-2003

1

Priority Ratings

- enabling technology if not solved, don't or can't go.
- **Severely Limiting** enabling technology but other systems can be used, but a steep price
- **Enhancements**
 - safety and reliability
 - weight savings
 - cost savings
- **Communication:** Analysis, modeling, existing resource awareness can overcome difficulties.

Method of Testing

- space-flight experiment (SF)
- ground-based reduced gravity testing (GB)
- normal gravity testing,
- analysis/modeling
- review of existing space-flight / ground-based data for its appropriateness.

13-May-2003

2

Critical Issues

Reduced Gravity Instabilities

- Flow/phase splitting through Parallel flow paths (system level)
- Phase Accumulation and release within Flow System Components
Transient Operations
 - Startup/Shutdown
 - Changes in Set Point Operation
 - Variable gravity over sustained time periods
 - 1 – g prior to launch & after landing
 - 1g during launch / landing
 - μ g, Martian, and Lunar
 - Variable gravity – sloshing

13-May-2003

3

Critical

- Phase separation, distribution and control
 - Control-- pick components, get in game
 - (not phase change part)
 - Take **best** tool, **best** data, design experiment to test (evaporator/condenser system) (one really **pertinent** example!)
- Critical heat flux in transient and oscillating flows (recovery)
Take **best** tool, **best** data, design experiment to test) (one really **pertinent** example!) Run transients
Evaporator/(not a system)
- Density wave oscillations in multiphase systems
Take **best** tool, **best** data, design experiment to test (evaporator/condenser system) (one really **pertinent** example!)
- Gravitationally insensitive evaporators/condensers
 - (same system)
- Scale-up
 - Do other scales (same idea)
 - Components

13-May-2003

4

Severely Limiting Phase Separation

- Active Separators based on Centrifugal concept. Unstable operations at flooding conditions
- *Multiphase (gas-liquid ?) pump*

13-May-2003

5

Severely-Limiting Phase Change

- CHF is not a problem unless some other instability initiates a flow interruption.
 - Recovery from dryout by quenching hot surface because of
 - Exceeding CHF due to other flow instability
 - Hydrodynamic rupture of liquid film at slow slugging/wave frequencies
 - High power density: Spray cooling.

13-May-2003

6

Severely Limiting

- Flow Splitting and Combining
- Packed Beds
 - Mass and Heat transfer coefficients
 - Phase Distribution and accumulation
- *Mass transfer in various systems*
- *Noncondensibles*

13-May-2003

7

Enhancements

Passive Phase Separation

- Inertial Driven
 - Cyclonic devices
 - Tees/manifolds

Phase Change

- Surface Enhancements
- Surfactants & Engineered Fluids

13-May-2003

8

Awareness Instabilities

Likely Problems in reduced gravity – Solve through Analysis and Awareness. Maybe look at existing data

- Ledinegg/Pumped Loop Instability
- Pressure Drop Oscillations
- Density Wave Oscillations

13-May-2003

9

Awareness

Phase Separation

- Bubble removal from rotating tanks through Needle suction

Flow Through Components

- Valves
- Pumps
 - Single phase – avoid cavitation

13-May-2003

10

Methods of Resolution

- ISS
 - Fluids Integrated Rack
 - Microgravity Science Glovebox
 - Express rack
 - other
- Ground-based Reduced Gravity Facilities
- Normal Gravity Testing and Modeling
- *Long duration partial/micro gravity*

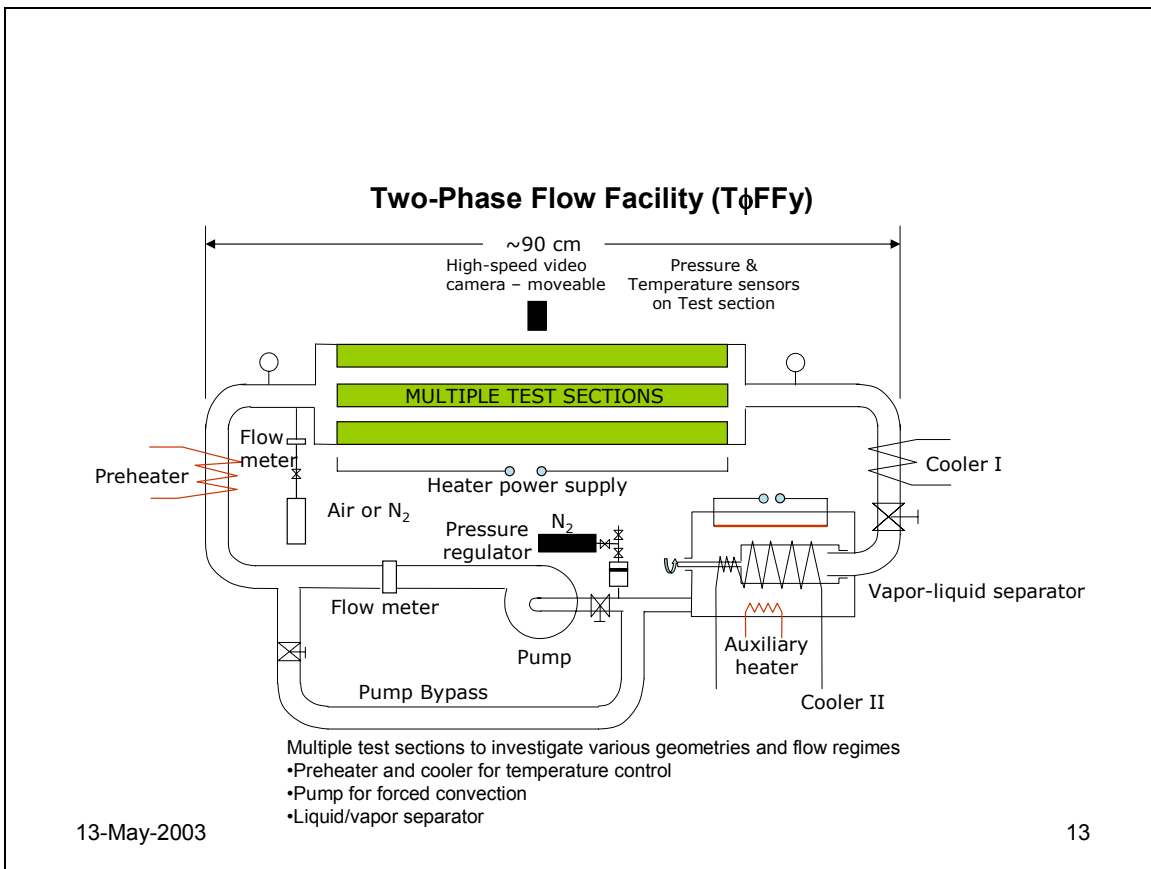
13-May-2003

11

- Liquid Supply
- Means of supplying vapor or gas
- Plumbing consisting of valves, tubing, accumulators, etc.
- Test article (s)
- Sensors – pressure, temperature, flowrate, *flow regime*
- Data Acquisition and Control System
- Ability to remotely change operational settings.
- Highly desired are Flow Visualization Sections, preferably high speed camera
- *Power, heat sink*
- *Ground control*

13-May-2003

12



- ## 2008 Space Flight
- Parallel flow channels with multiple evaporaters.
 - Flow through splitting manifold into the parallel channels
 - Parallel channels could focus on different aspects of boiling, namely critical heat flux and quenching,
 - Assess slugging phenomena on active separation device(s)
 - *Packed Bed hydrodynamic characterization*
- 13-May-2003 14

2003 – 2008

Ground – Based μ G Facilities

- Flow splitting and mixing tees and manifolds(airplane)
- Component separation (air-water, e.g., fuel cells)
- Cryogenic (??)
- Phase Change
 - determine wetting characteristics of solid-liquid combinations and strategies (additives) to modify/control the wetting and spreading.
 - Conduct testing for rewetting/quenching of hot surfaces
 - Investigate the effects of wetting characteristics of a condensing surface
- Passive two phase flow separation techniques
 - Drainage of condensate with refrigerators from their "cold plates. "
 - drainage of waste water, including urine from rat cages
 - continue bubble removal schemes for bioreactor
 - Propellants
- Initiate investigations of the effectiveness of techniques using acoustic, electric field, surfactants and surface enhancement for 1-g and low-g
- (To alleviate CHF problems)

13-May-2003

15

2003 – 2008

Other

- Evaluate current two-phase system designs for known and appropriate normal gravity instability mechanisms.
- Continue and complete development of mechanistic models for nucleate pool boiling
- Design tools/handbook
- Flow boiling

13-May-2003

16

2009 – 2015 Space Flight

- Continue parallel channel instability tests
- Demonstration/validation of scaling
- Conduct phase change experiments for CHF, Quenching & Spray cooling
- Conduct phase change experiments on condensation to determine condensation heat transfer coefficient in microgravity
- Conduct ISS experiments on liquid-gas flows in packed beds (mass transfer, reactions)

13-May-2003

17

2009 – 2015 Ground – Based μ G Facilities

- Conduct experiments for pool and flow boiling for the effect of boiling enhancement techniques.
- Conduct advanced phase separator tests for a wide variety of concepts, including passive methods.
- Exotic materials and fluids,
- Nuclear power components
- Setting up for the next grand and glorious project
- Electrical and electroacoustic manipulation of interfaces and fluids

13-May-2003

18

2009 – 2015 Other

- Bio power sources
- Nano-scale prototypes for power/etc
- Designed surfaces for heat transfer
- Combined comprehensive modeling effort for multiphase heat transfer and flow leading to user design code.

13-May-2003

19

2016 ++

- Space Flight
 - Phase change and heat transfer with exotic materials
 - High and low pressure and temperature experiments
 - Large scale system demonstrations
- Ground – Based μ G Facilities
 - Detailed verification of the comprehensive computation package.
- Other
 - two phase design and operations manuals
 - software package development?.

13-May-2003

20

APPENDIX C: WORKSHOP PRESENTATION: REPORT ON STABILITY AND DYNAMICS PANEL

Report of the Stability & Dynamics Session

Iwan Alexander
David Chato
Steven Collicott
Nihad Dadzic
Walter Duval
Steven Garoff
Gary Grayson

John Hochstein
Mo Kassemi
Emily Nelson
David Plachta
Enrique Rame
Lev Slobozhanin

Organized by NASA Glenn Research Center
Cleveland, Ohio
May 15, 2003

Plan for Session

1. Are issues in the Draft Document appropriate and complete?
2. Are the issues properly organized and prioritized?
3. Is the plan well defined and suitable?
4. Are the proposed facilities adequate?

Version 0.9

2

Are issues appropriate & complete?

In addition to present critique, document should be reviewed with respect to:

1. previous workshops
2. NRC Report
3. panel of current system designers

Version 0.9

3

Appropriate & Prioritized

Critical Issues

- Phase Accumulation within components (C,C)*
 - manifolds
 - porous media (i.e.. soils, packed beds)
 - wicking structures
- Contact Line Dynamics (C,C)
 - static & dynamic contact angle; values & fundamentals
 - in presence of evaporation, condensation
 - many lower priority applications need this information as an “input”

* First letter indicates priority in draft report,
Second letter is priority assigned by session participants.

Version 0.9

4

Appropriate & Prioritized

Critical Issues – cont'd

- Container Thermo/Fluid Management (L,C)
 - Pressure Control (i.e. TVS, cryocoolers, mixing & cooling times)

Limiting

- Phase Separation (L,L)
 - active & passive systems to separate phases
 - fuel cells
- Container filling & emptying (L,L)
 - preclude gas ingestion
 - flash evaporation

Version 0.9

5

Appropriate & Prioritized

Enhancement Issues

- Sloshing & Vibration
 - near-term applications
 - large mass spacecraft
- Phase Change (condensation, evaporation).
 - thermal stratification & convection in
Containers
Heat Pipes
- Liquid Positioning
 - LAD's, Impulsive, Magnetic

Version 0.9

6

Appropriate & Prioritized

Awareness Issues

- micro-g instability (A, A)
- Bubble Management (E,L)
 - strategic for both missions and experiments

Version 0.9

7

Additional Issues

Important issues not clearly addressed in draft document:

- Mass gauging
- Stability dynamics of disconnected capillary surfaces
- Slow capillary driven flow (i.e. wicking)
- Long-term material property evolution in micro-g

- Dumping – problem with freezing of dump lines

Version 0.9

8

Facilities

Critique of Proposed Facilities:

- proposed facilities do not well address the needs of container thermal/fluid experiments
- CLiDE is worthwhile
- Faster turnaround/easier access is crucial for improving productivity of research program

Version 0.9

9

Other Recommendations

- Review Panel composition and charge MUST clearly reflect the role of “Strategic Research”
- Roadmap development should focus on specific technology needs rather than more general phenomenological topics
- Verification & Validation of analytical and computational tools is crucial for reliable design. This will require planning and may require specialized experiments.

Version 0.9

10



**O
B
P
R**

Path to a Research Plan



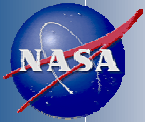
May 15, 2003
Fran Chiaromonte
(E. Trinh)
Code UG
NASA HQ





Cell Biotech, Macromolecular Biotech, Fluid Physics and Transport, Combustion and Chemical Reactions, Fundamental Physics, Materials Science and Engineering, Bioscience and Engineering, Biomolecular Systems



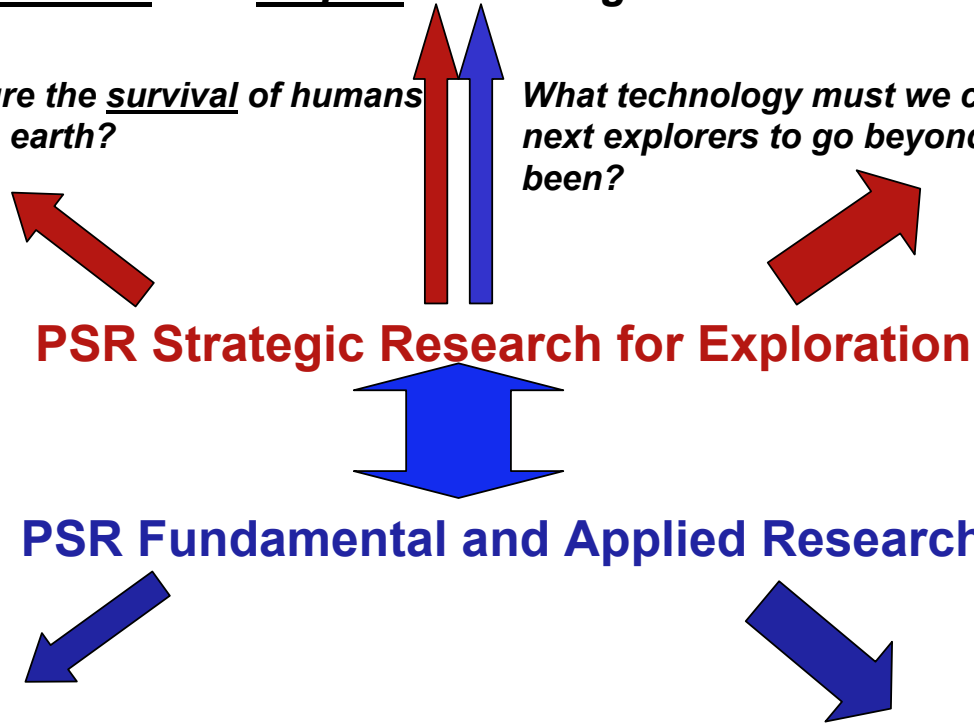


Physical Sciences Dual Thrust and the OBPR Organizing Questions

How can we educate and inspire the next generations to take the journey?

How can we assure the survival of humans traveling far from earth?

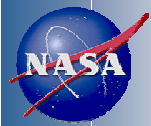
What technology must we create to enable the next explorers to go beyond where we have been?



What must we know about how space changes life forms, so that humankind will flourish?

What new opportunities can our research bring to expand understanding of the laws of nature and enrich lives on Earth ?





OBPR Physical Sciences Research Goals and Thrusts

Technology Roadmap

Research Plan

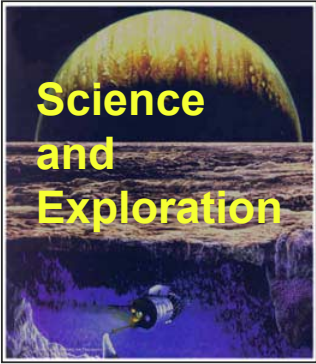
- Bioengineering
Biotechnology
Biomolecular
- Combustion
Fluids
Materials
- Low Temp
Atomic
Gravitational

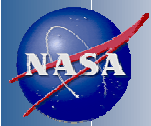
Strategic Research for Exploration

Research Theme 1
Research Theme 2

Fundamental & Applied Research

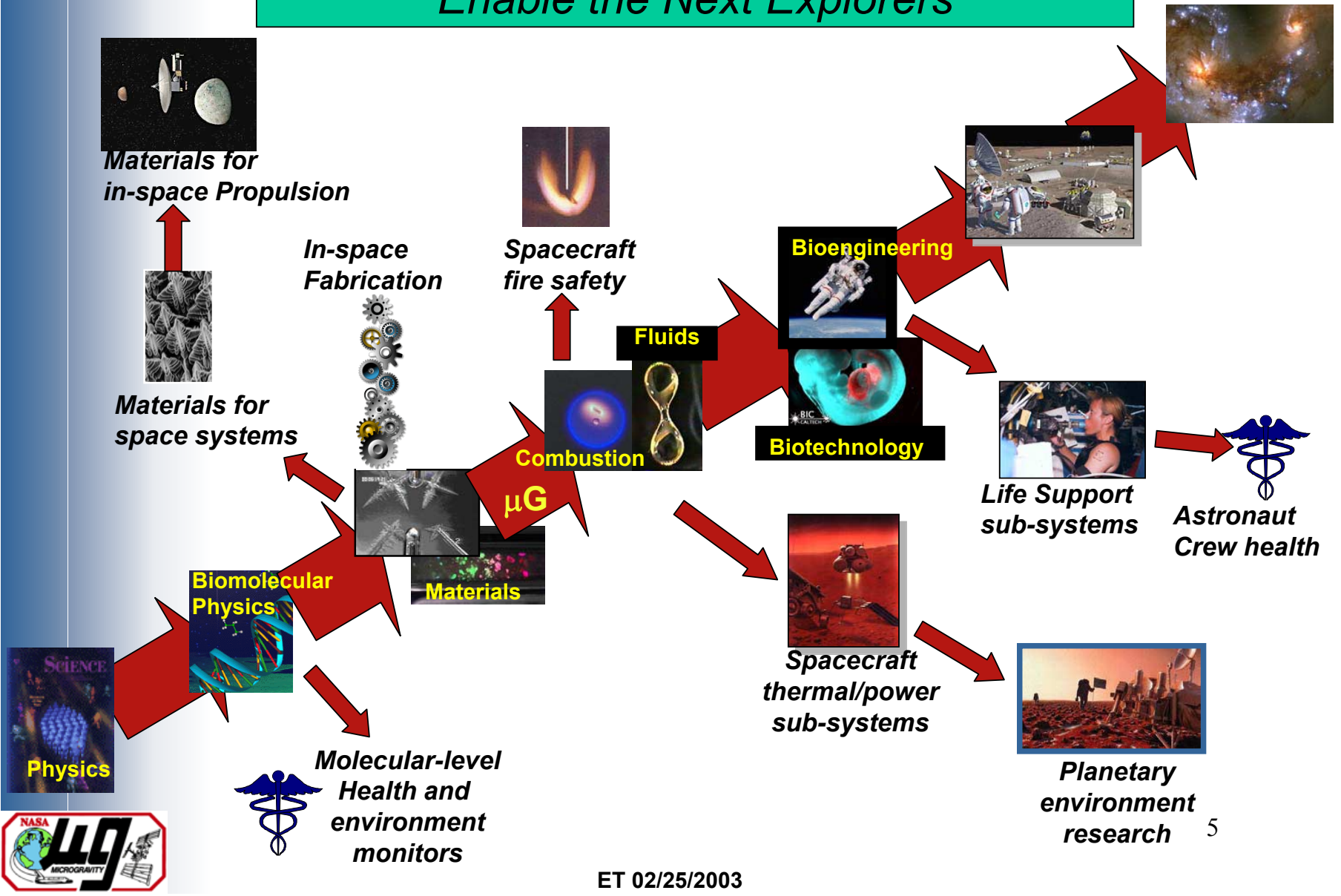
Research Theme 1
Research Theme 2
Research Theme 3
Research Theme 4





Strategic Research for Exploration

Enable the Next Explorers

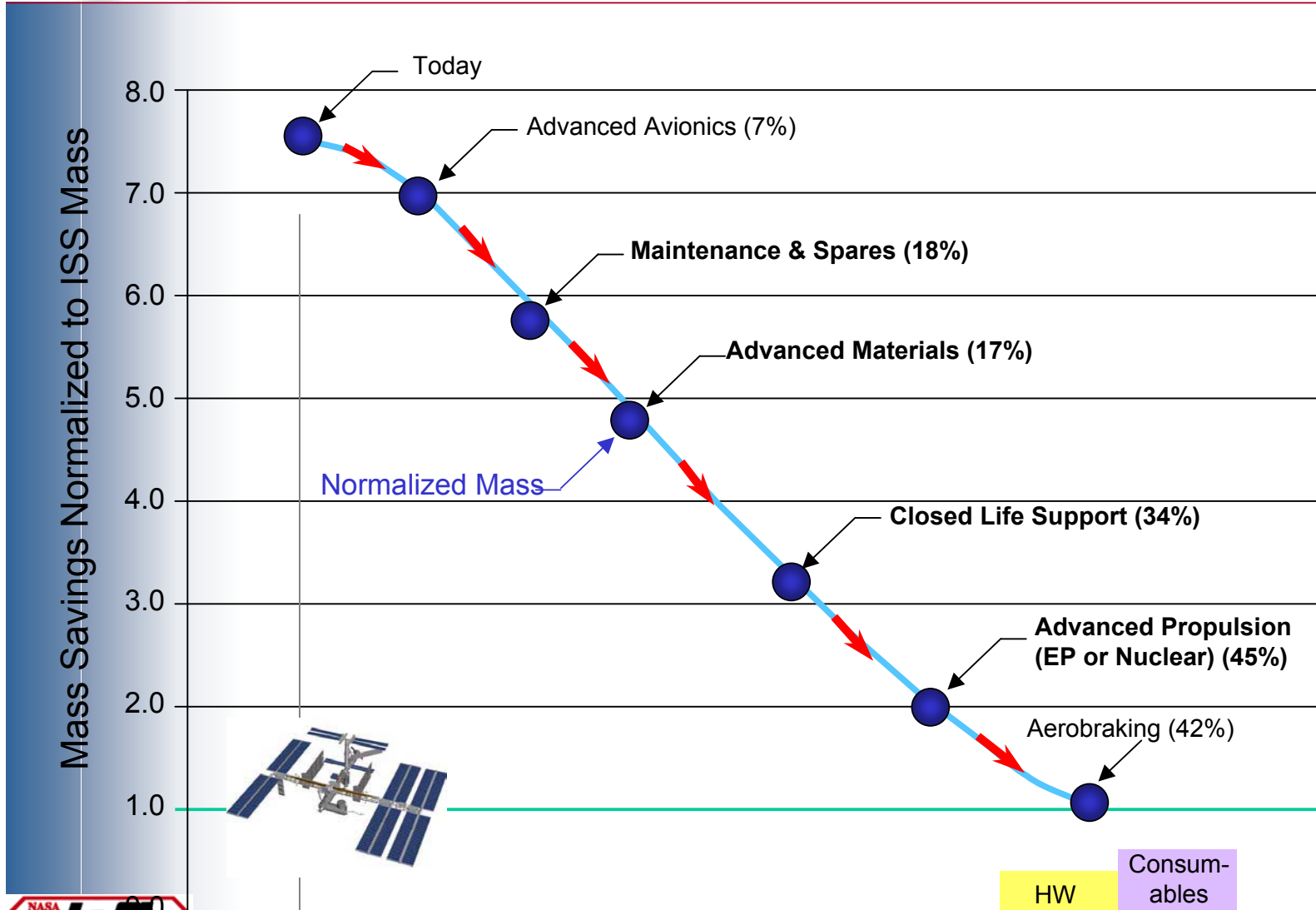


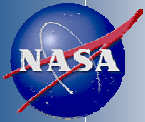
Molecular-level Health and environment monitors



Evaluating Technology Investments

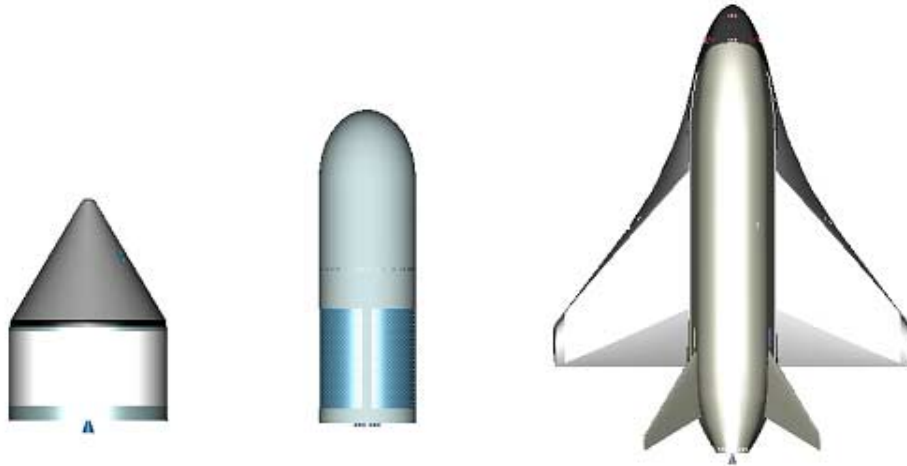
Example: Mars Human Mission





Orbital Space Plane Concepts

There is no preferred vehicle shape. Capsule; Lifting Body and Winged Vehicle are all being considered at this time. Must be able to launch on an Expendable Launch Vehicle.



Crew Transfer Vehicle (CTV) version will operate for about 5 days for a typical mission to ISS and back to Earth.

The Crew Rescue Vehicle (CRV) version could stay docked to ISS for up to 180 days, nominally, before returning to Earth.





Orbital Space Plane Overview

The Orbital Space Plane (OSP) is intended to provide crew and limited cargo access to and from the International Space Station (ISS).

Initially, NASA intends for development of the OSP to result in a crew rescue vehicle for the ISS, enabling a larger permanent crew to occupy the orbiting research facility and depart safely in the event of an emergency. This early version of the plane, expected to enter service within the decade, would be launched on top of an expendable rocket.

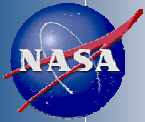
By 2012, the OSP will be used to ferry crew and light cargo to the ISS. In time, the project could become the foundation for a crew transfer vehicle routinely flown to space on a new launch vehicle.

Based largely on existing technologies, the OSP would provide safe, affordable access to the ISS.

The OSP Program is more than a spacecraft. The program will take an integrated systems approach to design the entire space transportation system — including ground operations, space vehicle and all supporting technologies needed to conduct a mission to and from the ISS.

In addition, flight demonstrators such as the X-37 vehicle will flight test advancing technologies to reduce the risk of future reusable launch vehicle systems including the OSP.

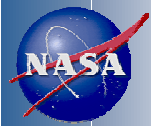




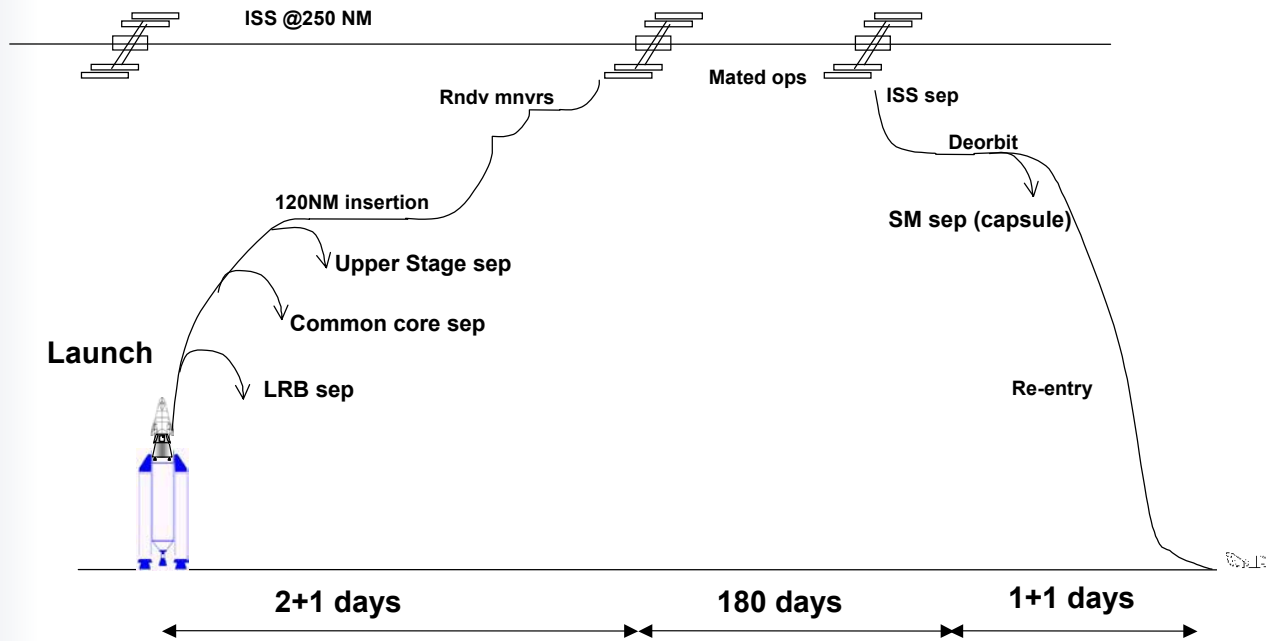
Priority List of Fluids Issues for OSP

1. ECLSS needs refrigeration that is reliable and uses less power than a thermoelectric device.
2. ECLSS needs to reject heat using a very small radiator space that is subjected to the launch pad environment (salt spray) and aerodynamic loads of ascent.
3. ECLSS needs a way to take dissolved gas out of Proton Exchange Membrane (PEM) fuel cell water to use for ECLSS reasons.

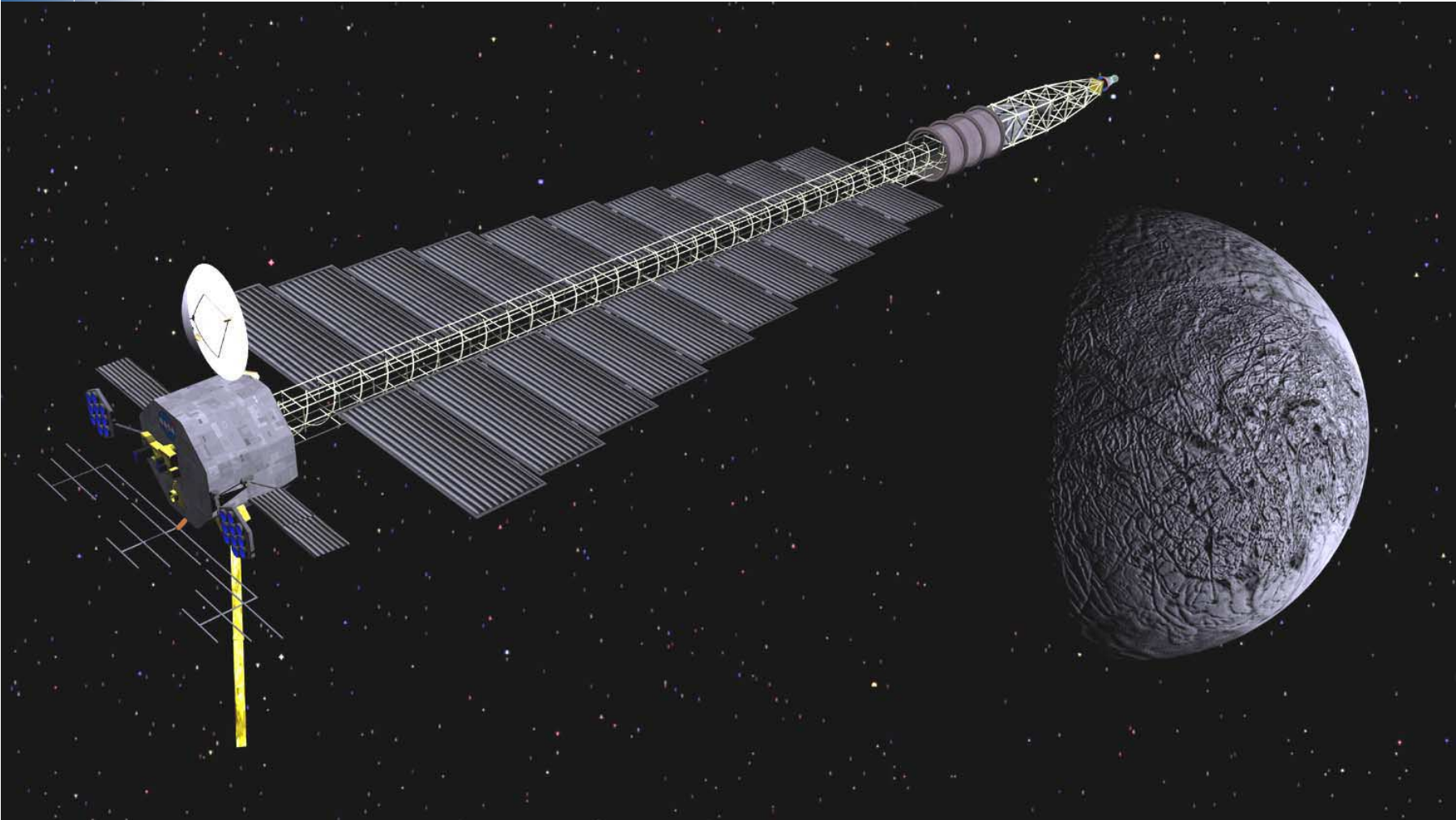




Typical Mission Profile



ET 02/25/2003



ET 02/25/2003

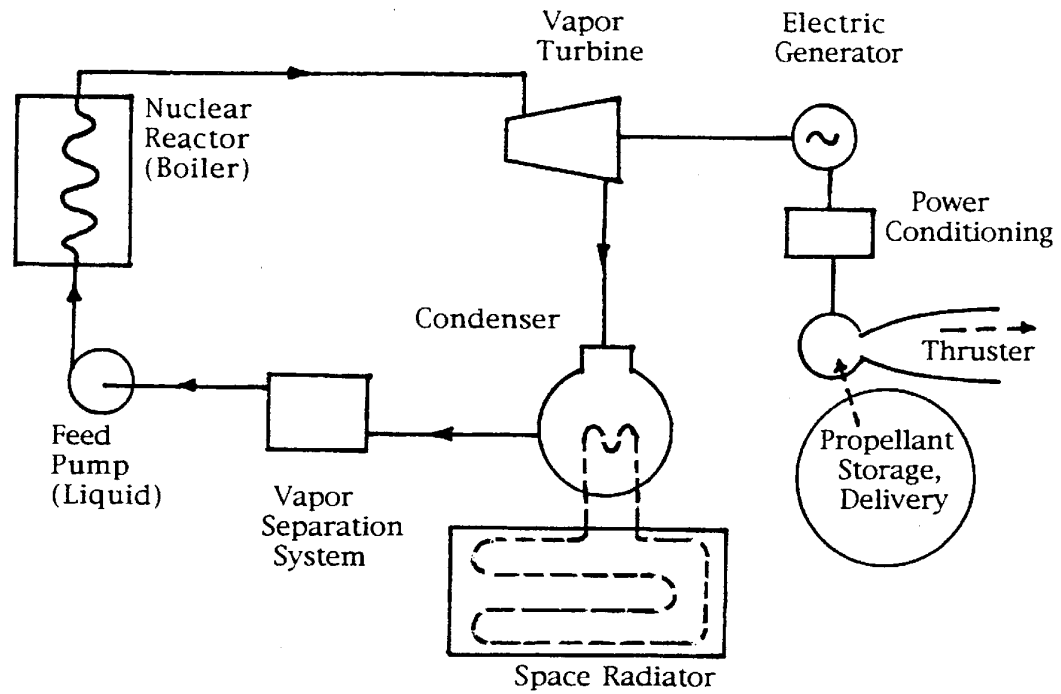
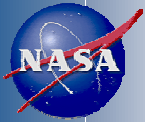


FIGURE III.B.3 Schematic showing major elements of a nuclear electric propulsion system.

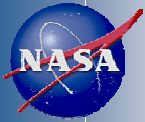




Physical Sciences Research (PSR) Program Status

- The OBPR Physical Sciences Research program has been comprehensively reviewed and endorsed by National Research Council. The value and need for the research have been re-affirmed
- The research program has been prioritized and resource re-allocations have been carried out through an OBPR-wide process. An increasing emphasis on strategic, mission-oriented research is planned. The program will strive to maintain a balance between strategic and fundamental research
- A feasible ISS flight research program fitting within the budgetary and ISS resource envelopes has been formulated for the near term (2003-2007). The current ISS research program will be significantly strengthened starting 2005 by using discipline dedicated research facility racks.
- A research re-planning effort has been initiated and will include active participation from the research community in the next few months. The research re-planning effort will poise PSR to increase ISS research utilization for a potential enhancement beyond ISS IP Core Complete
- The Physical Sciences research program readily integrates the cross-disciplinary requirements of the NASA and OBPR strategic objectives

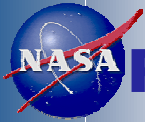




Physical Sciences Research and Technology Plan Development Process (cont.)

- **Each fundamental research thrust will develop a roadmap through technical workshops and Discipline Working Groups (DWGs)**
- **Most fundamental research thrusts will involve cross-disciplinary efforts**
- **A Technology Roadmap will guide the Strategic Research for Exploration thrust**
- **The Research Plan will integrate and coordinate fundamental Research Thrusts Roadmaps with the Technology Roadmap**
- **The Technology Roadmap will be developed in coordination with other OBPR programs as well as other Enterprise (R,S,M,N)**
- **International Partners will contribute to the roadmaps and through research coordination**
- **The research plan will be vetted with the discipline working groups, the BPRAC subcommittees, and with the BPRAC**
- **Recommendations from NRC past and current committees will be implemented whenever appropriate**





Physical Sciences Research and Technology Plan Development Process

- Proposed theme element content will be “missionized” around planned content and potential new projects (facilities, modules, initiatives) on approximately a five-year horizon, with the approval of PSRD management. Center/science working group teams will develop descriptions of “mission” objectives, value, and requirements. Purpose is to create a competitive environment for concept development and to stimulate community ownership/advocacy.
- Proposed theme elements reviewed and approved by PSRD management. Strawman roadmaps for themes developed. Program budget and technology requirements verified.
- Theme elements are prioritized with the input of advisory groups. Integration into program themes (questions) and required technology investments are defined by science and technology roadmaps. Review and assessment by OBPR management.

The effort this year will be a learning experience, and will produce a best-effort product as the precursor to the second-generation effort to begin next year.



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 - fuel cells
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Appropriate & Prioritized

Enhancement Issues

- Sloshing & Vibration (E)
 - near-term applications (E)
 - large mass spacecraft (L)
- Phase Change (condensation, evaporation). (E)
 - thermal stratification & convection in
Containers (L)
Heat Pipes (L)
- Liquid Positioning (L,L)
 - LAD's, Impulsive, Magnetic

Appropriate & Prioritized

Awareness Issues

- micro-g instability (A, A)
- Bubble Management (E,L)
 - strategic for both missions and experiments

Additional Issues

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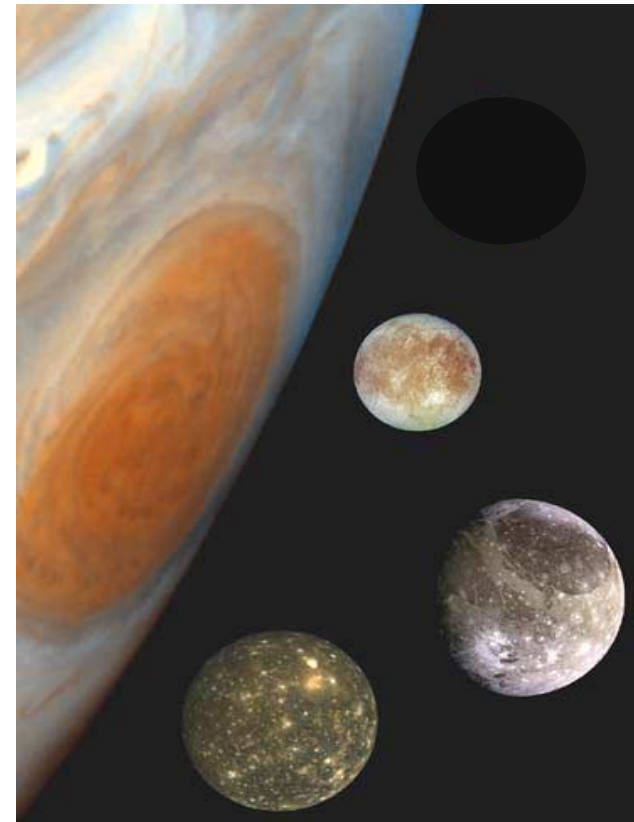


PROJECT PROMETHEUS

Two-Phase Flow, Fluid Stability and Dynamics Workshop

Steve Johnson
Power Implementation Manager

May 15, 2003



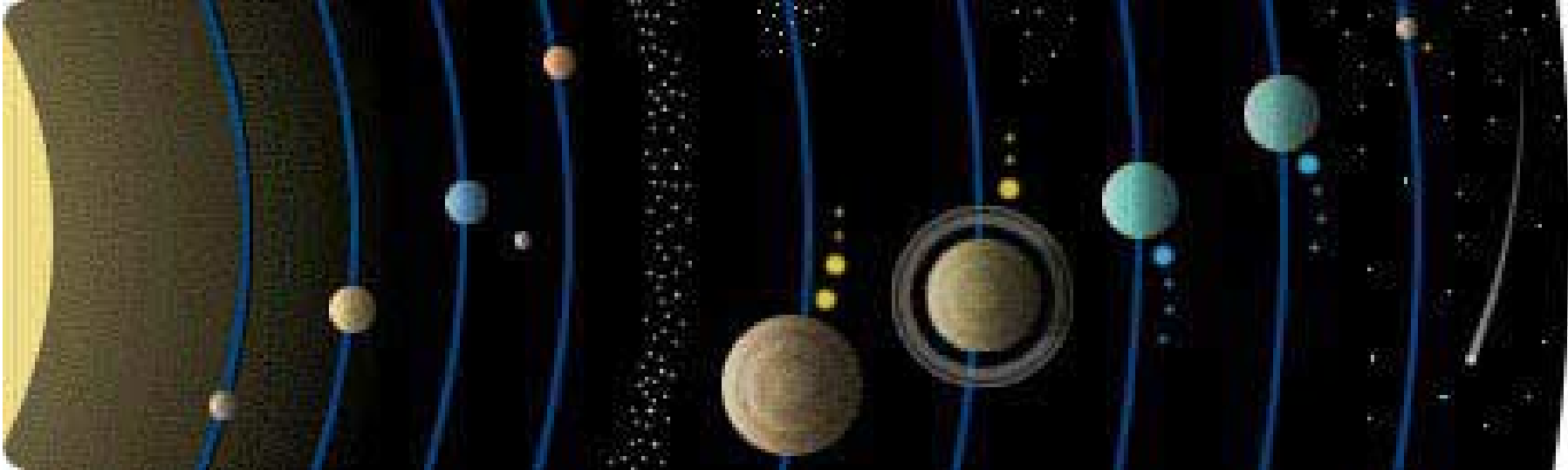
*“...the navigation of interplanetary space
depends for its solution on the problem of
atomic disintegration...”*

Robert H. Goddard, 1907



Match the Power System to the Destination

	Main Asteroid Belt	Trojan Asteroids	Centaur Minor Planets	Trans-Neptunian Objects	Kuiper Belt Objects / Comets
<p>Inner Planets</p> <p>Solar Electric Confined to Inner Solar System</p> <ul style="list-style-type: none"> - Also limited reach to large outer planetary bodies with aerocapture (Jupiter, Saturn, Uranus, Neptune only) 	<p>Jupiter and Moons</p> <p>Saturn and Moons</p>		<p>Uranus and Moons</p>	<p>Neptune and Moons</p>	<p>Pluto/Charon</p>
	<p>Radioisotope Electric for New Frontiers Class Outer Solar System Missions</p> <ul style="list-style-type: none"> -Targets with low Mass - 500 W Class RTG - <50 kg payload -Delta II Launchers 			<p>Nuclear Electric for Large Flagship Missions to Outer Planets</p> <ul style="list-style-type: none"> -Large Targets -100 kW Class Reactor ->500 kg Payloads -Delta IV Launch Vehicles 	
<p>RTG for Surface Lander</p>					





Project Prometheus

Overview

- Safety is the absolute highest priority
- Key components of Project Prometheus
 - Radioisotope power systems development
 - Nuclear propulsion research
 - Jupiter Icy Moons Orbiter (JIMO) development
- Project Prometheus is in addition to the In-Space Propulsion Program already in the baseline

Project Prometheus will enable a new strategic approach to planetary exploration and is likely to play a key role in NASA's future



PROJECT PROMETHEUS

Objectives and Benefits

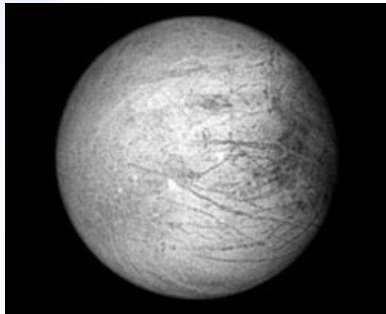
Revolutionize space exploration using space nuclear power and propulsion to enable reaching and studying natural laboratories of the Solar System, and to stimulate future generations of explorers and students.

Direct Benefits

- **Nuclear Power** (radioisotope) enables detailed and extended *in situ* scientific exploration of Solar System locations that cannot be explored in detail using solar or battery power, such as Mars, Europa, Titan, and the Neptune system.
- **Nuclear Propulsion** enables unprecedented exploration of the Solar System, including locations that cannot be reached using chemical propulsion, and lays the foundation for potential future human missions.

Indirect Benefits

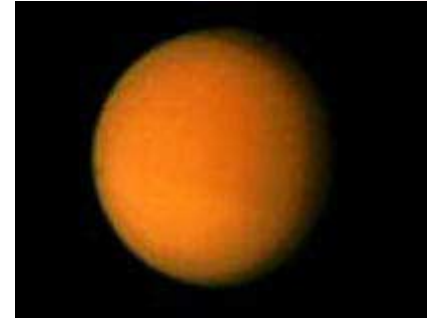
- Compelling stimulus to student interest in technical education from the combination of exciting new space exploration and nuclear propulsion development.
- Terrestrial systems, including next-generation nuclear power, **benefit** from the development of advanced technologies required for space nuclear propulsion.



Europa



Neptune's Triton



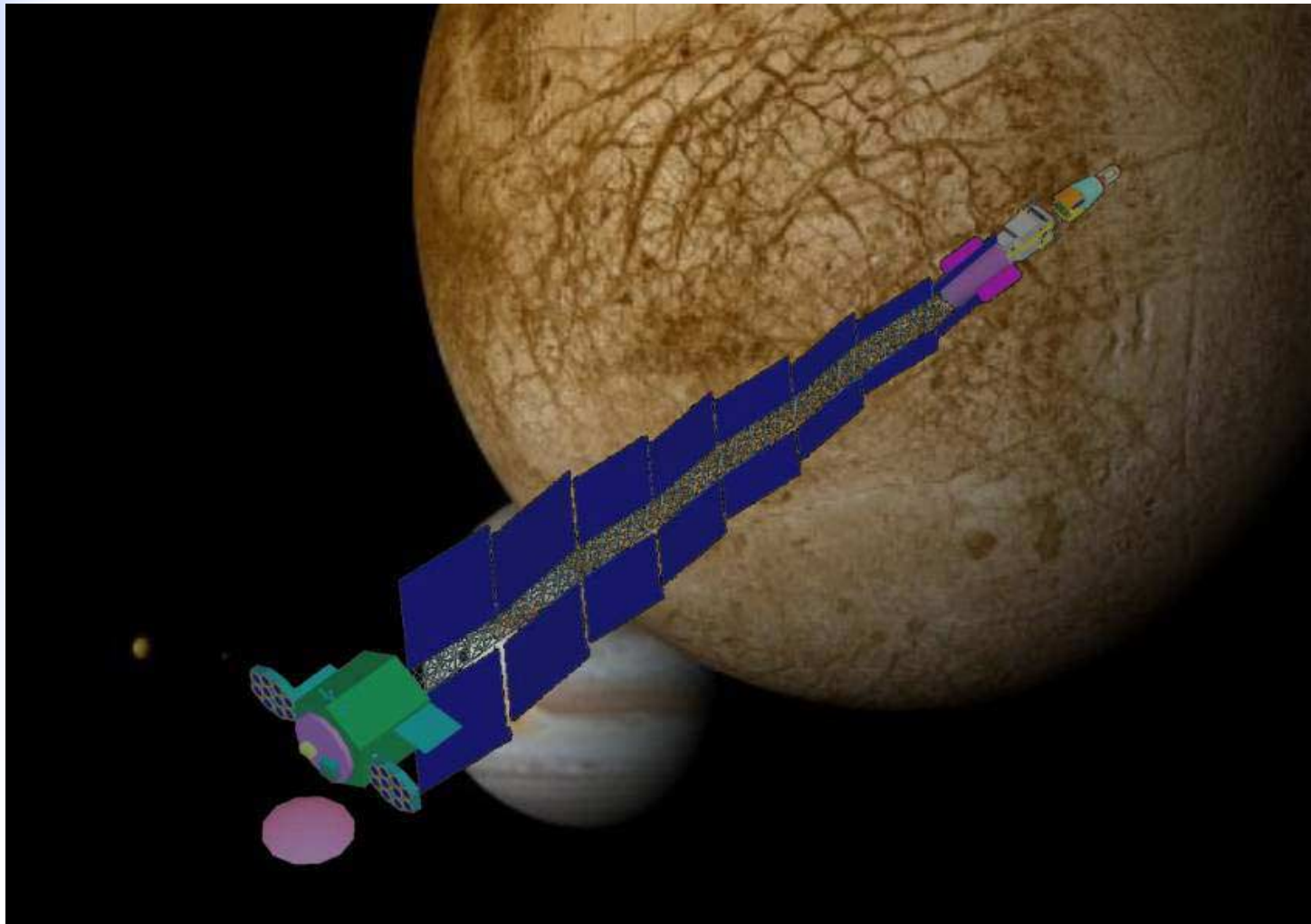
Titan

NSP builds on NASA and DOE's history of safety in the use of nuclear power for space applications



Jupiter Icy Moons Orbiter

Conceptual Design, Animation





Jupiter Icy Moons Tour

Charting the Water Worlds of Jupiter

- Completely new level of exploration not possible with chemical propulsion orbiters:

Full characterization of all three icy moons

- Interior structure and crustal thickness from geodesy, magnetics
 - Full range of remote sensing
 - Hi resolution imaging to study moons' history
 - IR and thermal spectral studies to search for organics, salts
 - Multi-frequency radar 'tomography' of icy crusts to depths of 30-40 km
 - Determine processes which 'bring the ocean to us'
 - Search for shallow liquid layers
- Mass and power margins enable complete investigation suite, orders of magnitude larger data return than single Europa Orbiter



Jupiter Icy Moons Tour

Building for the Future

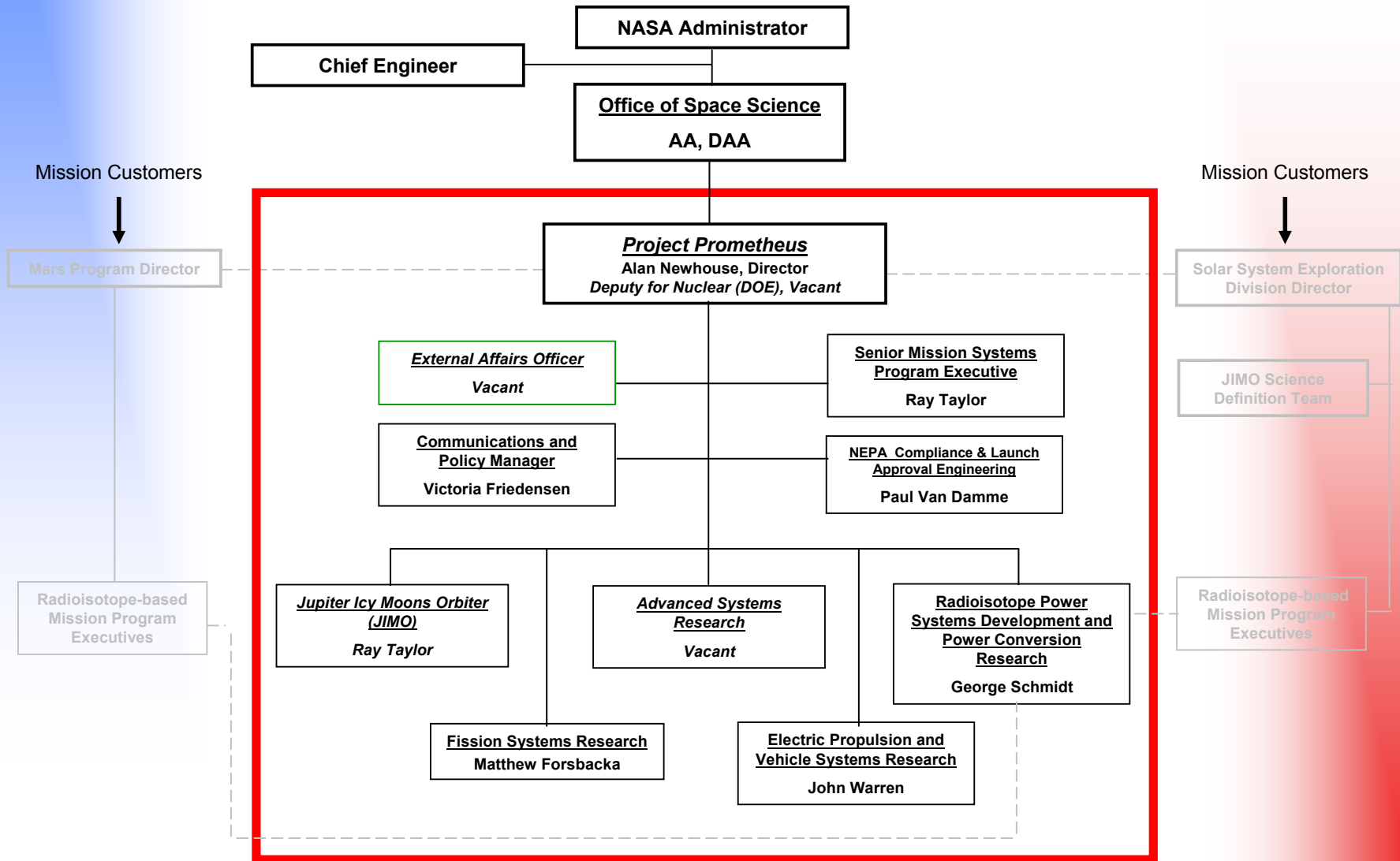
Building for the Future

- Orbital reconnaissance of all three icy moons sets the stage for next phase of exploration at Jupiter
 - Surface chemical and organic exploration
 - Probe to explore sub-surface
- Demonstrates capabilities to open the rest of the outer solar system to detailed exploration
 - Titan atmosphere and surface exploration
 - Neptune Orbiter, Triton exploration
 - Kuiper Belt tour
- Advances the ability to address multiple NRC Decadal Survey priorities with single missions



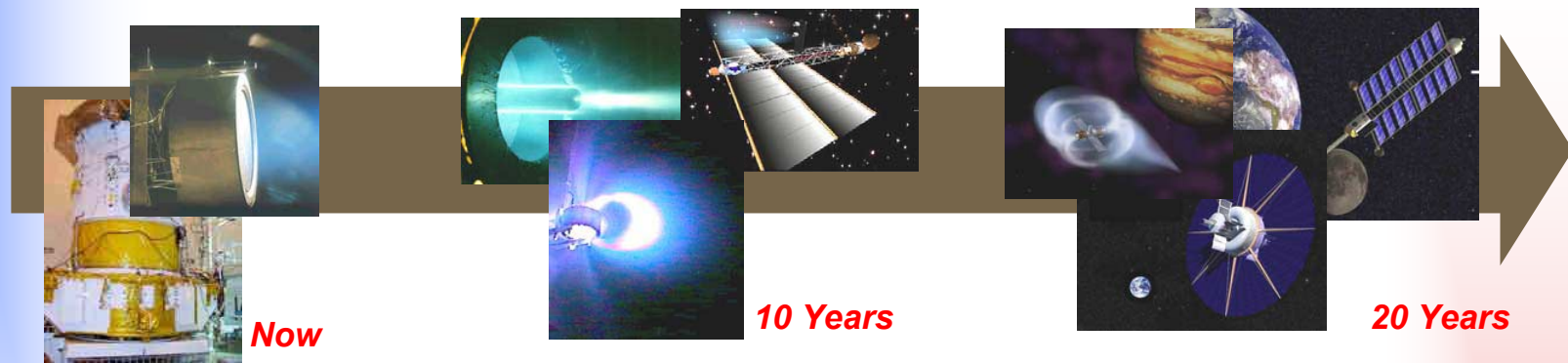
PROJECT PROMETHEUS

NASA Headquarters Organization





Many Technologies Extend to a Broad Range of Future Space Exploration Missions



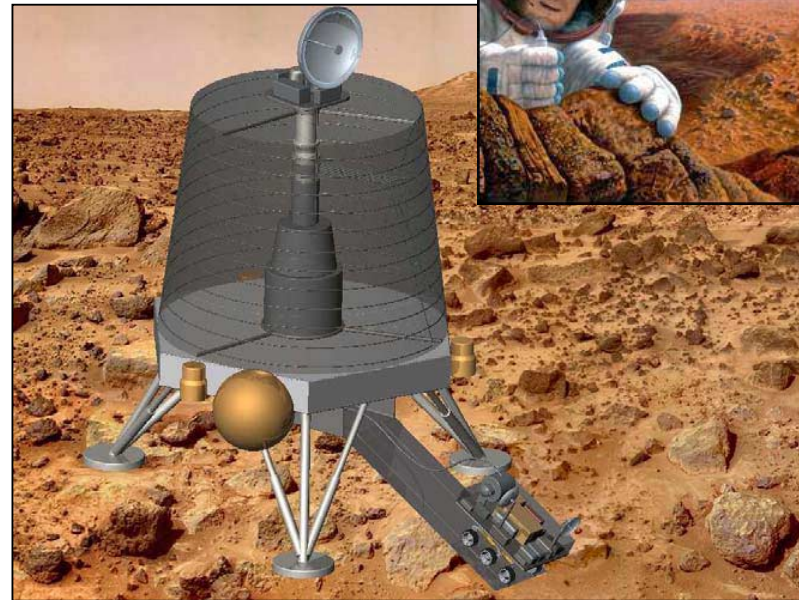
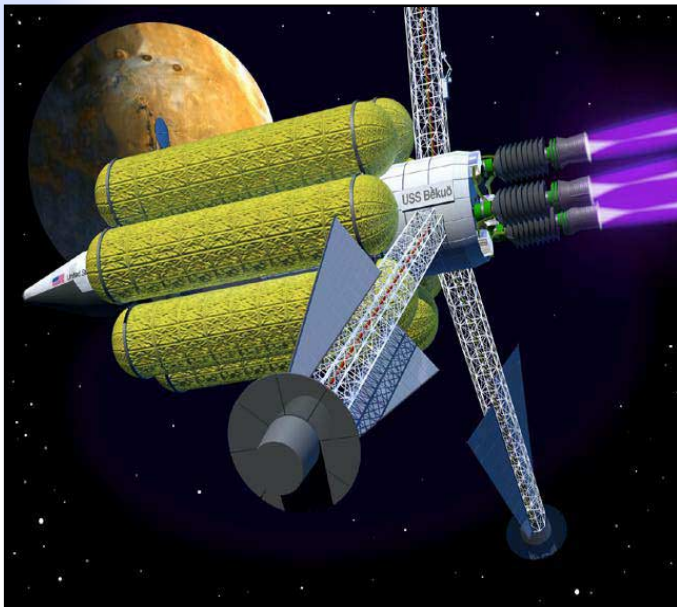
- **Many of the technology, fabrication, and ground-based capacities developed for the first space nuclear propulsion mission have direct application to follow-on missions**
 - Nuclear fuel and clad & fabrication capacity
 - Nuclear reactor design, analysis, and qualification methodology and software
 - Neutron and gamma shield, and neutron reflector & fabrication capacity
 - Radiation-tolerant nuclear reactor instrumentation and control & fabrication capacity
 - Space nuclear reactor power system autonomy
 - Power conversion & fabrication capacity
 - Low mass, large-scale radiation-tolerant thermal radiators & fabrication capacity
 - High power density electrical power control and distribution & fabrication capacity
 - High power electric propulsion & fabrication capacity
 - Safety and launch approval procedures, National Environmental Policy Act procedures and actions
 - **Ground test facility and support equipment (both for zero-power critical testing, and potential full power testing)**

Evolvable technologies for follow-on science driven exploration missions



Potential Support to Human Space Exploration

- **Nuclear power and propulsion are key enablers of expanded human exploration**
 - Enables human exploration beyond earth orbit
 - Provides high power for human protection against charged solar particles
 - Provides abundant power at destination
 - Enables complex, long duration missions
- **Nuclear surface power is essential for extended reconnaissance of the Mars surface**
 - Long-range surface and sub-surface exploration
 - Human habitat and life support
 - *In-situ* manufacturing of consumables
 - *In-situ* propellant production





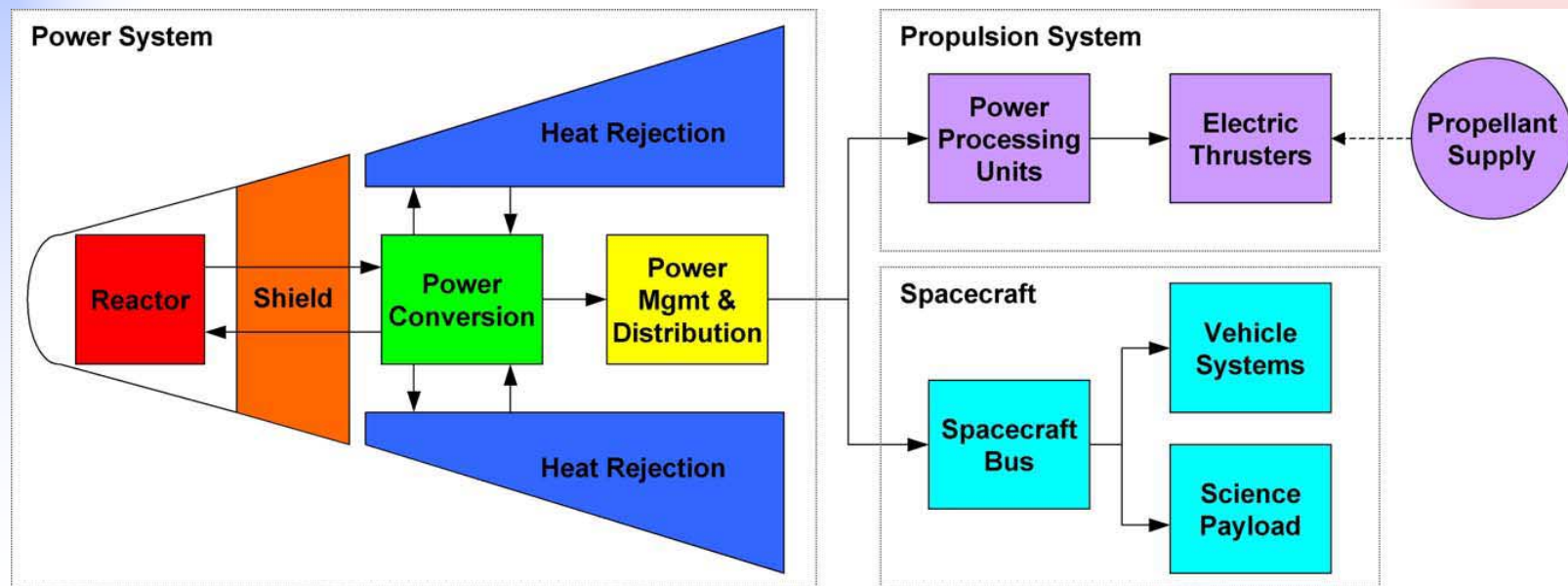
Conclusion

- **Project Prometheus will enable a new paradigm in the scientific exploration of the Solar System**
- **The proposed JIMO mission will start a new generation of missions characterized by more maneuverability, flexibility, power and lifetime**
- **Project Prometheus organization is established at NASA Headquarters:**
 - **Organization established to carry out development of JIMO, nuclear power (radioisotope), and nuclear propulsion research**
 - **Completed broad technology and national capacity assessments to inform decision making on planning and technology development**
 - NASA HQ Request for Information on nuclear propulsion
 - DOE/NASA evaluation of space reactor power system concepts
 - NASA / DOD workshop on solar power generation and power conversion
 - **Awarded five NRA's for nuclear propulsion research**
 - **Radioisotope power systems in development, and Plutonium-238 being purchased from Russia**
- **Formulated science driven near-term and long-term plan for the safe utilization of nuclear propulsion based missions**
- **Completed preliminary studies (Pre-Phase A) of JIMO and other missions**
- **Initiated JIMO Phase A studies by Contractors and NASA**



Microgravity Related Fluid Flow Topics

- Reactor
- Power Conversion
- Heat Rejection
- Propellant Management





Power Conversion Top-Level Requirements

- **Near-term (JIMO, other robotic missions):**
 - Up to 100 kWe to Electric Propulsion System (EPS)
 - 15-year operational lifetimes (10-yr at 100% power, 5-yr at 20% power)
 - Subsystem mass to enable achievement of system specific mass (alpha) ≤ 50 kg/kWe
- **Mid-term: (lower alpha, higher reliability, “2nd generation JIMO”):**
 - 50 to 500 kWe to EPS
 - 15-year operational lifetimes (10-yr at 100% power, 5-yr at 20% power)
 - Subsystem mass to enable achievement of system specific mass (alpha) ≤ 30 kg/kWe
- **Far-term (potential for human mission applications):**
 - 2 to 10 MWe to EPS
 - 15-year operational lifetimes
 - Subsystem mass to enable achievement of system specific mass (alpha) ≤ 10 kg/kWe
 - Continued improvement of 50 – 500 kWe systems

(sample return,
surface outposts &
rovers, ISRU, etc.)



Power Conversion Options

X O



X



O

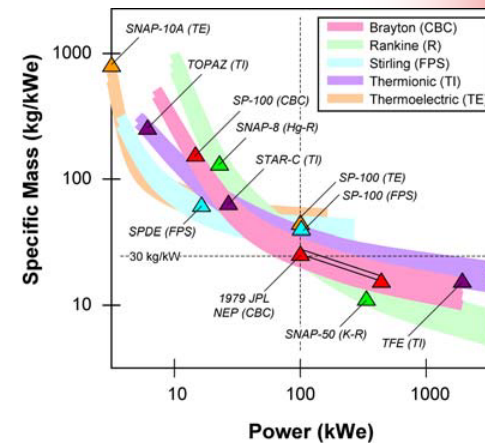
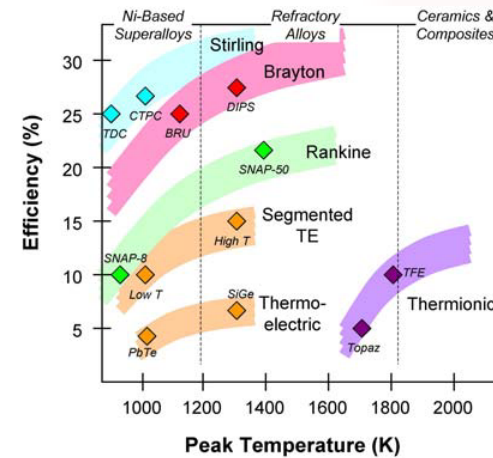


X O



X JIMO Trade-Space
O Code S NRA Award

- Closed Brayton Cycle
 - Heat engine with inert gas in turbo-alternator
 - **Mature Technology with High Efficiency and Growth Potential**
- Free-Piston Stirling
 - Heat engine with reciprocating piston & linear alternator
 - **High Efficiency & Scales Well to Low Power**
- Liquid Metal Rankine
 - Heat engine with two-phase fluid in turbo-alternator
 - **Potential for Low Mass at High Power, has Technical Issues & no infrastructure**
- Thermoelectric
 - Electrical potential produced by dissimilar materials exposed to temperature difference
 - **Flight Proven with Long Life, but Low Efficiency**
- Thermionic
 - Heated emitter passes electrons to cooled collector across very small Cs-filled gap
 - **Extensive Database, but Life Issues Remain**

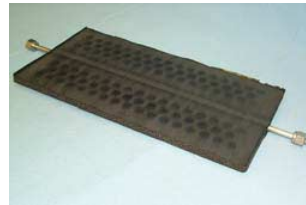




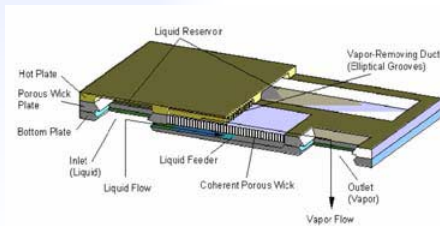
Heat Rejection



ISS Radiator



**Carbon-carbon
Heat Pipe Radiator**



**Integrated Loop Heat Pipe
Evaporator**

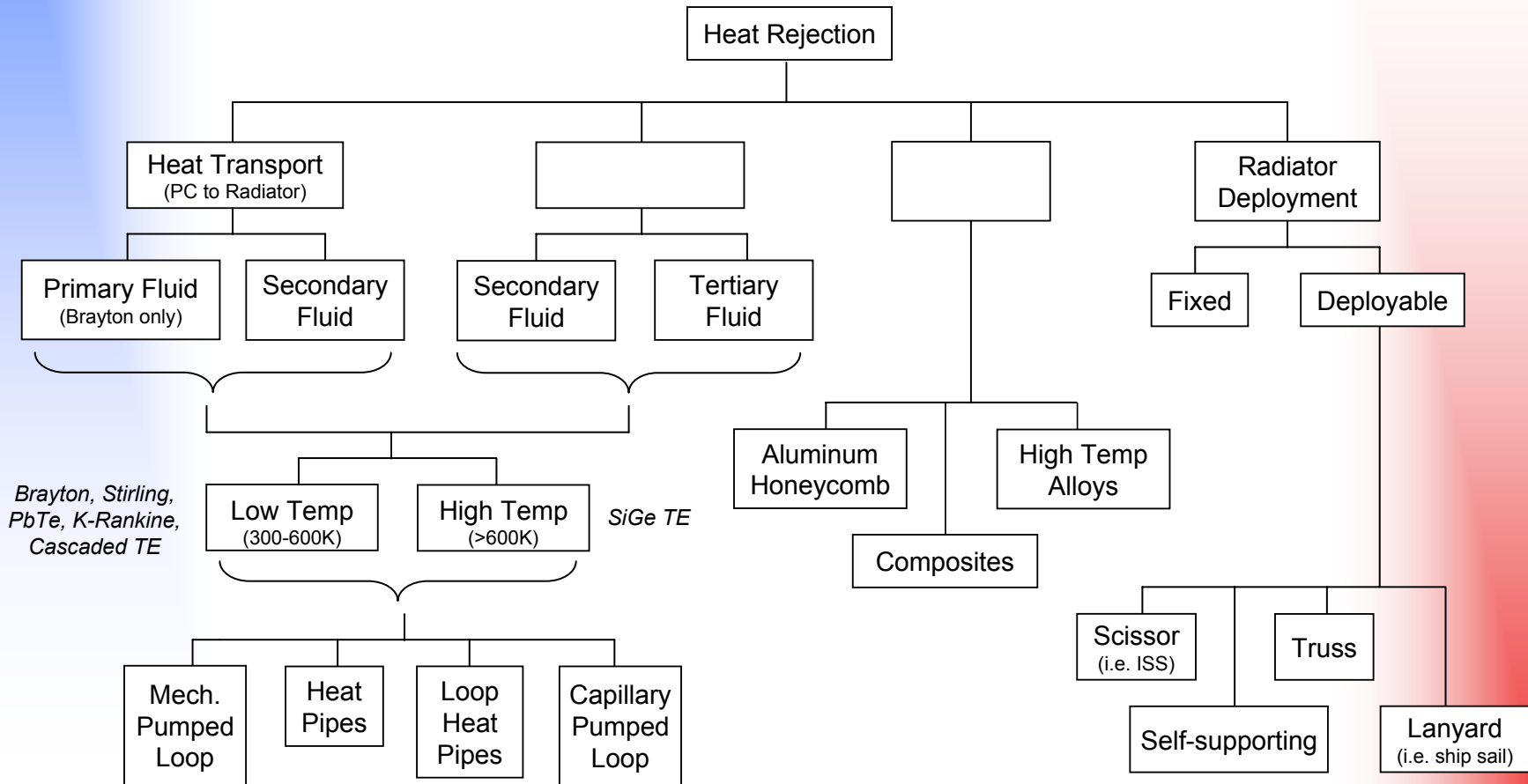


**Annealed Pyrolytic Graphite
Space Radiator**

- Heat Transport
 - Mechanical Pumped Loop
 - Conventional Heat Pipes
 - Loop Heat Pipes, Capillary Pumped Loops
- Fluid Selection
 - Power Conversion Compatibility
 - Containment Material Compatibility
 - Freeze Tolerance
- Lightweight Radiator Surfaces
 - Composite Materials
 - Heat Distribution
 - Long Life, High Emissivity Coatings
 - Radiation Tolerance (Bonds, Coatings)
- Fault Tolerance/Survivability
 - Micrometeoroid Protection
- Deployment Mechanisms



Heat Rejection Trade Tree





Heat Rejection Technology for Advanced Systems

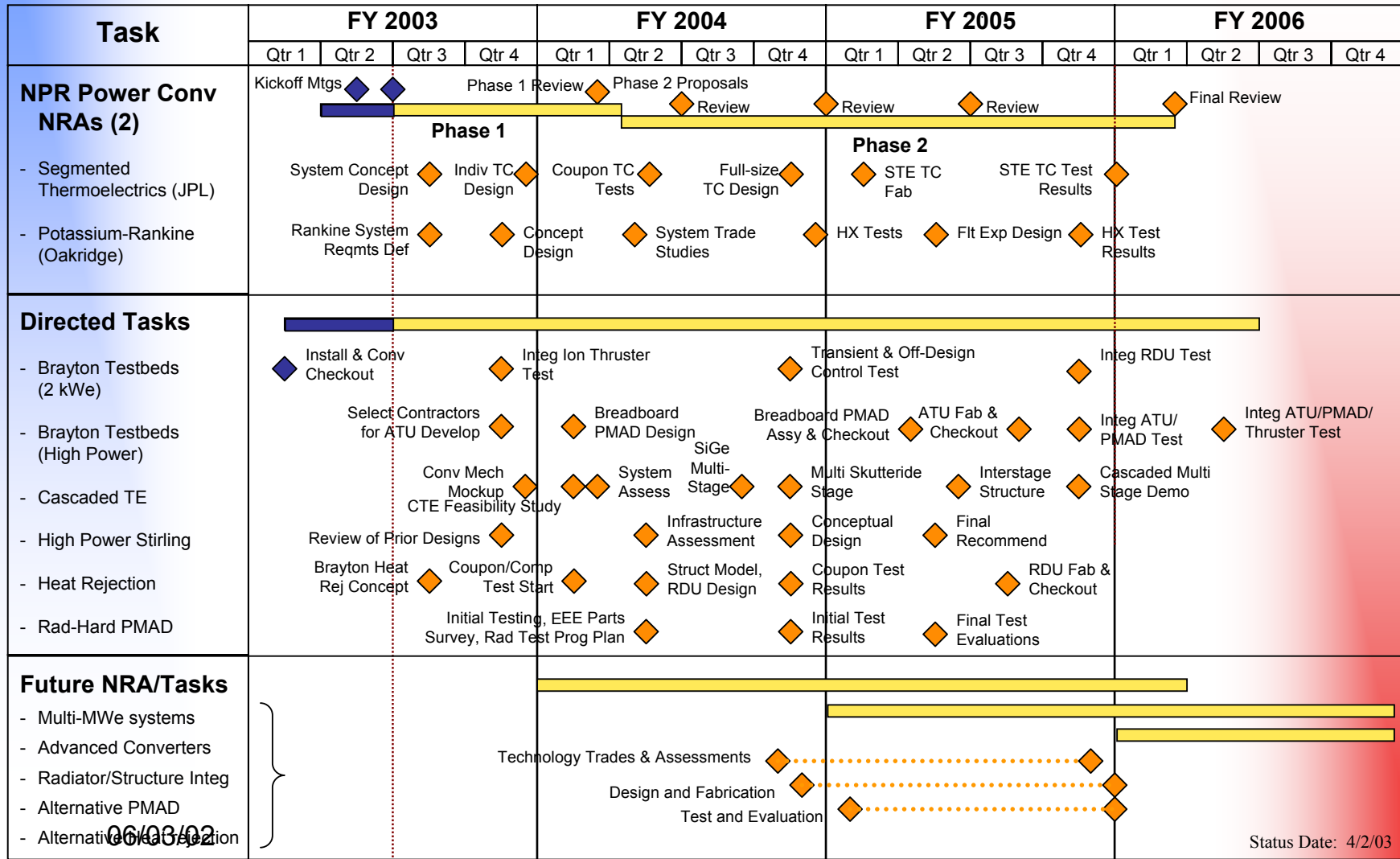
- **Critical Needs:**
 - Mass Reduction with Lightweight Materials
 - Long Life Component Development (Pumps, Mechanisms, Coatings, etc.)
 - Power Conversion Compatibility and Integrated Thermal Testing

- **Current Funded Activities:**
 - Heat Rejection Systems Modeling and Development (GRC/JPL)
 - Heat Rejection Concepts
 - Materials and Fluids Studies
 - Thermal and Structural Design Models
 - Design, Fabricate, and Test Radiator Demonstration Unit (RDU) for 2 kWe Brayton
 - SBIRs (GRC)
 - Carbon-Carbon Radiators (Allcomp)
 - Annealed Pyrolytic Graphite Radiator (K-Technology)
 - Pulsed Thermal Loops (TDA)



Nuclear Propulsion Research (NPR)

Power Conversion (Draft)



06/03/02

Status Date: 4/2/03



Summary

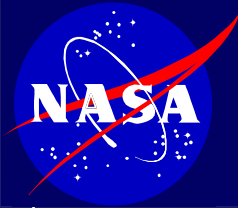
- **Potential gravity-sensitive systems & components**
 - Liquid metal cooled reactor startup
 - Potassium-Rankine Conversion
 - Boiler
 - Liquid/vapor separator
 - Condenser
 - Heat Rejection
 - Startup and restart of heatpipes, loop heatpipes, capillary pumped loops
 - Propellant management

- **In-house, Contractor and competed research tasks will address relevant issues**



Human Support Technology Research to Enable Exploration

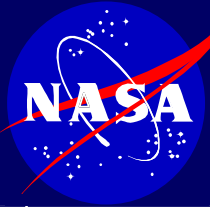
**Jitendra Joshi, Ph. D.
Deputy Manager,
NASA AHST Program**



National Aeronautics and Space Administration

Acknowledgements

- Michael Flynn
- Dr. Donald Henninger
- Dr. Darrell Jan
- Dr. Mark Kliss
- Dr. Raymond Wheeler



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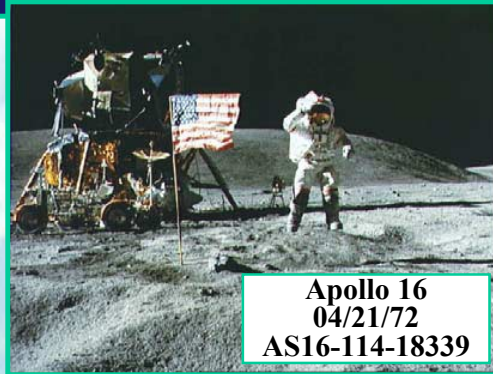
Gemini 11
0912/66
S66-53900



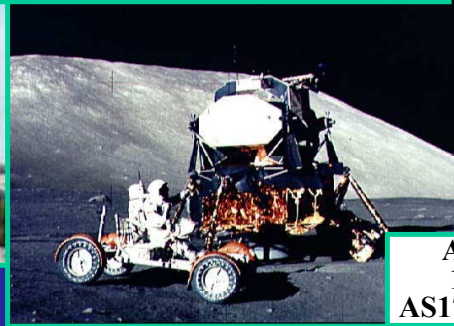
Mercury-Atlas 9
05/16/63
S63-07603



Apollo 17
08/28/72
S72-48728



Apollo 16
04/21/72
AS16-114-18339



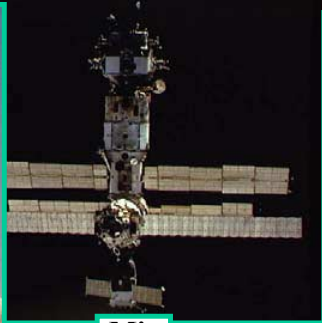
Apollo 17
12/10/72
AS17-147-22527



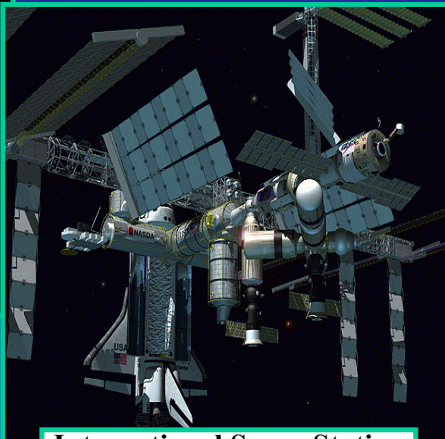
Skylab
02/08/74
SL4-143-4706



Shuttle
STS 41-C
04/06/84
STS41C-3058



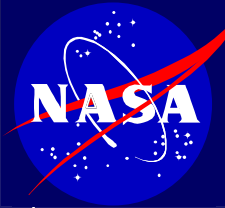
Mir



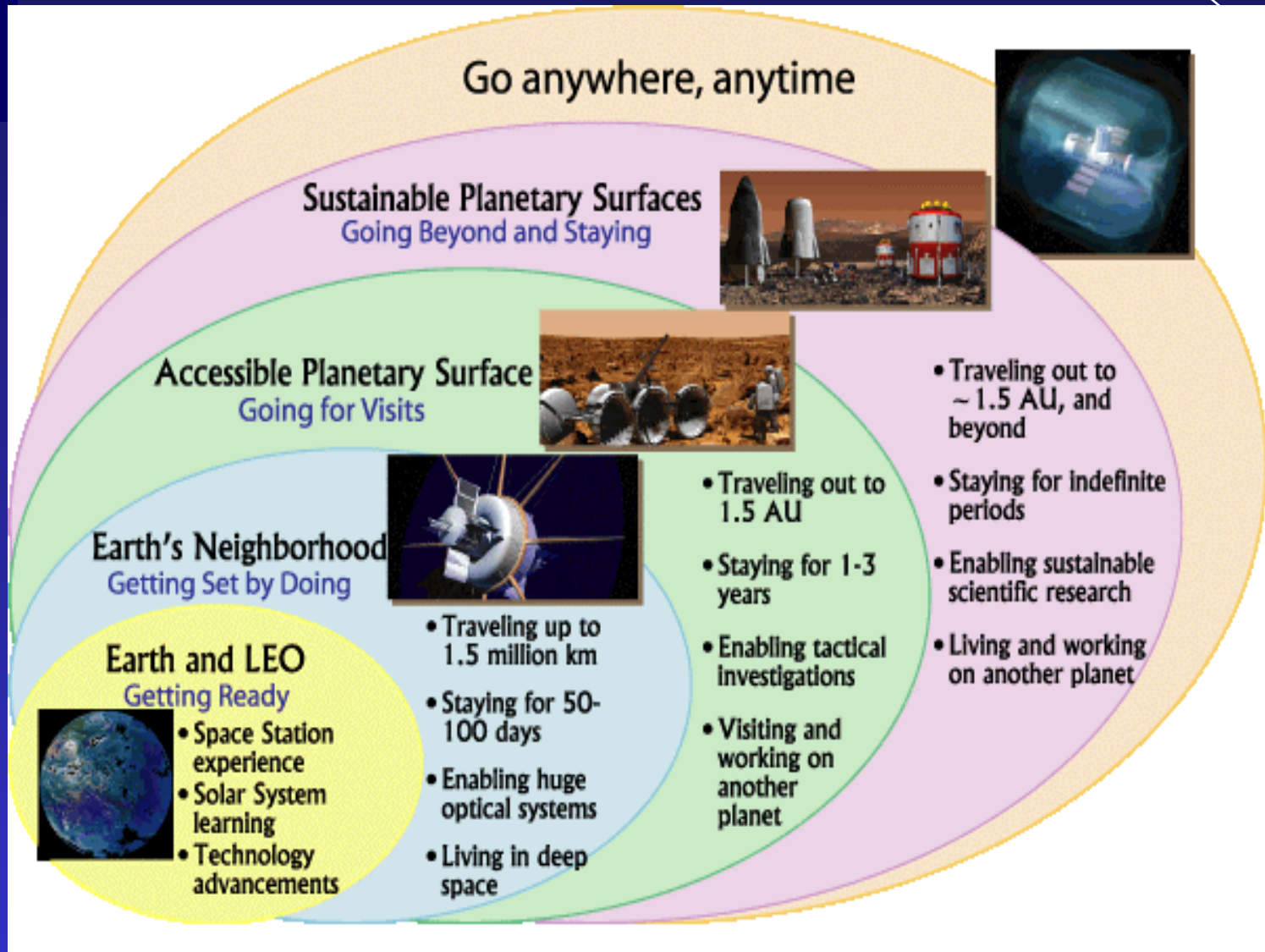
International Space Station

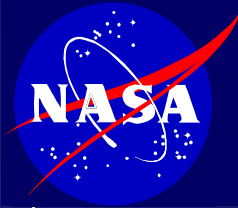


Mars



National Aeronautics and Space Administration

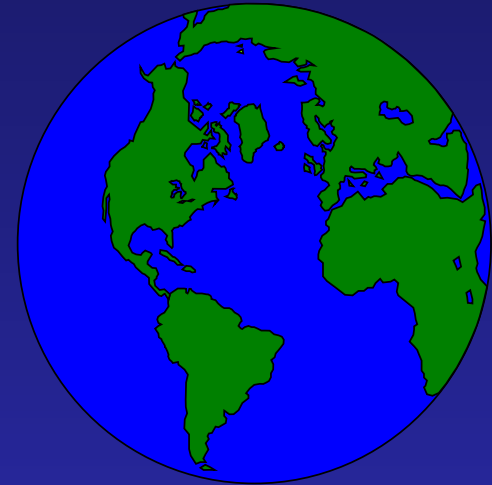


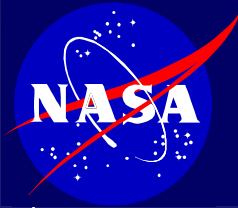


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Advanced Life Support

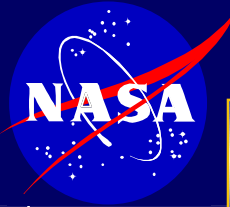
- Duplicate the functions of the Earth in terms of human life support
- Without the benefit of the Earth's large buffers --- oceans, atmosphere, and land masses
- Question is one of how small can the requisite buffers be and yet maintain extremely high reliability over long periods of time in a hostile environment
- Space-based systems must be small, therefore must exercise high degree of control





Advanced Life Support

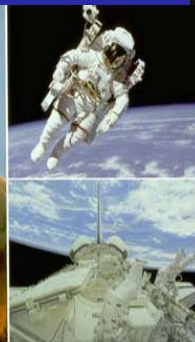
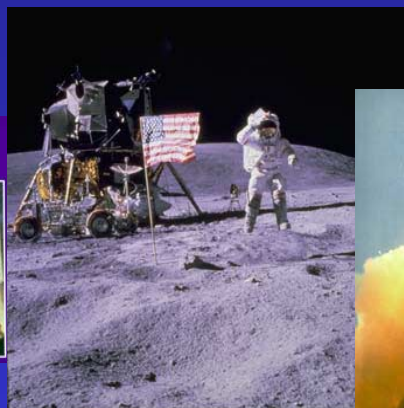
- **Enabling technology for human exploration and development of space**
- **Long-duration missions dictate regenerative systems --- minimize re-supply**
- **Minimize mass, volume, power, thermal requirements**
- **Such systems will be replete with physicochemical and biological components**



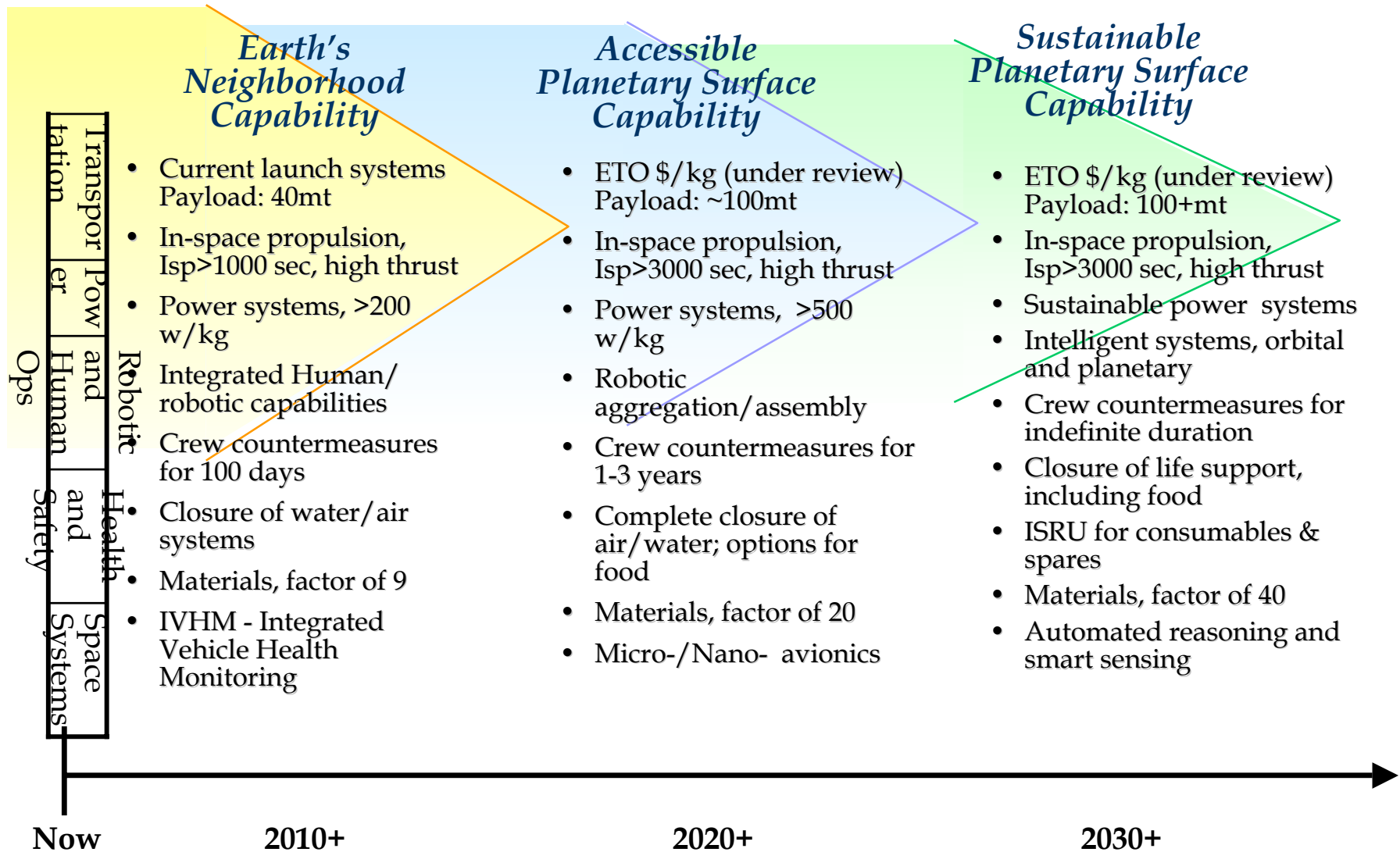
National Aeronautics and Space Administration

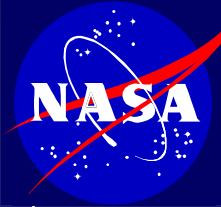
Systems Integration, Modeling, and Analysis

- **Mission objectives drive the functional requirements of Advanced Life Support technology development.**
 - **Systems Engineering enables R&TD efforts to meet the functional requirements the best way possible.**
 - Identification and evaluation of feasible designs
 - Performance of technology/configuration trade studies
 - Optimization of operational strategies
 - Provide guidance for future R&TD efforts

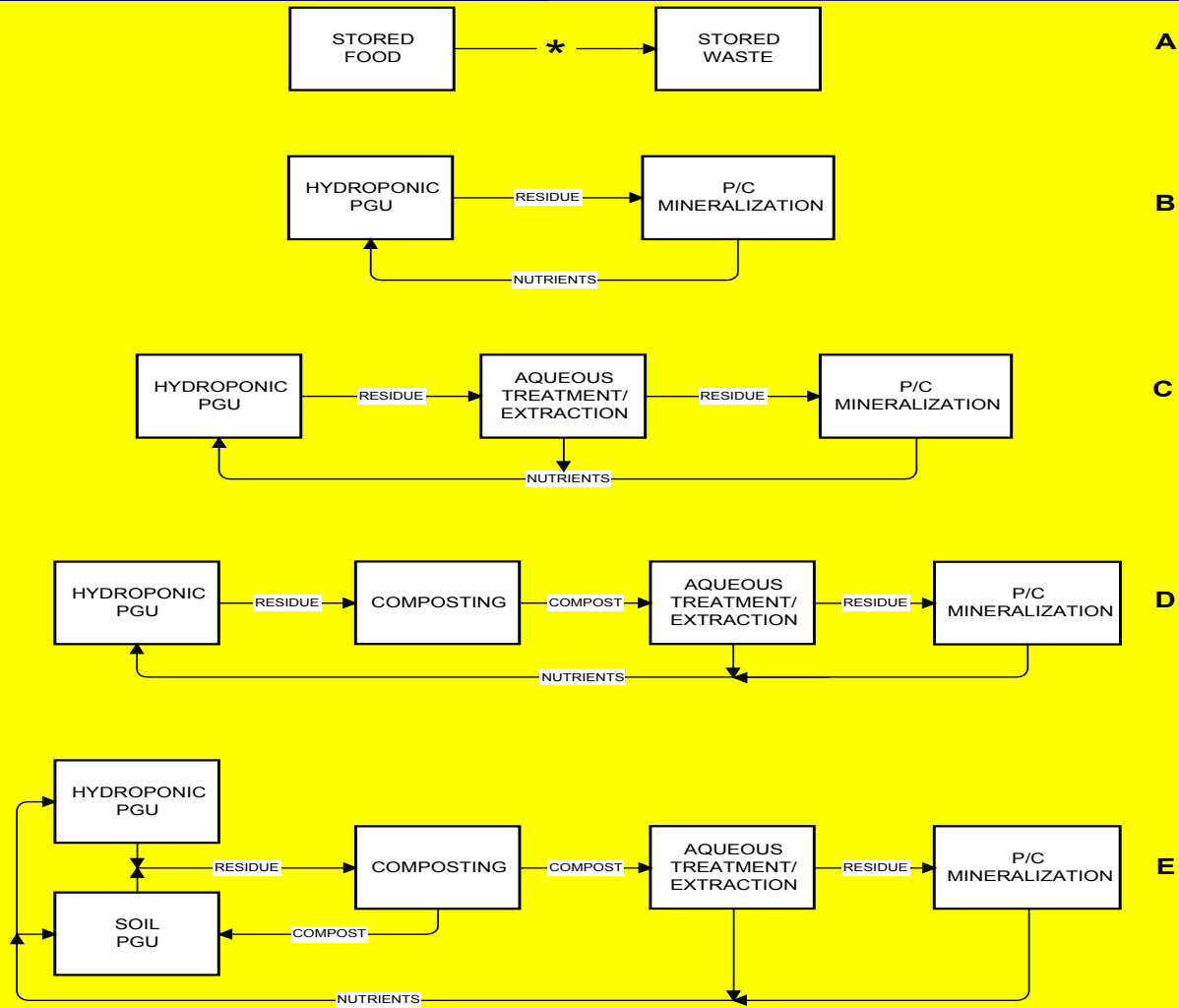


Progressive Capabilities

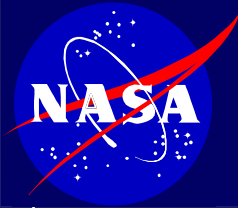




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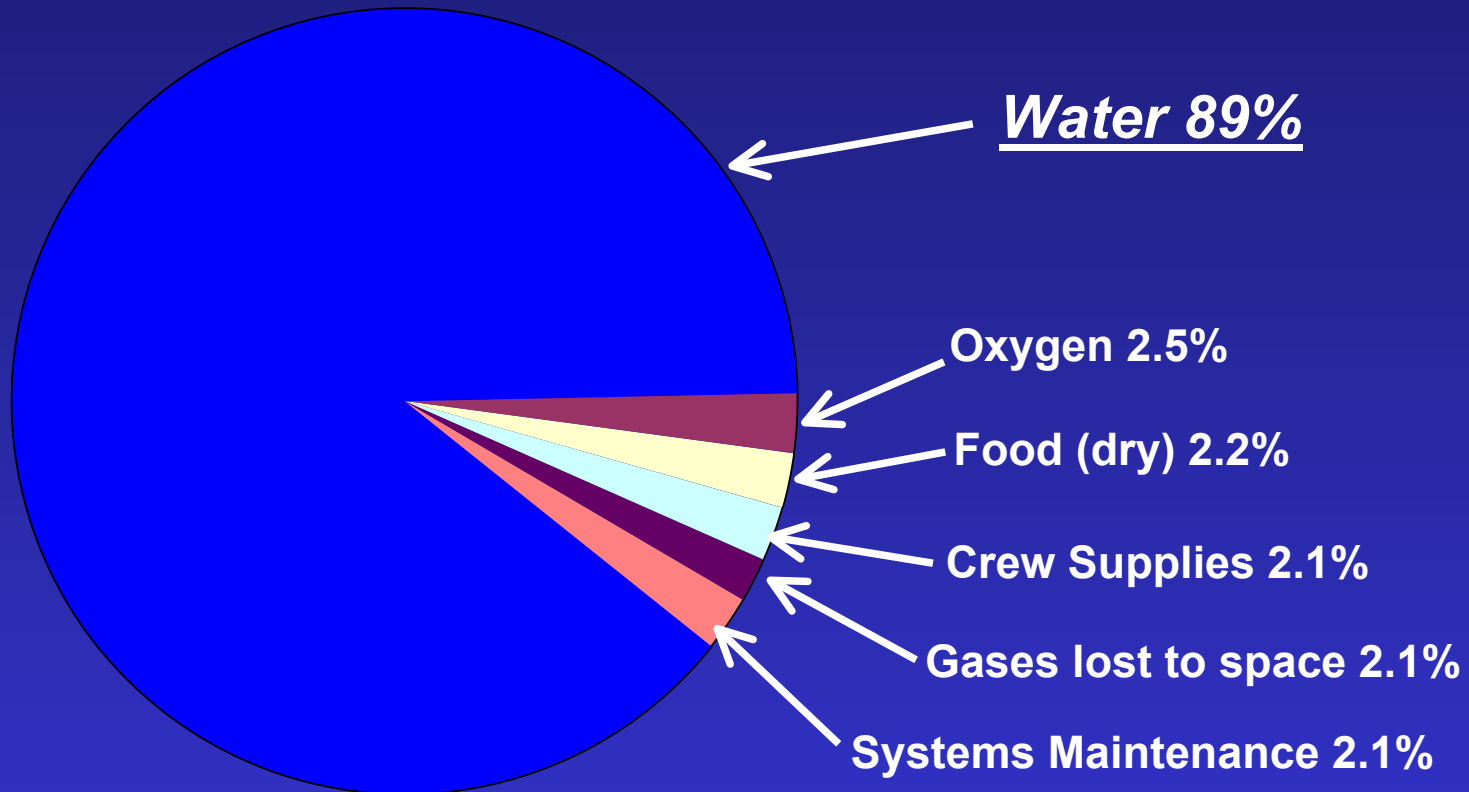
* = Incorporation of food regeneration in ALS

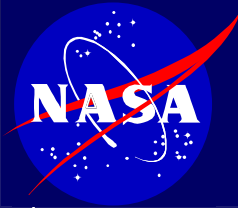


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Advanced Life Support

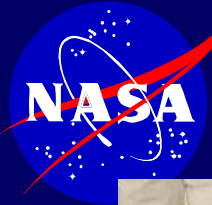
Partially closed Life Support System
Resupply Mass - 12,000 kg/person-year





Water Processing

- Goal is to develop a processing system that is capable of generating potable water.
- Current baseline recycles only a fraction of the water at the cost of expendables and power.
- Future technologies (VPCAR, biological processors) have to be optimized for microgravity compatibility.



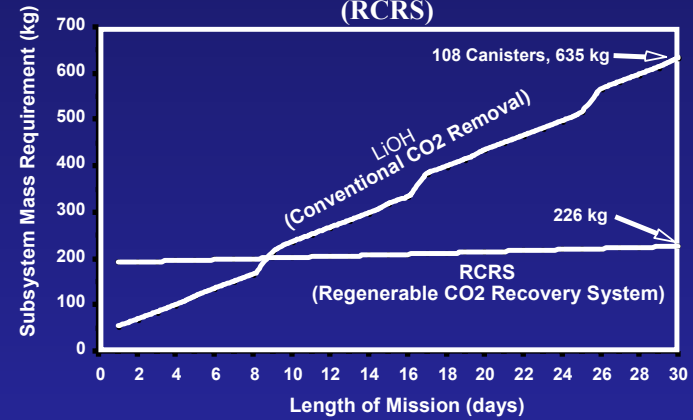
National Aeronautics and Space Administration

Air Revitalization Systems

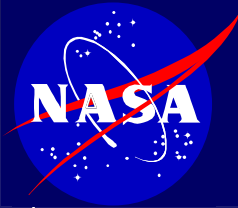


**Commander Lousma replaces
ARS LiOH
canisters on middeck
S82-28921 03/31/82**

Mass Savings Using a Regenerative Physicochemical Subsystem: Shuttle Regenerable Carbon Dioxide Recovery System (RCRS)



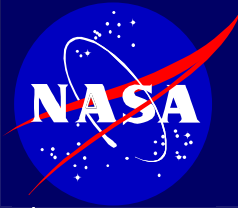
**Mission Pilot Ken Bowersox repairing the
Regenerable Carbon Dioxide Removal
System wiring.
07/09/92 STS050-20-012**



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Why Advanced CO₂ Removal Technologies?

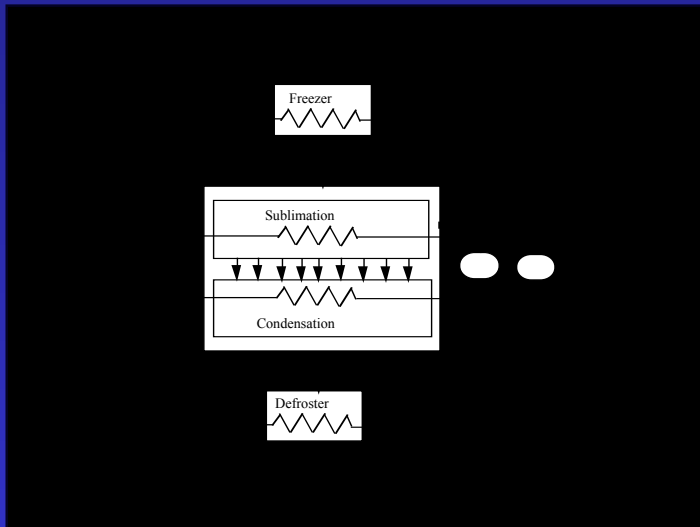
- The ISS CO₂ removal subsystem has the highest power penalty of any ISS life support subsystem (~ 3200 W-hr/kg CO₂). Current technology has a thermodynamic efficiency of about 3%.
- Current CO₂ removal & reduction technology in closed-loop mode (with Sabatier/oxygen recovery) will require ~ 5400W-hr/kg CO₂.
- Life scientists are calling for lower CO₂ levels on International Space Station.
 - ISS requirement is 7000 ppm, compared to ~400 ppm Earth-normal
 - Achieving lower concentrations translates directly into more energy consumption.
 - Power will be an extremely critical resource for a Mars transit vehicle.
 - The Mars Reference Mission would use a solar-powered transit vehicle with total estimated available power of 30 kW; 12 kW for ECLS
- Develop CO₂ removal technology that consumes 10x less power than current Space Station technology for same performance.
(or maintains substantially lower concentrations of CO₂ for no increase in power)

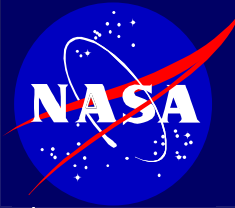


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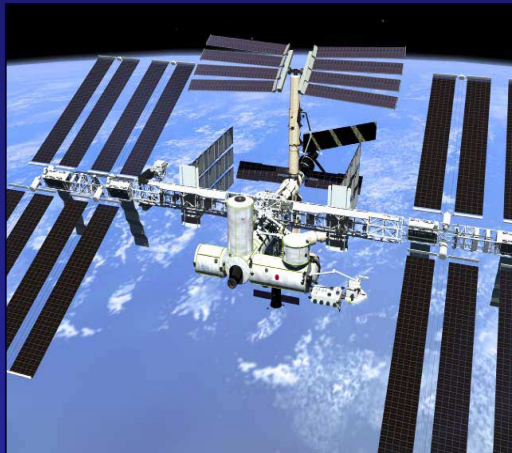
Solid Waste Resource Recovery Systems: Lyophilization

- **Low pressure, low temperature process (potential for low power operation).**
- **Complex solids pumping or handling techniques are not required.**
- **The technique should not produce CO_2 , NO_x , SO_x , or any other undesirable oxidation byproducts (gases generated are primarily water vapor).**
- **The final product is a stable dried material with 1 to 3% H_2O .**
- **The approach is fully regenerable, meaning that the process requires no consumables, only energy.**





ISRU Technologies for Mars Life Support



Self-Sufficiency Options
for Life Support

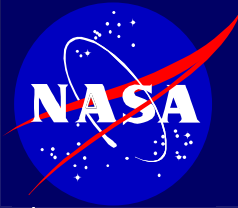


Complete regeneration
No leaks
Total closure (100%)

Relatively relaxed closure and
leakage requirements,
reliance on local resources
(ISRU)

Design Drivers are

- **Reduced mass and power**
- **Increased safety and reliability**

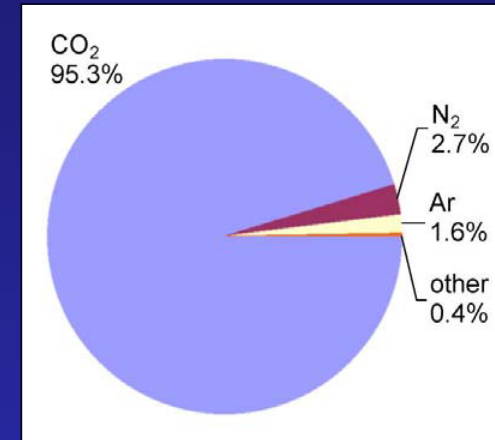


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Atmospheric Resources of Mars

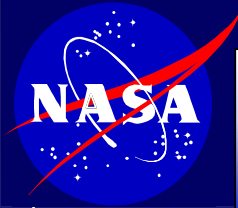


Mars Pathfinder, 1997



Mars atmosphere composition

- Pressure: ~1% of Earth's
- Temperature: 180 – 290 K (equatorial)
- Dusty, windy



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N₂ Consumables / Make-up for Mars Life Support

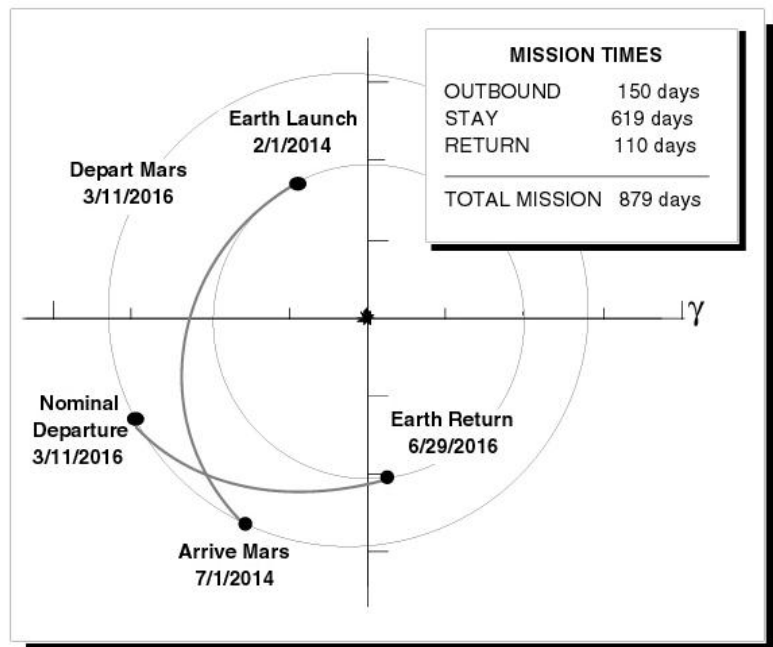


Figure 3-4 Fast-transit mission profile

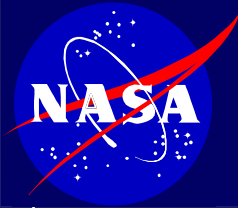
NASA SP 6107, Mars Reference Mission, 1997.

- Transit Leakage Losses:
- 0.1 kg/day leakage,
- 260 days = 26 kg N₂

- Surface Leakage Losses:
- 0.1 kg/day leakage,
- 619 days = 62 kg N₂

- Surface/Airlock Losses:
- 1 kg/cycle, 2 cycles/day,
- 619 days = 1200 kg N₂

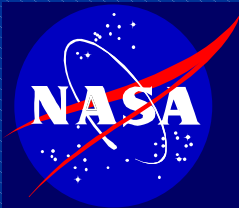
- Total Mission N₂ Losses:
- ~1.3 tonnes N₂ lost
- (2x safety factor = 2.6 tonnes)



Integrated Test beds

Why do we need integrated test beds?

- Allows for validating a subsystem in a relevant environment
- Subsystems get exposed to off-nominal loads which allows for testing the limits that the system can effectively tolerate
- Effect of the test article on the optimal functioning of other subsystems
- Subsystems get exposed to real streams which can not be simulated in laboratory studies



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INTEGRITY

Integrated Human Exploration Mission Simulation Facility

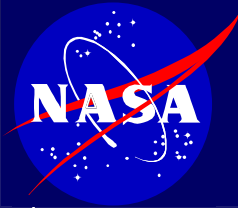
SUMMARY

- ❖ Human exploration missions are very complex and risky – duration and distance from Earth
- ❖ Integration issues are difficult to identify
- ❖ Individual technologies & systems have inherent risk
- ❖ Integration of all systems & procedures on the ground will allow risk to be more effectively managed
- ❖ Integrated procedures can be developed and validated
- ❖ Definition of “missions” provides focus for R&D
- ❖ INTEGRITY is a cost-effective way to prepare for future human exploration missions beyond low earth orbit
- ❖ INTEGRITY will facilitate:
 - ✓ Development of improved management techniques, including cost & risk estimation
 - ✓ International, Commercial, Academic partnering
 - ✓ Education & Public involvement
 - ✓ Re-invigorate NASA workforce
 - Recruiting tool



Visitors' viewing area

24 April 2003



National Aeronautics and Space Administration

Advanced Life Support Lunar - Mars Life Support Project

**Phase I: 15-day, 1-Person Test
March 1995**



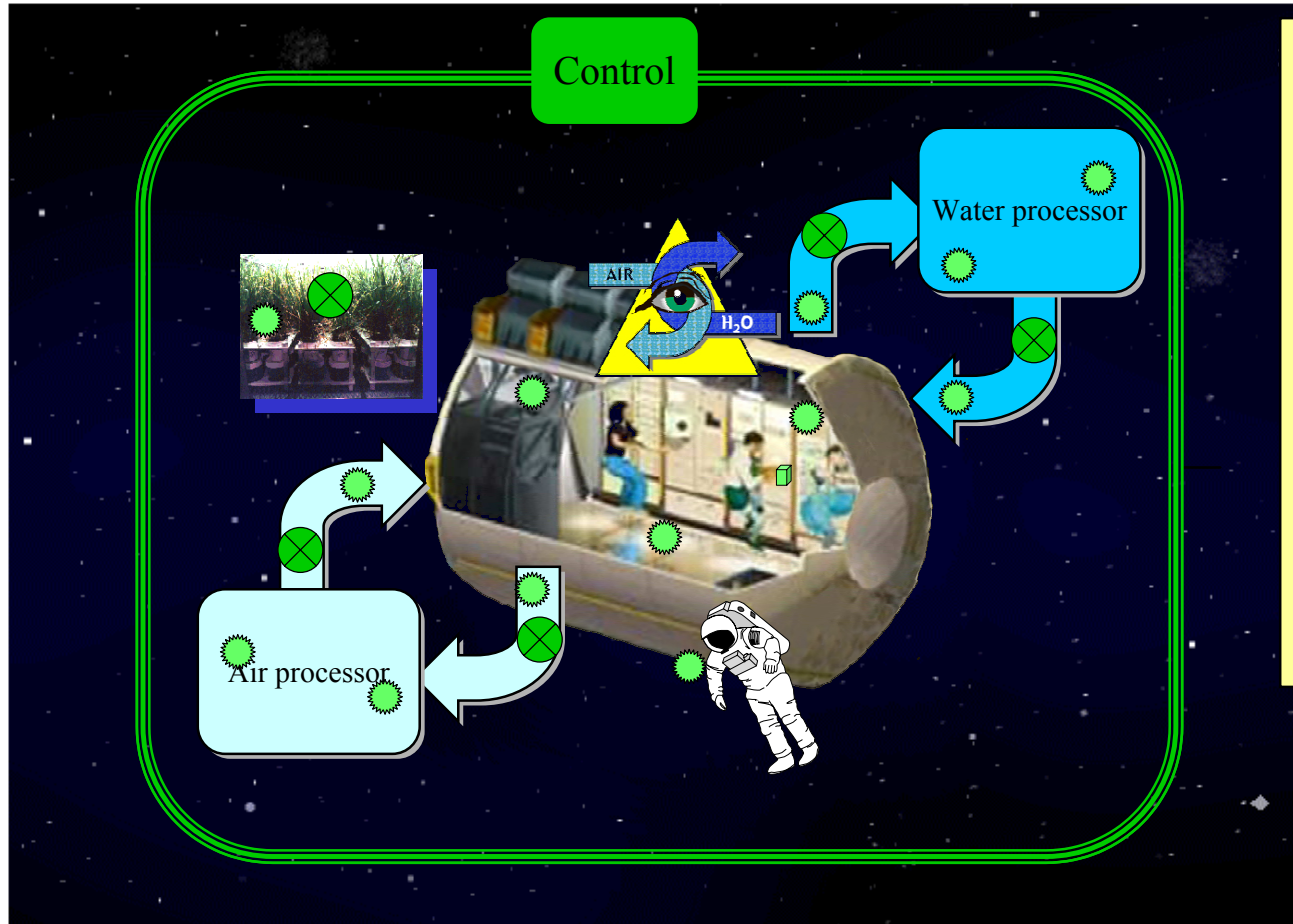
Early Human Testing Initiative (EHTI) Phase II Crew
June 1996

Phase II: 30-day, 4-Person Test - June 1996
Phase IIA ISS: 60-day, 4-Person Test - January 1997
Phase III: 90-day, 4-Person Test - September 19, 1997






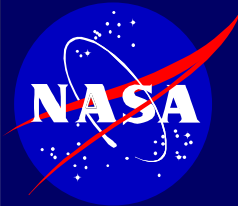
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Monitoring & Controlling the environment

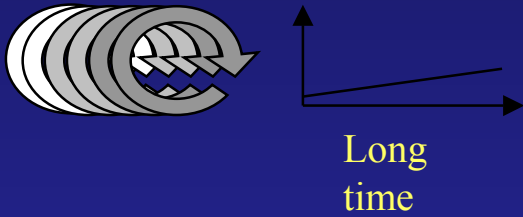


- Air
- Water
- Plant chambers
- Food and Food Preparation surfaces
- Gradual buildup of toxic species
- Hazardous events
- Chemical
- Biological

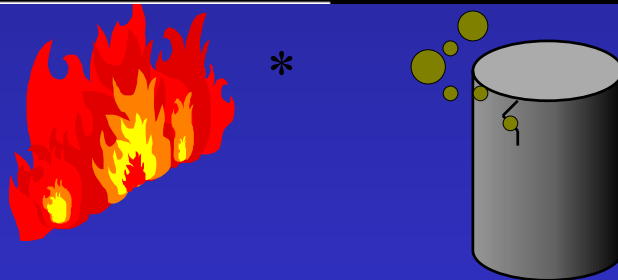
  **sensors**
 **actuators**



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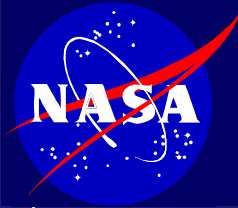
COMPOUND	DETECTION LIMIT
PRIORITY 1	PPM
Acetaldehyde	0.1
Formaldehyde	0.01
Methanol	0.2
Dichloromethane	0.03
Perfluoropropane (F218)	10
Acetone	1
Octamethylcyclotetrasiloxane	0.05
2-Propanol	3
Freon 82	5



*microgravity combustion not shown

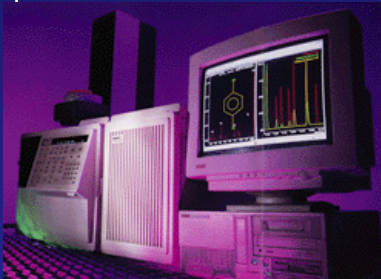
Gradual buildup of harmful chemical or microbials

Hazardous event such as fire or leakage



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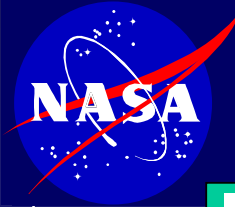
Ground-based Commercial technology



- High mass
- High power requirement
- High operator skill
- High capability
- May require gravity

- Lower mass
- Lower power requirement
- Low operator skill
- Low capability
- May require gravity

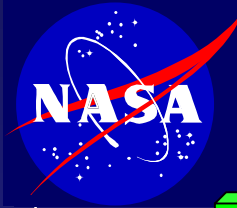
• Breakthroughs needed to achieve high capability and low mass/power plus autonomy



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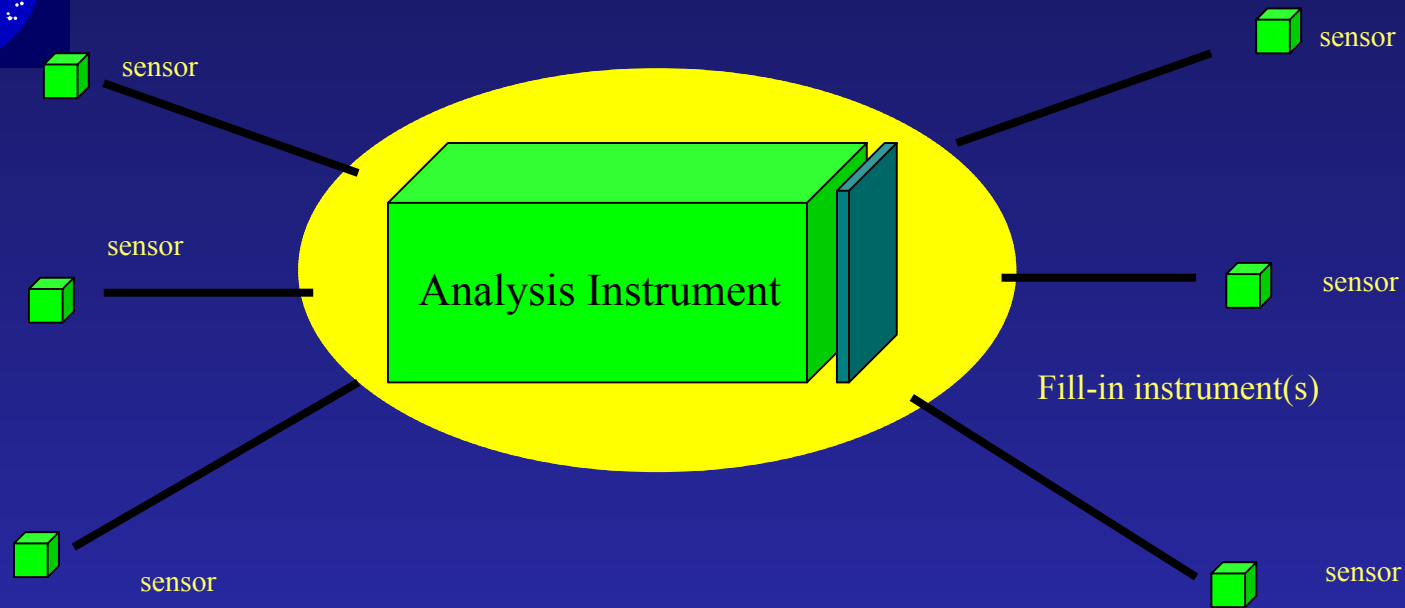
Optimizing Size vs Capability



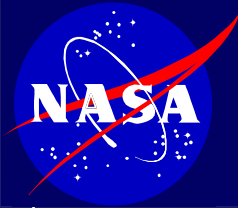


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AEMC Vision: Hierarchical monitoring/control



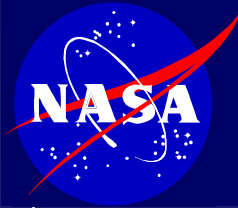
- Analysis Instrument: eg GCIMS, GCMS, FTIR
 - Analyzes for almost everything
 - Complex, expensive (although low mass)
 - Probably only one on board
 - “Fill-in” covers the few things that the Analysis Instrument doesn’t cover (eg, formaldehyde, O₂, CO₂...)
 - eg TDL, SERS
- Sensor is simpler, cheaper, more robust
 - May be fixed or portable
 - Much more capable than off the shelf
 - eg Enose, Bioarray



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Some Top level Issues for Wastes Processing

- Gas-liquid Separation
 - All P/C, Bio water treatment systems
 - Humidity control systems
- Solid-liquid Interactions
 - Settling problems in Bio and P/C systems
 - Optimal functioning of P/C systems
- Thermal Control
 - Heat Rejection
 - Heat Transport



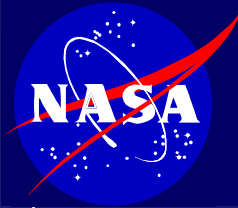
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Water Recovery Systems Flight Verification Topics



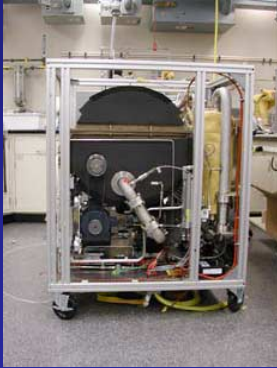
- Thermal properties of thin fluid films
- Two phase flow in open chambers
- Splashing in liquid/gas boundaries
- Centrifugal separations, what occurs during start and stop events
- Pumping of saturated fluids
- Surface tension directed flow stability





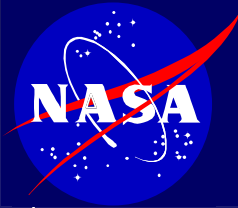
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Water Recovery Systems Flight Verification Topics (Cont.)



- Reaction kinetics in packed beds, effects of channeling and condensation
- Stability of packed beds during launch
- Deterioration of packed beds during operation
- Lubrication of rotating gears

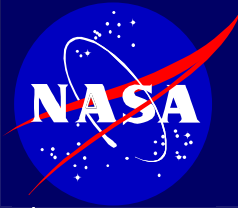




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Issues for Plant Growth Systems

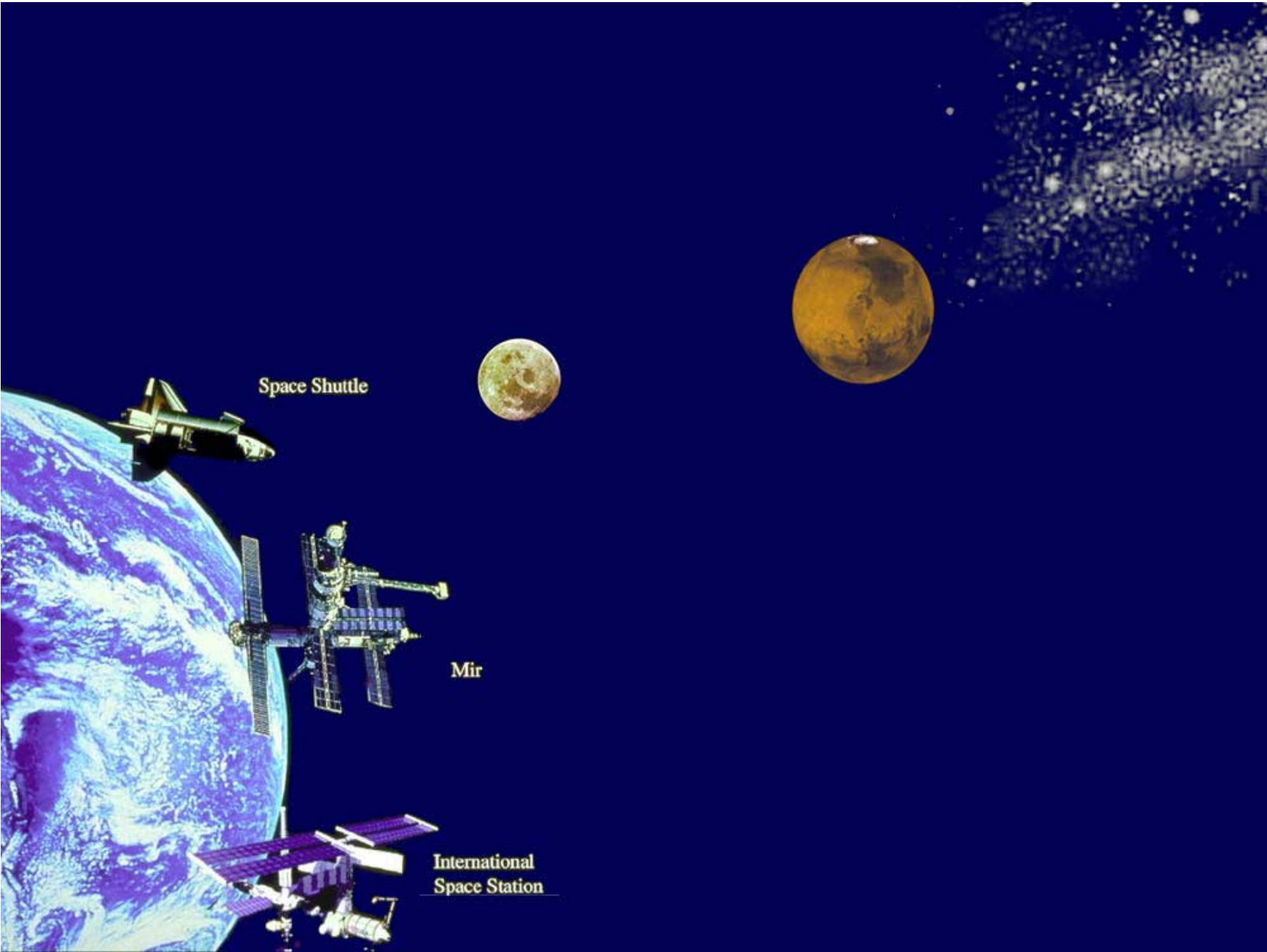
- Delivery of adequate water and oxygen to rooting systems
- Recovery and recycling of transpired water from plant systems (typically can expect $\sim 5 \text{ L m}^2/\text{day}$)
- Liquid / gas phase separation issues for both water delivery and retrieval systems
- Maintain adequate air flow around leaves and "soil" surface to offset lack of thermal stirring



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Some Top level Issues that Prevail

- **Particles issues in air filtration systems**
 - Fine particles in air treatment systems (CDRA)
 - Settling issues and clogging (Bends in systems)
 - Gravity effects
- **Sensors and Monitoring Systems**
 - Particulate pre-filtering (MCA)
 - Fine particles in miniaturized monitoring systems
- **Health issues associated with PM_{10} and less?**



Optimized Capillary Liquid Artery / Evaporator in Microgravity

A Research Topic Suggested for
NASA Multiphase Workshop for Flow in Power and Propulsion &
Fluid Stability and Dynamics
By Massoud Kaviany, University of Michigan, Ann Arbor

Many space-based (microgravity) systems rely on passive (capillary) liquid supply to evaporators. The evaporators can be divided into completely *separated liquid and vapor phase evaporators* (as in heat pipes, liquid acquisition, and AMTEC arteries), or *liquid-submerged evaporators* (as in porous-coating enhanced pool boiling). In both of these, a porous medium provides the capillarity suction for the liquid flow, but there are various liquid choking limits. The proposed optimal capillary liquid artery and evaporation in microgravity and its experimental examinations, may be suitable for the planned NASA multiphase flow experimental facility. This problem is identified as one of the critical issues in the early draft of the Workshop strategic planning.

An example of how the criticality of the capillary liquid supply in evaporation systems is addressed in the concept of enhanced pool-boiling CHF and evaporation/condensation by modulated porous coating reported in (Liter, S.G. and Kaviany, M., "Pool-Boiling CHF Enhancement by Modulated Porous-Layer Coating: Theory and Experiment," *Int. J. Heat Mass Transfer*, **44**, 4287-4311, 2001) is also shown in Figure 1. The various regimes in the heat flux versus surface superheat are shown. The concepts presented there are addressed for normal gravity, but the results are readily extended to the microgravity. Figure 2 gives a schematic of the deep porous coating, thin uniform porous coating, modulated porous coating, and unit-cell based artery evaporation-condensation loop.

The safe operating condition for the artery/evaporator is along the inclined line and the slope of the line is determined by the geometry and the effective thermal conductivity porous layer. The liquid viscous drag limit is raised by optimizing the capillary pressure and the viscous drag.

In Figure 1, the various liquid choking limits, namely, the *deep porous coating* (counter liquid-vapor flow) limit, the *hydrodynamic* (plain surface) limit, the *modulated hydrodynamic* (modulated porous coating) limit, *viscous drag modulated coating* limit, and the *kinetic* limit (the highest amongst them). Amongst these, the hydrodynamic limit is a gravity concept and does not exist under zero gravity (gravity is both assisting and hindering in pool boiling). The remaining limits continue to be present in microgravity and raising them would allow for optimal performance of such capillary liquid supply systems. The experimental results for normal gravity are also shown and are in good agreement with the theoretical predictions.

The counter, two-phase flow results in a rather low limit (critical liquid flux), and in general should be avoided.

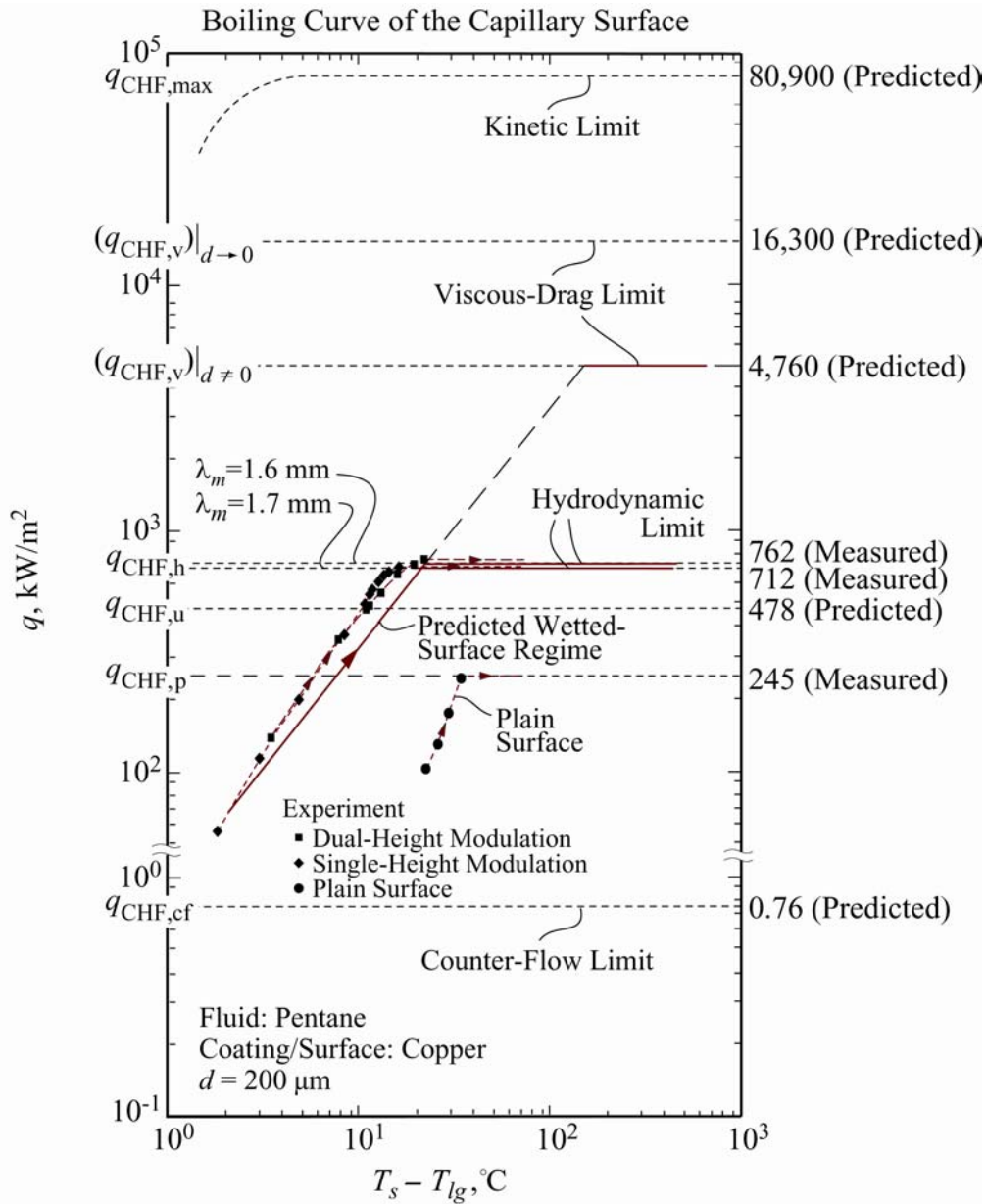


Figure 1 Heat flux versus surface superheat for plain and porous coated surfaces. The various liquid chocking limits are shown.

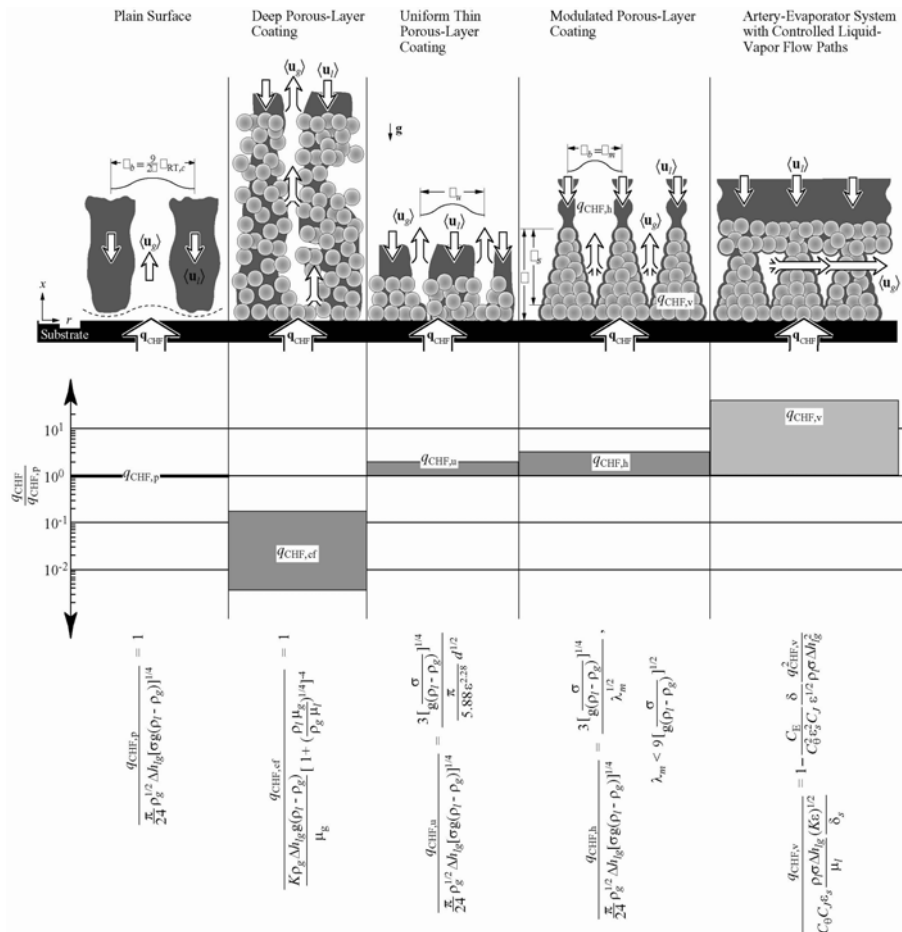


Figure 2 Comparison of various liquid chocking limits for critical heat flux on porous coated horizontal surface.

For the NASA multiphase research facility, both the modulated porous coating pool-boiling and the modulated porous stack evaporator/condenser, are impacting research problems offering a combined fundamental understanding and design optimization of capillary flow and evaporation, under microgravity.

Keywords: capillary pumped looped, looped heat pumped, enhanced critical heat flux, porous media flows, evaporation

COMMENTS ON THE DRAFT FOR NASA'S WORKSHOP ON , "TWO-PHASE FLOW, FLUID STABILITY AND DYNAMICS"

R. T. Lahey, Jr.

Rensselaer Polytechnic Institute

The upcoming workshop appears to be an interesting one and I am looking forward to attending. However, I have a few specific comments on the write-up and a general comment on what I believe NASA should do to develop the analytical capabilities that it needs to support future HEDS missions involving multiphase flows.

General Comments

As I am sure you folks at GRC know very well, because of current uncertainties in the performance of multiphase systems and processes in space, NASA has always tried to avoid using this technology. As a consequence, NASA designers have not been able to fully realize the power-to-weight advantages inherent in phase change systems and processes (i.e., they have not been a realistic design option for NASA).

Fortunately, technological (i.e., modeling and computational hardware) progress during the last two decades has shown us that we currently do have the capability to develop reliable 3-D multiphase predictive methods for space-based multiphase applications. This will require the acquisition of a suitable data base, and the development of flow-regime-specific closure laws for 3-D multiphase CFD codes, however, this can be done, and , if so, NASA should have a reliable way to perform design optimization and to systems scale-up. It is important to note that this physically-based approach to scale-up should be much more reliable and shouldn't take any longer to develop than the empirically-based approach that seems to be favored in the draft you sent to me for the workshop.

In any event , I believe that your priorities are correct (i.e., phase separation, CHF, etc. , is crucial mission enabling technology) but I would urge you to reconsider the importance of multiphase system instabilities. There have been many spectacular failures of phase change systems and processes on earth simply because, while there was a good understanding of, and modeling for, the performance of each component separately, it was forgotten that when they are put together the resultant system may be unstable (leading to degradation of performance and/or system failure).

Next , my specific comments on your draft are summarized below:

Comments on Page-5

Phase distribution and phase separation are intimately linked. That is, one must be able to predict the lateral distribution of the phases if one is to accurately predict phase separation. To do this will require the development and use of a reliable 3-D multiphase CFD code which is capable of handling the various flow regimes of interest to NASA. To this end, we need:

- Appropriately scaled μg experiments to identify the flow regimes expected in representative apparatus and components of interest.
- The development of mechanistic closure laws for a 3-D multiphase CFD model (none currently exists for μg conditions).
- Proof tests in the ISS to verify model predictive capabilities (including the reliability of scale-up).

Please note that the ability to predict phase distribution is also essential in conduits and plena, and in phase change equipment (e.g., boilers), if accurate predictions of CHF, two-phase pressure drop, etc. are to be available to the designers of equipment and processes to be operated in μg .

Moreover, if Rankine Cycle power plants are ever to be seriously considered by NASA designers for use in HEDS missions (e.g., a Rankine cycle has been proposed as the primary multi-Megawatt (nuclear) power conversion system for the Manned Mission to Mars), then there is an urgent need for detailed μg flow boiling data with which to benchmark CFD code predictions.

Comments on Pages 9-10

There seems to be some confusion about what we currently can and cannot do concerning the analysis of two-phase system instabilities; in particular, for density-wave oscillations (DWO). First of all, contrary to what was noted in the draft, DWO are due to the lag caused by the transport delay of the void waves passing through adiabatic or diabatic channels, and the feedback-induced inlet velocity perturbations due to the pressure boundary conditions which are applied. Currently we do not have any reliable μg data on DWO in parallel channel arrays or loops. Some appropriately scaled ISS data on DWO, including coupled pressure drop instability modes (i.e., involving an accumulator), is urgently needed. To do a good job of predicting two-instability phenomenon and better understand what happens in μg we need to develop a system instability code which can predict these data (fortunately this code may be the same as the CFD code discussed above; indeed, this is what is currently done for boiling water nuclear reactors (BWR) on earth). Speaking as one of the world's leading authorities in this area of technology, I can assure you that reliable predictions on μg instability phenomenon are currently not possible.

John, hope that this input is useful to you and I look forward to the Workshop.

Significant Open Design & Operational Issues For Thermal Management Systems.

David.W.Lee

TRW, Inc.

Flight qualification of multiple evaporator capillary pumped loops (CPL). Key technical issues involve bubble generation at startup and the development of a low thermal shock reservoir design. Enclosed are 2 references that highlight our recent CPL development efforts at Northrop Grumman Space Technology (NGST, formerly TRW). Reference 1 is our final report for our Advanced Lightweight Thermal Management Systems contract with AFRL. Reference 2 is a point paper written for the DoD Space Experiments Review Board (SERB) that describes the need for proceeding with our flight experiment, the EOS Chemistry Capillary Pumped Loop Qualification (CCQ), which would flight qualify a multiple evaporator CPL. These references provide background information as well as describe issues associated with multiple evaporator CPLs. (Note: prior to the Columbia accident, the SERB assigned CCQ a high priority for manifest on the shuttle).

The development and optimization of heat transport technology in support of space nuclear electric propulsion.

Pumped fluid loops at high temperature and pressure

Liquid metal heat pipe development

High temperature water CPLs

Road Map

Multiple Evaporator CPLs. Please see Reference 1- Section 5.0 (Conclusions and Recommendations) and Reference 2 - Table 1 (CPL Flight Qualification and Design Evolution).

Heat transport technology for space nuclear electric propulsion. We are currently in the process of defining our long range development plans for the Jupiter Icy Moon Orbiter (JIMO) program.

References (enclosed)

"Advanced Lightweight Thermal Management Systems, Final Report" (CDRL Item. No. A002), dated 15 November 1999. Contract no. F29601-95-C-0214. TRW Report No. 64766-020.

"EOS Chemistry Capillary Pumped Loop Qualification", Point Paper to 2002 DoD Space Experiments Review Board.



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Discussion of Priorities



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Prioritization Scheme

Priority Ratings

- **Critical:** enabling technology if not solved, don't or can't go.
- **Severely Limiting:** enabling technology but other systems can be used, but a steep price
- **Enhancements**
 - safety and reliability
 - weight savings
 - cost savings
- **Communication:** Analysis, modeling, existing resource awareness can overcome difficulties.

Method of Testing

- space-flight experiment (SF)
- ground-based reduced gravity testing (GB)
- normal gravity testing,
- analysis/modeling
- review of existing space-flight / ground-based data for its appropriateness.



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Critical Issues

Reduced Gravity Instabilities

- Flow/phase splitting through Parallel flow paths (system level)
- Phase Accumulation and release within Flow System Components
Transient Operations
 - Startup/Shutdown
 - Changes in Set Point Operation
 - Variable gravity over sustained time periods
 - 1 – g prior to launch & after landing
 - 1g during launch / landing
 - μ g, Martian, and Lunar
 - Variable gravity – sloshing



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Critical

- Phase separation, distribution and control
 - Control-- pick components, get in game
 - (not phase change part)
 - Take **best** tool, **best** data, design experiment to test (evaporator/condenser system) (one really **pertinent** example!)
- Critical heat flux in transient and oscillating flows (recovery)
 - Take **best** tool, **best** data, design experiment to test) (one really **pertinent** example!) Run transients Evaporator/(not a system)
 - Density wave oscillations in multiphase systems
 - Take **best** tool, **best** data, design experiment to test (evaporator/condenser system) (one really **pertinent** example!)
- Gravitationally insensitive evaporators/condensers
 - (same system)



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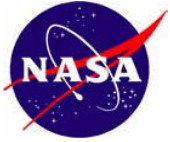


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Critical

- Scale-up
 - Do other scales (same idea)
 - Components



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Severely Limiting Phase Separation

- Active Separators based on Centrifugal concept. Unstable operations at flooding conditions
- *Multiphase (gas-liquid ?) pump*



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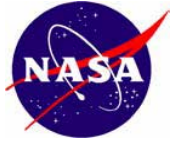
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Severely-Limiting Phase Change

- CHF is not a problem unless some other instability initiates a flow interruption.
 - Recovery from dryout by quenching hot surface because of
 - Exceeding CHF due to other flow instability
 - Hydrodynamic rupture of liquid film at slow slugging/wave frequencies
 - High power density: Spray cooling.



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Severely Limiting Flow Through Components

- Flow Splitting and Combining
- Packed Beds
 - Mass and Heat transfer coefficients
 - Phase Distribution and accumulation
- *Mass transfer in various systems*



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Severely Limiting

- *Noncondensibles*



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Enhancements

Passive Phase Separation

- Inertial Driven
 - Cyclonic devices
 - Tees/manifolds

Phase Change

- Surface Enhancements
- Surfactants & Engineered Fluids



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Awareness Instabilities

Likely Problems in reduced gravity – Solve through Analysis and Awareness. Maybe look at existing data

- Ledinegg/Pumped Loop Instability
- Pressure Drop Oscillations
- Density Wave Oscillations



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Awareness

Phase Separation

- Bubble removal from rotating tanks through Needle suction

Flow Through Components

- Valves
- Pumps
 - Single phase – avoid cavitation



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Methods of Resolution

- ISS
 - Fluids Integrated Rack
 - Microgravity Science Glovebox
 - Express rack
 - other
- Ground-based Reduced Gravity Facilities
- Normal Gravity Testing and Modeling
- *Long duration partial/micro gravity*



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Comment: Elements of ANY Two Phase Flow Experiment

- Liquid Supply
- Means of supplying vapor or gas
- Plumbing consisting of valves, tubing, accumulators, etc.
- Test article (s)
- Sensors – pressure, temperature, flowrate, *flow regime*
- Data Acquisition and Control System
- Ability to remotely change operational settings.
- Highly desired are Flow Visualization Sections, preferably high speed camera
- *Power, heat sink*
- *Ground control*



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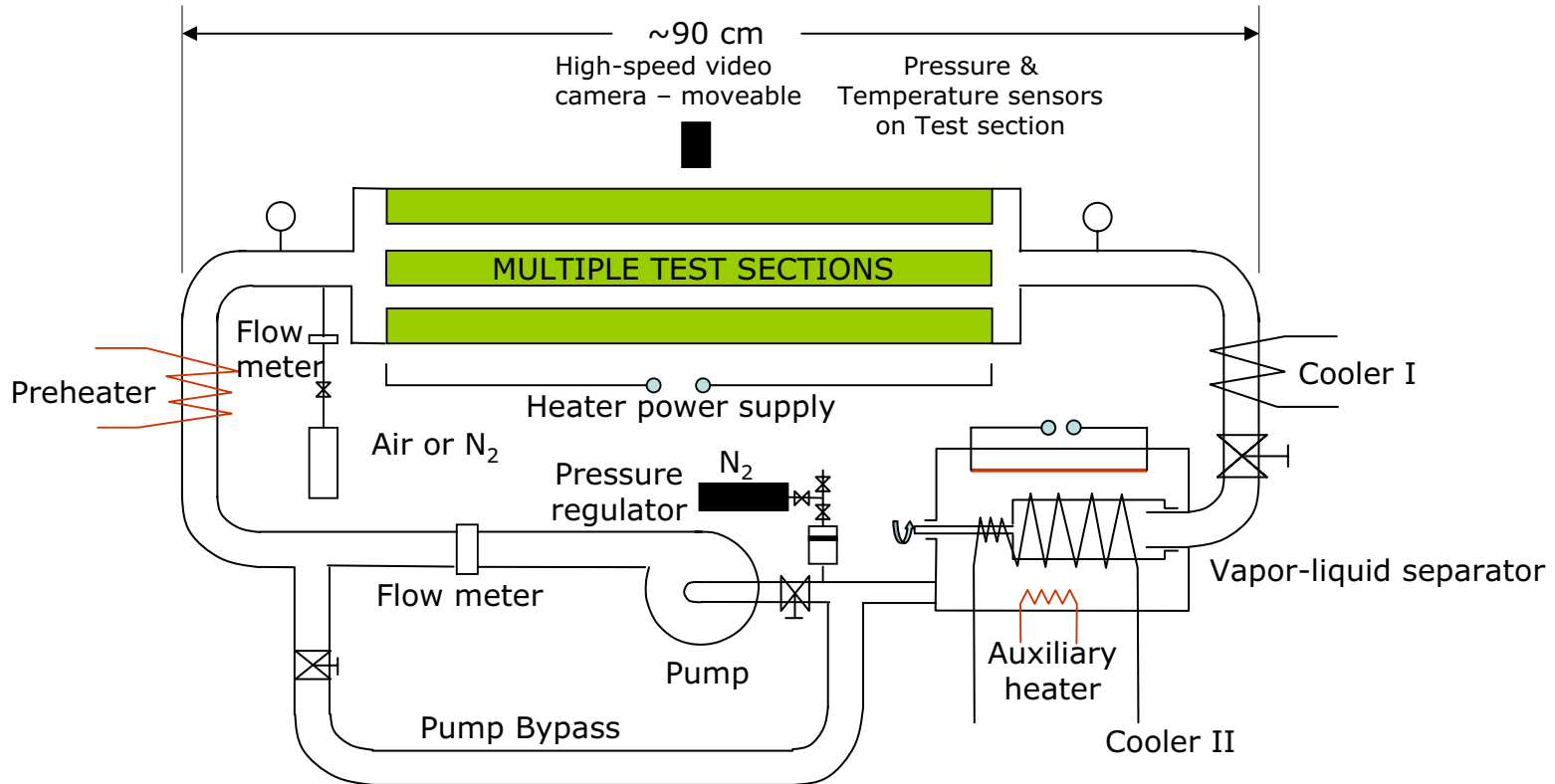
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Two-Phase Flow Facility (T₂FF₂)



Multiple test sections to investigate various geometries and flow regimes

- Preheater and cooler for temperature control
- Pump for forced convection
- Liquid/vapor separator



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2008 Space Flight

- Parallel flow channels with multiple evaporators.
 - Flow through splitting manifold into the parallel channels
 - Parallel channels could focus on different aspects of boiling, namely critical heat flux and quenching,
- Assess slugging phenomena on active separation device(s)
- *Packed Bed hydrodynamic characterization*



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2003 – 2008

Ground – Based μ G Facilities

- Flow splitting and mixing tees and manifolds (airplane)
- Component separation (air-water, e.g., fuel cells)
- Cryogenic (??)
- Phase Change
 - determine wetting characteristics of solid-liquid combinations and strategies (additives) to modify/control the wetting and spreading.
 - Conduct testing for rewetting/quenching of hot surfaces
 - Investigate the effects of wetting characteristics of a condensing surface
- Passive two phase flow separation techniques
 - Drainage of condensate with refrigerators from their "cold plates."
 - drainage of waste water, including urine from rat cages
 - continue bubble removal schemes for bioreactor
 - Propellants
- Initiate investigations of the effectiveness of techniques using acoustic, electric field, surfactants and surface enhancement for 1-g and low-g
 - (To alleviate CHF problems)



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**2003 – 2008****Other**

- Evaluate current two-phase system designs for known and appropriate normal gravity instability mechanisms.
- Continue and complete development of mechanistic models for nucleate pool boiling
- **Design tools/handbook**
- **Flow boiling**



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2009 – 2015

Space Flight

- Continue parallel channel instability tests
- Demonstration/validation of scaling
- Conduct phase change experiments for CHF, Quenching & Spray cooling
- Conduct phase change experiments on condensation to determine condensation heat transfer coefficient in microgravity
- Conduct ISS experiments on liquid-gas flows in packed beds (mass transfer, reactions)



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2009 – 2015

Ground – Based μ G Facilities

- Conduct experiments for pool and flow boiling for the effect of boiling enhancement techniques.
- Conduct advanced phase separator tests for a wide variety of concepts, including passive methods.
- Exotic materials and fluids,
- Nuclear power components
- Setting up for the next grand and glorious project
- Electrical and electroacoustic manipulation of interfaces and fluids



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**2009 – 2015****Other**

- Bio power sources
- Nano-scale prototypes for power/etc
- Designed surfaces for heat transfer
- Combined comprehensive modeling effort for multiphase heat transfer and flow leading to user design code.



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2016 ++
Space Flight

- Phase change and heat transfer with exotic materials
- High and low pressure and temperature experiments
- Large scale system demonstrations



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2016 ++
Ground – Based μ G Facilities

- Detailed verification of the comprehensive computation package.



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2016 ++
Other

- two phase design and operations manuals
- software package development?.



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**Multiphase Flow in Power and
Propulsion Workshop
Fluid Stability and Dynamics
Workshop**

Sponsored by the
Office of Biological and Physical Research,
NASA HQ

Hosted by
NASA Glenn Research Center
15 May 2003



Two-phase Flow, Fluid Stability and Dynamics Workshop Microgravity Science Division



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Agenda

- 7:30-8:00 AM Continental Breakfast
- 8:00- 10:00 AM Opening Plenary
 - 8:00 -8:10 Opening Welcome (Ostrach - NCMR)
 - 8:10 - 8:20 Logistics (Kassemi - McQuillen)
 - 8:20 - 8:35 Overview Roadmap (Singh)
 - 8:35 – 8:55 Nuclear Propulsion - (Johnson - GRC)
 - 8:55 - 9:15 Advanced Life Support (Joshi - HQ)
 - 9:15 - 9:35 Strategic Research (Chiaramonte - HQ)
 - 9:35 - 9:50 **Overview of Draft Document**
 - 9:50 -10:05 Facility Description
 - 10:05 – 10:15 Charge to the Panels (McQuillen)
- 10:15 - 10:45 Break
- 10:45 – 2:30 Parallel Sessions
 - Multiphase Flow Session McCreedy
 - Stability & Dynamics Hochstein &
- 12:00 - 1:00 Working Lunch
- 2:30 – 4:00 Plenary Technical Discussion
- 4:00 – 5:00 Closing Plenary Session - Panel Reports
- 5:00 Dinner/Adjourn

12-May-2003

Overview - McQuillen

2



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Workshop Purpose

- Short term: Present a research plan and a “roadmap” developed for strategic research for the Office of Biological and Physical Research.
- Long term: Conduct necessary ground-based and space-flight low gravity experiments, complemented by analyses, resulting in a documented framework for parameter prediction of needed by designers.



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Various Strategic Planning Exercises

- Research Maximization and Prioritization (ReMAP), August 2002.
- NASA Exploration Team (NExT)
- Led to OBPR's Strategic Research Initiative.



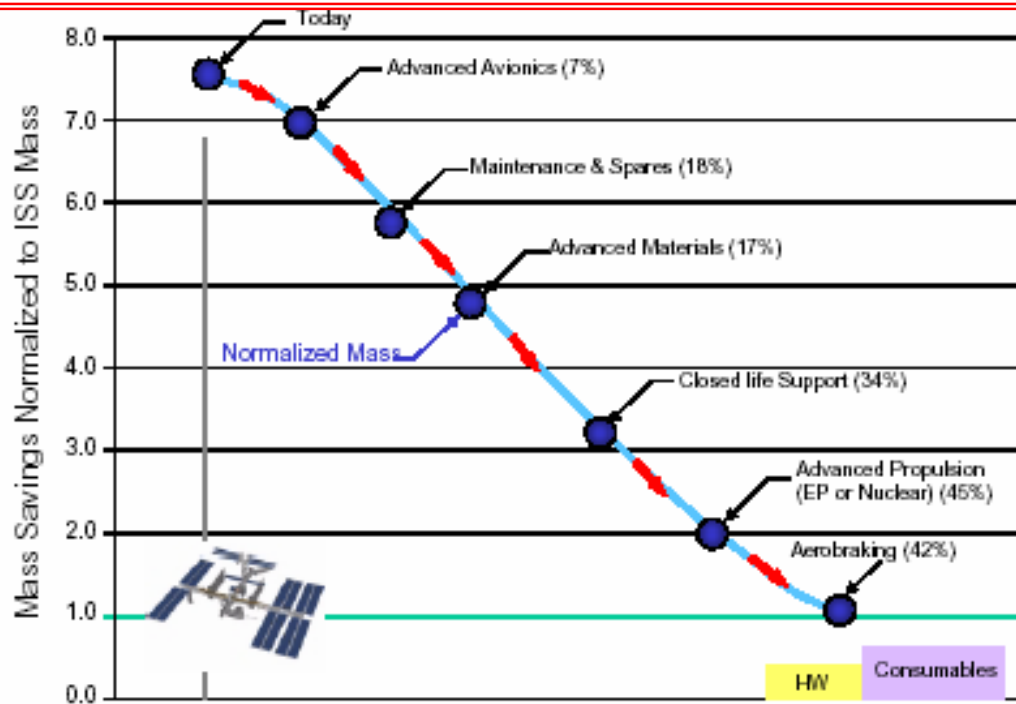
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Planned Improvements to Reduce Mass for a Manned Mars Mission





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Some Previous Two-phase Flow Workshops & Studies

- 1986 - Microgravity Fluid Management Symposium
- 1989 - Workshop on Two-Phase Fluid Behavior in a Space Environment
- 1990 - The Workshop on the Commercialization of Space Fluid Management
- 2000 - Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies – NRC Report
- 2000 - Workshop on Research Needs in Space Thermal Systems and Processes for Human Exploration of Space
- 2000 - Workshop on Research Needs In Fluids Management for the Human Exploration of Space

These Workshops have emphasized the importance of multiphase flow and phase change for NASA's exploration mission.



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Goal of these Previous Workshops

- Brainstorm
- Prioritize
- Develop a roadmap



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What's Different

- To Brainstorm, our “team”
 - Used previous studies/workshop outputs
 - Received additional input from technology developers
- To Prioritize, our “team” using non-research perspectives
 - Engineer needing to design
 - Operator needing to know how to operate
 - Project/Program Manager deciding whether or not to “buy” technology.
- To Develop roadmap, our “team” considered
 - Two-phase Priorities
 - Available Space Station Resources
 - Available Manifesting Opportunities
 - Schedules for Technology Cutoff Dates



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Put on our “engineering” hats
What do they “need” to know

1. Will it Work?
 - Over What Range of Conditions?
 - What are its advantages over other means?
2. How does system respond to transients in setpoints?
 - How do I start it on a reliable basis?
 - How do I safely shut it down so I can restart it later?
 - How does the system respond to changes in operating conditions and set-points.
3. What about system instability?
 - What can cause it?
 - What sequence of events can cause it?
 - How do I identify it?
 - Can the system recover?
 - What is the result of the instability?
 - What sort of damage can result?



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Put on our “technology shopper” hat
What do they need to know before they buy into
using technology

Be able to test systems in normal gravity and have a high degree of confidence that they will function in a variety of gravity levels with no problems. (The upside down and sideways test)

OR

See an identical system currently performing well for a very similar set of conditions. (Someone else is first)



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Prioritization Scheme

Priority Ratings

- **Critical:** enabling technology if not solved, don't or can't go.
- **Severely Limiting:** enabling technology but other systems can be used, but a steep price
- **Enhancements**
 - safety and reliability
 - weight savings
 - cost savings
- **Awareness:** Analysis, modeling, existing resource awareness can overcome difficulties.

Method of Testing

- space-flight experiment (SF)
- ground-based reduced gravity testing (GB)
- normal gravity testing,
- analysis/modeling
- review of existing space-flight / ground-based data for its appropriateness.



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Why are we here?

- We have provided you a “strawman” Research Plan and Roadmap
- Review Priorities and Roadmap
- Provide Feedback
 - Does the plan make sense? If not, then let us change it so it does.
 - Will the proposed space-flight experimental facilities adequately address significant questions?
 - What other facilities & tests are needed to address critical and severely-limiting issues?
 - Are there any other elements missing in the plan?



Physical Sciences Research POP 2003 Fluid Physics Program

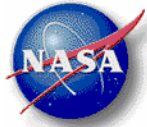


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Human Research Initiative (HRI)

INTRODUCTION:

- A code U initiative starting in the FY04 budget includes specific funding for “Phase Change” and “Multiphase Flow Research” on the ISS.
- NASA GRC developed a concept for two facilities based on funding/schedule constraints:
 - Two Phase Flow Facility (T²FFy) – assumed integrating into FIR
 - Contact Line Dynamics Experiment Facility (CLiDE) – assumed integration into MSG
- Each facility will accommodate multiple experiments conducted by NRA selected PIs with an overall goal of enabling specific NASA strategic objectives.
- May also be a significant ground-based component.



Physical Sciences Research POP 2003
Fluid Physics Program



Glenn Research Center

Two-Phase Flow Facility (T ϕ FFy)

OBJECTIVES:

Develop a multi-user mini facility for conducting strategic research in the area of two-phase flow. The research will consist of experiments to conduct focused studies and provide critical data on boiling, condensation and two phase flow. Specifically, experiments will study the effects of microgravity on modes of heat transfer and flow regimes during convective boiling and the flow characteristics of two-phase flow through fluidic components and porous media.

APPROACH:

A forced-flow loop with multiple test sections and controlled heating and cooling will be developed for utilization in the FCF-FIR. Maximum use of facility provided capabilities will be utilized.

BENEFITS:

Improved understanding of heat transfer processes in multi-phase flow, which will allow for the development of lower-mass space thermal systems and advanced space power systems. Experimentation will support power generation and storage, space propulsion and life support systems.

Project Milestone Schedule





Physical Sciences Research POP 2003
Fluid Physics Program



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Two-Phase Flow Facility (T ϕ FFy)

Flow Boiling Heat Transfer

- Conduct focused studies on the effects of microgravity on the modes of heat transfer and the corresponding flow patterns in forced convective boiling.
- Provide data on the effects of gravity and liquid inertial forces on CHF.
- Develop advanced optical techniques to understand multiphase flow dynamics, including bubble growth and transport, liquid and vapor droplet sizing, and velocity measurements.
- Investigate techniques for CHF enhancement.

Flow Through Fluidic Components

- Conduct studies of 2-phase flow in microgravity through geometries representing fittings, accumulators, and valves.
- Investigate incidence of metastable states in flow of flashing liquid and choking in fluidic system components.

Porous Media

- Conduct focused studies on the effects of microgravity on a gas-liquid fixed Packed Bed Reactor.
- Provide critical data on the effects of gravity on the hydrodynamic properties of gas-liquid flow through porous media.

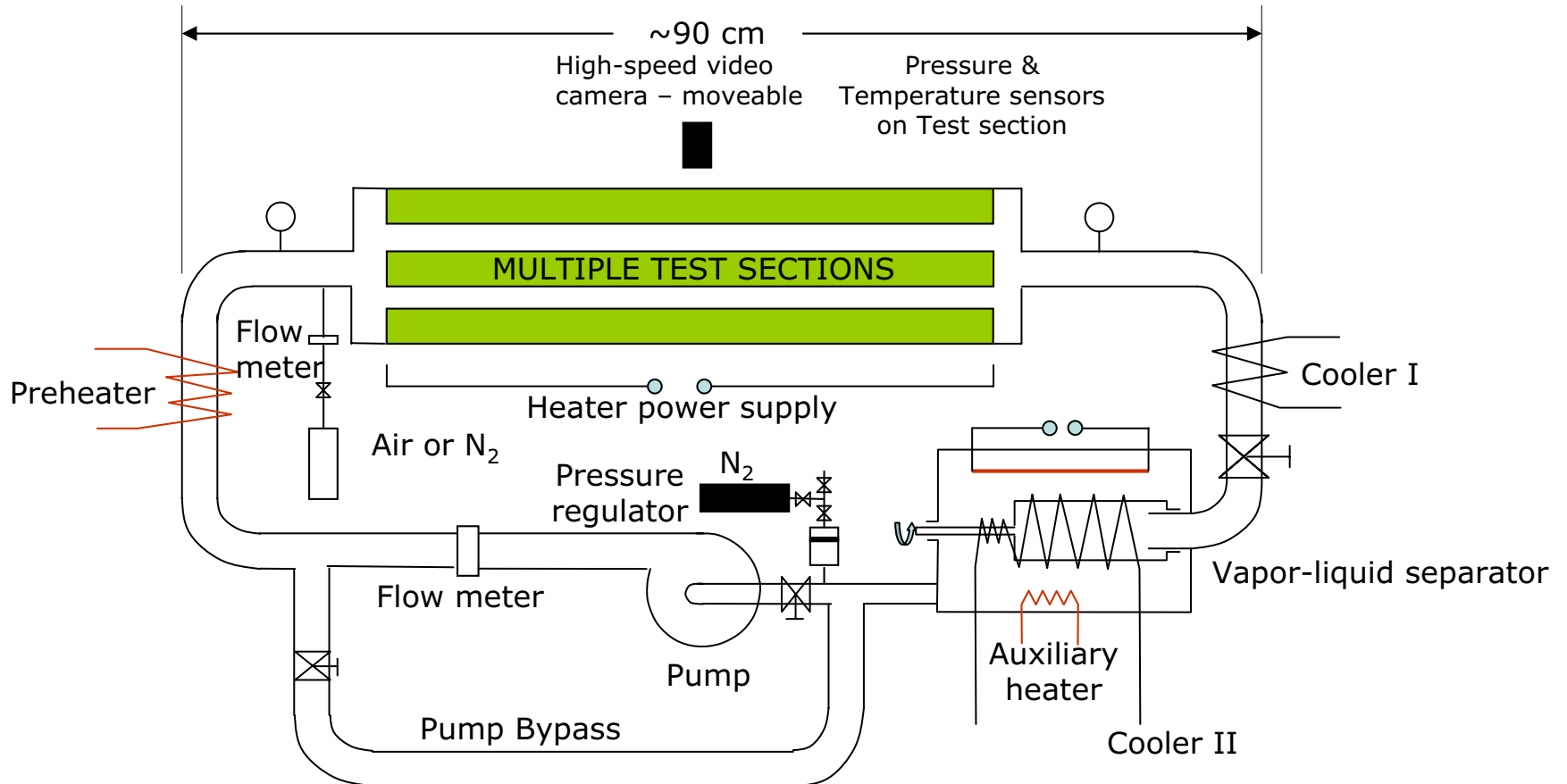


Physical Sciences Research POP 2003
Fluid Physics Program



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Two-Phase Flow Facility (T ϕ FFy)



Multiple test sections to investigate various geometries and flow regimes

- Preheater and cooler for temperature control
- Pump for forced convection
- Liquid/vapor separator

HRI - Motil



Physical Sciences Research POP 2003
Fluid Physics Program



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Contact Line Dynamics Experiment Facility (CLiDE)

OBJECTIVES:

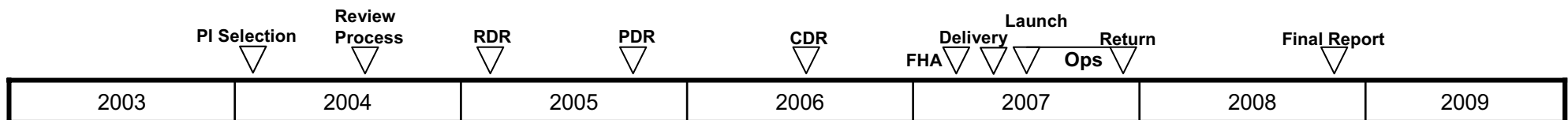
Develop facility for conducting strategic research on the effects of contact line dynamics on the behavior of liquid-vapor systems that are controlled by capillarity.

APPROACH:

A circular pinning edge will be placed on the periphery of the cell. An indexing motor will move a cylindrical tube along its axis and perpendicular to the plane of the pinning edge. An axially symmetric fluid-vapor interface will form between the tube and the pinning edge. Various modes of tube motion will be possible, depending on the specific objective. The facility will be able to handle any fluid and solid surface including realistic fluids used in space fluid systems and suitably wettability-modified solid surfaces.

BENEFITS:

Improved understanding of the effect of contact line dynamics in microgravity will improve fluid and heat transfer models. This enhanced understanding will also lead to more efficient propellant tank, heat-pipe, and evaporator designs.





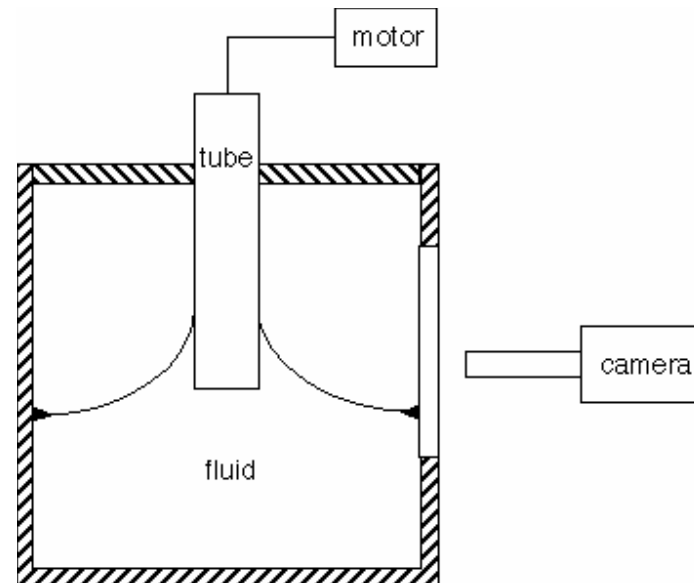
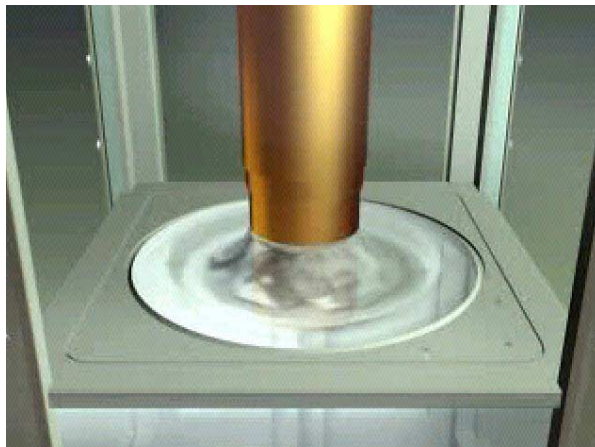
Physical Sciences Research POP 2003
Fluid Physics Program



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Contact Line Dynamics Experiment Facility (CLiDE)

- Develop an understanding on how contact line dynamics affects interface behavior in low gravity.
- Investigate the use of surface properties to control interface dynamics.
- Develop an understanding of the contact line boundary condition to be used in CFD models.





Physical Sciences Research POP 2003 Fluid Physics Program



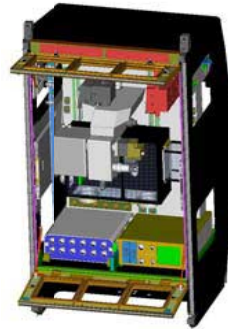
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FCF Flight Segment

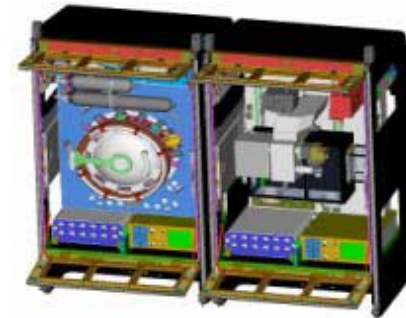
Fluids and Combustion Facility



**Combustion
Integrated
Rack (CIR)
ULF-2**



**Fluids
Integrated
Rack (FIR)
UF-3**



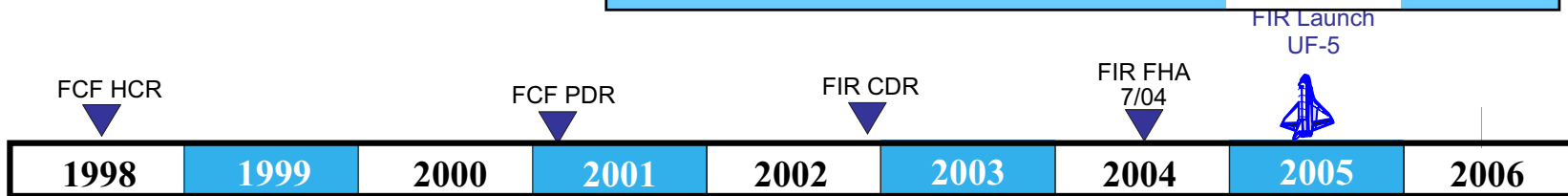
**Combustion
Science
Rack**

↔ data ↔

**Fluids
Physics
Rack**

CIR and FIR will operate independently, however the capability has been scarred to connect to available diagnostics and mass storage devices from the other rack. This capability will enable the Fluid Physics and Combustion Science disciplines to share mutually necessary hardware/software.

FCF will be able to accommodate experiments at the rate of 10 or more per year for the lifetime of the Facility.



HRI - Motil



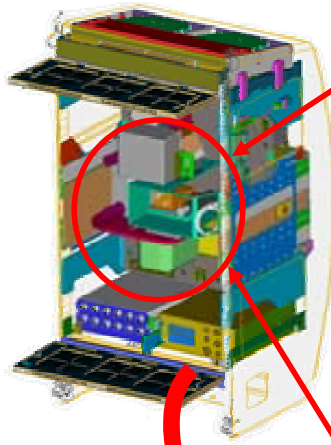


Physical Sciences Research POP 2003 Fluid Physics Program



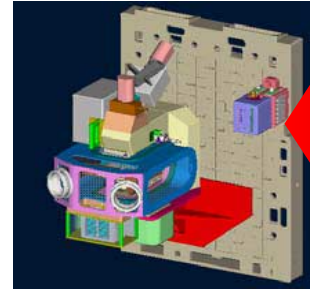
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*FCF Fluid Integrated Rack
with Multi-User PI Hardware*

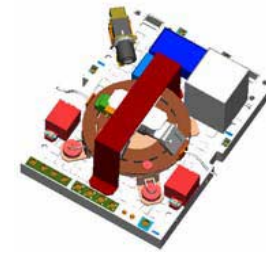


ISS US Lab Module

Multi-User PI Inserts



Light Microscopy Module



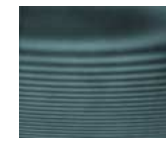
Granular Flow Module

PI Specific Insert

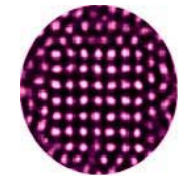


**Microgravity Observations
of Bubble Interactions (MOBI)**

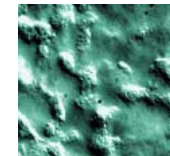
*Light Microscopy
Experiments*



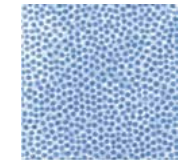
CVB



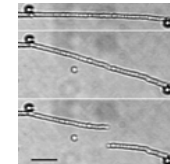
PHaSE-2



PCS-2



LΦ CA



LMM-5 / GAST



LMM-6 / Clark



**Muscle tissue
fiber strands**



Physical Sciences Research POP 2003 Fluid Physics Program

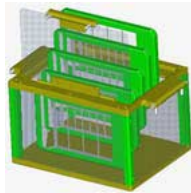


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FIR/Payload Integrated Configuration

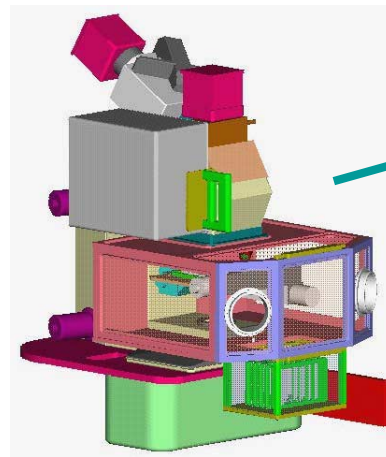
The FCF FIR includes support subsystems and laboratory style diagnostics common to the specific researchers and supplements the laboratory with unique science hardware developed for each Principal Investigator (PI).

PI-specific and multi-user hardware customizes the FIR in a unique laboratory configuration to perform fluids research effectively.



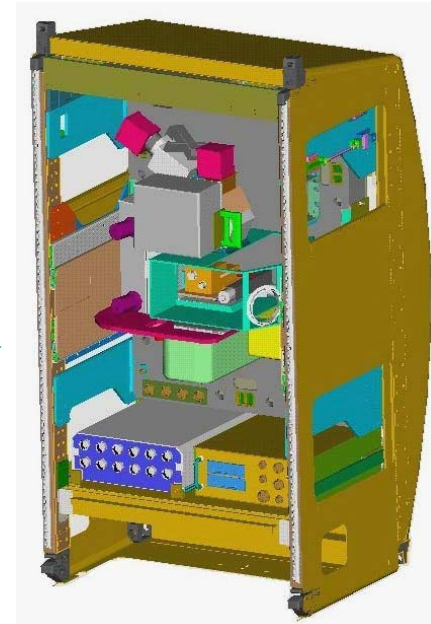
PI Specific Hardware (Fluids or other discipline)

- PI Sample Cell with universal Sample Tray
- Specific Diagnostics
- Specific Imaging
- Fluid Containment



Multi-Use Payload Apparatus

- Test Specific Module
- Infrastructure that uniquely meets the needs of PI fluid physics experiments
- Unique Diagnostics
- Specialized Imaging
- Fluid Containment



FCF Fluids Integrated Rack

- Power Supply
- Avionics/Control
- Common Illumination
- PI Integration Optics Bench
- Imaging and Frame Capture
- Fluid Diagnostics
- Environmental Control
- Data Processing
- Light Containment

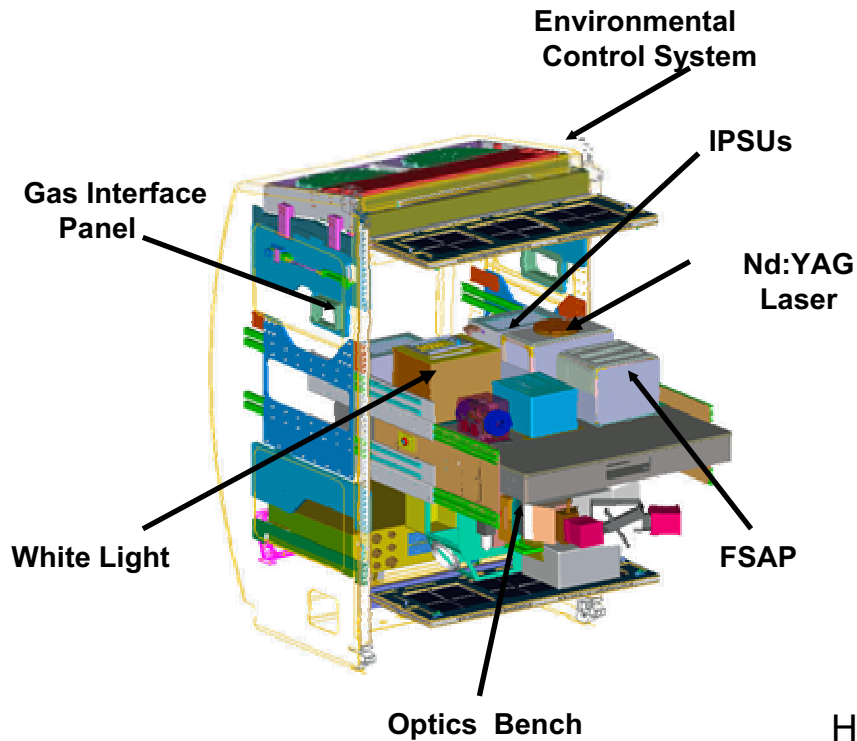
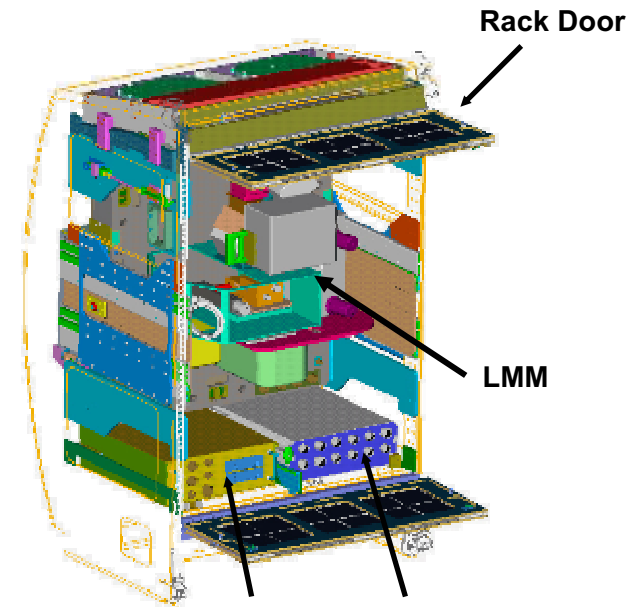


Physical Sciences Research POP 2003 Fluid Physics Program



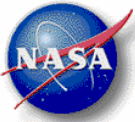
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- Volume ~ 0.49 m³ (1100mm x 895mm x 495mm)
- Power
 - 672 W at 28Vdc
 - 1450 W at 120Vdc
- Thermal Cooling
 - 3 kW water (MTL)
 - 500 W air (provided at 20°C to 30°C)



- Video
 - Analog Color Camera
 - C-IPSU - IEEE 1394 FireWire & Analog Frame Grabber Interfaces for PI provided cameras
 - C-IPSU - Image processing & storage units for real time and post processing of image data
 - Illumination
- Control & Data Acquisition
 - FSAP - Standard control and data acquisition interfaces (e.g. analog & digital I/O's, motion control, RS-422)
 - MDSU & IOP - 1.3 TB of Data Storage

HRI - Motil



Physical Sciences Research POP 2003 Fluid Physics Program



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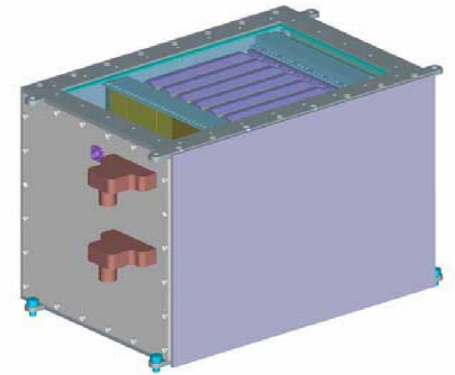
•C-Image Processing and Storage Unit (C-IPSU)

•Function

- Stores digital image data received from a camera
- Perform automated real-time image analysis, processing and reduction
- Provide control signals to camera diagnostic control modules and to illumination packages

•Features

- IEEE 1394, FireWire Interface for camera control and image acquisition
- Analog video, RS-170A, input
- Analog video output from scan converter that converts digitally acquired data to an RS-170A signal
- Sync bus for synchronizing illumination sources and cameras
- Two 36 GB hard drives



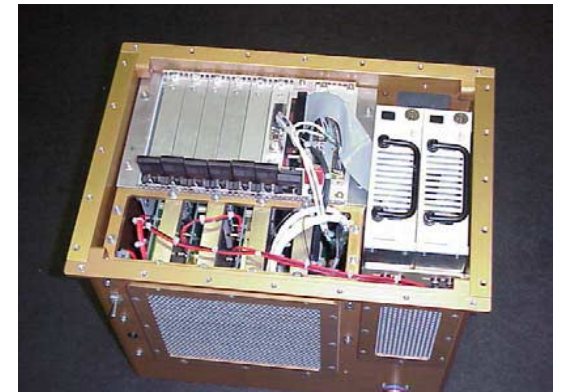
•Fluids Science Avionics Package (FSAP)

•Function

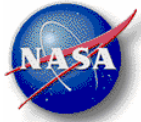
- Serves as the control and data acquisition system for the payload.

•Features

- RS-422, 2 channels
- Analog and discrete inputs and outputs (A/D, D/A, DIO)
- Motion control, 4 channels
- Analog video frame grabber
- CAN bus control of diagnostics and PI H/W
- Hard drive storage, 72 GB



HRI - Motil



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•Nd:YAG Laser

•Function

- Provides a laser source for various diagnostic techniques such as Particle Induced Velocimetry (PIV).

•Features

- 532 nm, 150mw Output power
- Analog control of laser functions
 - Laser pump On/Off
 - Diode drive current (electrical attenuation)
 - Attenuator stepper motor (mechanical attenuation)
- Bench mounted rear, fiber coupled to front of bench
- Laser output power monitoring
- Controlled by FSAP

•White Light Package

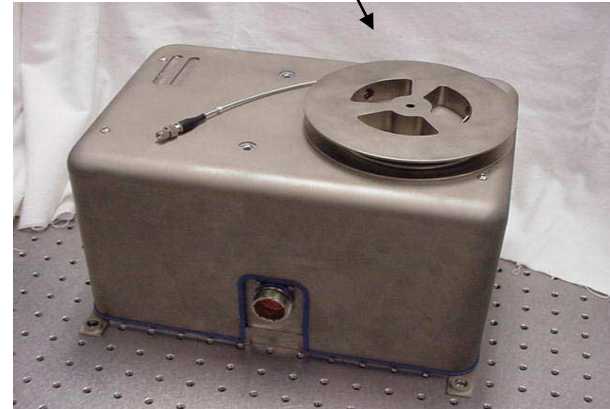
•Function

- Provides uniform, broad band lighting

•Features

- Two independent light engines
- Easy replacement of light engine
- Adjustable intensity
- Fiber Optic Quick disconnects
- Mounted to rear of bench, quick connect/disconnect of fiber bundles
- Controlled by the FSAP

Fiber Optic Cable Spool





Physical Sciences Research POP 2003 Fluid Physics Program



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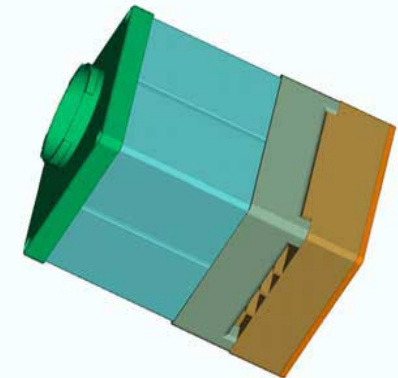
-Initial Capability

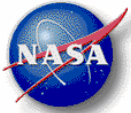
- Color Camera
 - 24 Bit, 3 chip CCD
 - 1/3 inch array, 768 X 494 pixel
 - RS 170C output (30 FPS)
 - Remote and interchangeable head allowing for in-situ calibration with controller



•Planned Facility Upgrade

- High Resolution Camera
 - SMD camera
 - 1k X 1k, 144 mPixels
 - 15 – 30 – 60 FPS
 - 12 Bit gray scale
- High Frame-rate Camera
 - 512 X 512 array
 - Firewire, IEEE 1394
 - CMOS imager, 1000 fps @ 512 X 512 for a minimum of 4 seconds
 - Capable of 32,000 fps @ 32 x 32



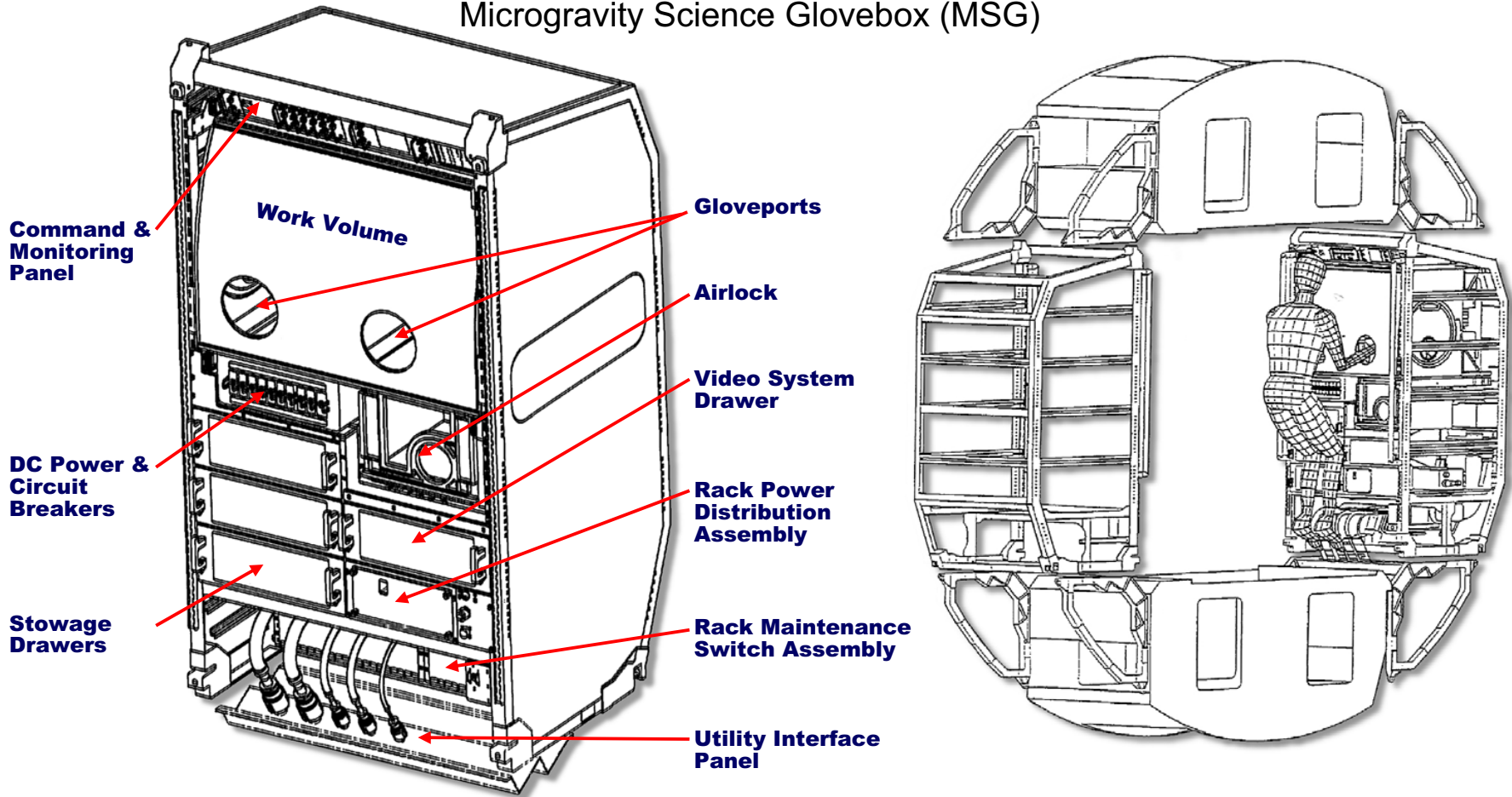


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Microgravity Science Glovebox (MSG)



HRI - Motil



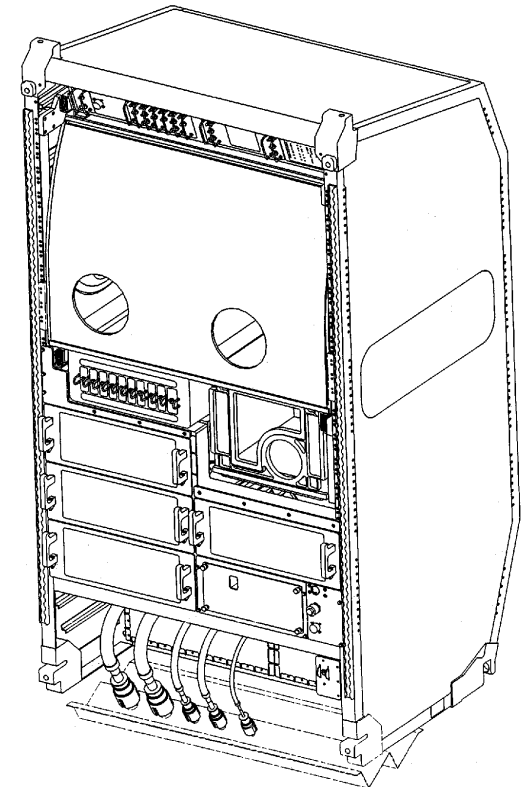
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Fluid Physics Program



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Microgravity Science Glovebox (MSG)

Work Volume	255 liters, ~906 mm wide, ~637 mm high, ~500 mm deep (at the floor)
Maximum size of single piece of equipment in WV	406 mm diameter, 406 mm high (through side ports) 254x343x299 mm (through airlock)
Power available to investigation	+28V at useable 7 Amps +12V at useable 2 Amps -12V at useable 2 Amps (not independent of +12V) + 5V at useable 4 Amps 120V at useable 8.3 Amps (Maximum total power draw from all outlets is 1000W)
Maximum heat dissipation	1000W (800 from coldplate, 200 from air circ)
General illumination	1000 lux @ 200 above the WV floor
Video	Color and B&W cameras, dedicated recorders
Data handling	RS422 between investigations in WV and MSG Laptop Two MIL1553B connections between MSG and Facility Laptop (one inside, one outside WV) 8 differential analog and 8 discrete signals in WV 2 Ethernet connections inside WV
Filtration	HEPA/charcoal/catalyst - replaceable on orbit
Other resources available	Nitrogen Vacuum HRI - Motil





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RESEARCH**

**A COOPERATIVE VENTURE
between
NASA GLENN RESEARCH CENTER
UNIVERSITIES SPACE RESEARCH ASSOCIATION
and
CASE WESTERN RESERVE UNIVERSITY**



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RESEARCH

NCMR
FLUIDS AND COMBUSTION

MICROGRAVITY RESEARCH

AN AGENCY-WIDE ASSET

Using NASA-Generated Knowledge to Solve Its Own Problems



- Many NASA facilities and enabling technologies involve transport phenomena whose behavior is unknown at reduced g
- NASA is limited to low-earth orbit human operations by primitive technologies (at enormous cost for resupply)
- Need self-generating and self-sustaining technologies to be efficient under unprecedented conditions in alien environments

No Knowledge Bases For Such Designs



MICROGRAVITY RESEARCH SCIENTIFICALLY IMPORTANT AND ALSO ESSENTIAL FOR DESIGN AND DEVELOPMENT OF ENABLING ADVANCED TECHNOLOGIES AND FACILITIES

- Fluid and Thermal Sciences are the CORE for both research and applications



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RESEARCH

Research for Design

Current Situation

- **The technologies required to exit from low-earth orbit do not exist**
 - **Lack of microgravity knowledge bases to design advanced technologies**
- **Mission Planners and Research Scientists are not working together early enough to bring about needed advances**
 - **Technical interchange between designers and researchers enhances engineering creativity and increases opportunities to develop enabling technologies and significantly maximizes life cycle cost savings**



Original List of R4D Candidate Topics

Cryo Fluid Management

- In-tank heat exchanger/in-space and surface
- Fluid behavior/mixing
- Impacts of varying g-level and tank size
- Liquefaction
- Thermal diode cooler-tank
- Fluid gaging
- Liquid acquisition

TCS

- 2 Phase Flow
 - Evaluation of developing length necessary for “fully developed two-phase flows”
 - Pressure drop characterization for fittings quick-disconnects, elbows, tees, manifolds, etc.
 - Instability issues for two-phase flows in manifolds
 - Development of mechanistic scaling techniques for two-phase systems (e.g., Earth-g system to zero-g system)
 - Development of advanced instrumentation (e.g., void fraction and film thickness sensors) for use with refrigerants or ammonia
 - Expand two-phase database for zero-g and partial-g with different size tubes and different fluids (enables validation of models and scaling techniques)
 - Engineering models/correlations for use in two-phase system design and verification

Power

- Regen fuel cell operating over varying g-level
- Surface reactor heat transfer
- Heat rejection system-viability of 2-phase and/or heat pipes
- Liquid metal reactor startup

Fire Safety/Combustion

- Extinguishment – use CO₂?
- Detection
- Transhab materials testing



Original List of R4D Candidate Topics

ECLSS

- Unsaturated flow in porous media (mass transfer)
 - Plant Growth
- Environmental control (temperature, humidity, dust)
 - CO₂ removal
 - Methods to control CO₂ to low concentrations (below 0.3% by volume)
 - Reduced power
- Trace contaminant control system
 - Regenerable sorbent materials
 - Investigations of catalyst poisoning/upsets
- Gas/liquid separators
- Sensors
 - O₂, CO₂, humidity, combustible gases, organic contaminants
 - Dust control methods
- Water tank/radiation shield
 - Hydrophilic/hydrophobic membranes
- Flow through catalytic reactors
 - 2 Phase flow modeling
 - Oxygenation (single phase)
 - Temperature/pressure effects

- Micro-g compatible bioreactors
 - Oxygenation/O₂ mass transfer
 - Product gas separation
 - Biomass management
 - Flow rate measurement
 - Dissolved oxygen measurement
 - Methods to reduce channeling of packed bed bioprocessors
- Membrane Separation
 - Biofilm control/fouling prevention
 - 2 Phase/3 Phase separation of process stream
 - Oxygenation of aqueous streams
 - Wicking properties for evaporative systems
 - Management of air/water vapor mixtures (vis-à-vis, condensing heat exchange)

ISRU

- Phase separation
- Liquid-Liquid separation
- Micro-channel flow
- CO₂ acquisition at low pressure
- Gas/dust separation
- Thermal processing of Mars atmosphere and soils



THE NATIONAL CENTER FOR MICROGRAVITY RESEARCH

Research for Design

Fluids and Combustion Microgravity Research Relevance to Space Exploration Activities

	Interfacial Phenomena	Multiphase Flow and Transport	Phase Change Heat Transfer	Combustion	Phase Separation	Granular Materials
Power Generation and Storage	Ö	Ö	Ö	Ö	Ö	
Propulsion	Ö	Ö	Ö	Ö	Ö	
Life Support	Ö	Ö	Ö	Ö	Ö	
Fire Safety				Ö		
ISRU	Ö	Ö	Ö	Ö	Ö	Ö
Construction and Maintenance	Ö	Ö				Ö
Cryogenics Fluid Management	Ö	Ö	Ö		Ö	
Thermal Management	Ö	Ö	Ö			



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National Center for Microgravity Research on Fluids and Combustion “Value Added Tasks”

Research for Design

Objective of Research for Design

Develop the knowledge for the design and development of self-sustaining technologies by involving fluids and combustion scientists and technologists directly with mission analysis/system designers in early space exploration project definition, design and development

Unique Features

- Customer driven (close coordination with the developer)
- Research done to a schedule – answers to specific questions in a timely manner
- Develops unique knowledge databases
- Brings to bear wealth of microgravity knowledge developed by NASA
- Solves enabling problems





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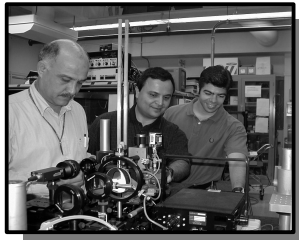
**Control of Flow and
Nutrients to Plant Roots
Under Microgravity and
Variable Gravity**



Understand the physical transport phenomena in porous media to be able to control the air, water and nutrient transport to root zone for successful plant growth in microgravity.

**Zero Boil-Off Pressure
Control of Space Propellant
Tanks**

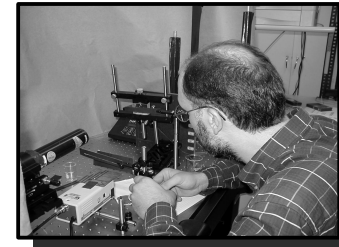
Investigate ways of preventing boil-off of cryogenic propellants during long duration



interplanetary missions which could include stops at the moon.

Research for Design

**Control of Two-Phase Flow
in the Microchannel of
Proton Exchange
Membrane Fuel Cells**



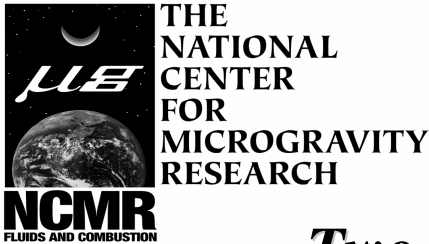
Predict the flow of air and water in the microchannel of PEM fuel cells to design a gravitationally independent device.

**Effect of Reduced Gravity
on the Soldering Process**



Develop a quantitative understanding of the effect of a low-gravity environment on the soldering process

*R4D
Pilot
Projects*



Characterization & Control of Two-Phase Flow in Microchannels (PEM Fuel Cells)

Objectives:

- assist NASA in developing a gravitationally insensitive, regenerative fuel cell
- quantify low-Bond number, non-inertial, 2-phase flows in complex geometries
- use scientific results to develop design tools for predicting liquid holdup, phase separation and mixing in complex channels for various wetting conditions and geometric configurations
- ability to predict behavior of non-fully-developed two-phase flow; such as flow through fittings and short channel lengths
- assist in developing predictive tools for designing flow passages for fuel cell stacks and manifolds

Applicability and Impact:

- Low-temperature, regenerative fuel cells hold great promise for providing renewable power for human exploration of both low-Earth orbit and interplanetary space missions.
- Research is applicable to miniature fuel cells as replacement to batteries in portable electronic devices for terrestrial and/or microgravity applications.
- Research is applicable to high throughput screening applications; such as bioreactors, proteomics, genomics, and protein crystallization.

Approach:

- systematic microchannel experiments to investigate 2-phase flow in fuel cell channels; varying gas/liquid ratios, flow rates, aspect ratio, entrance conditions, and geometries
- comprehensive computational study of microchannel experiments
- macrochannel experiments using low-gravity test rig on KC-135; testing two-phase flow behavior in manifolds and in various fittings typical of fuel cell stack manifolds

Team:

Principal Investigator(s): J. Allen, M. Kassemi/NCMR, J. McQuillen/GRC

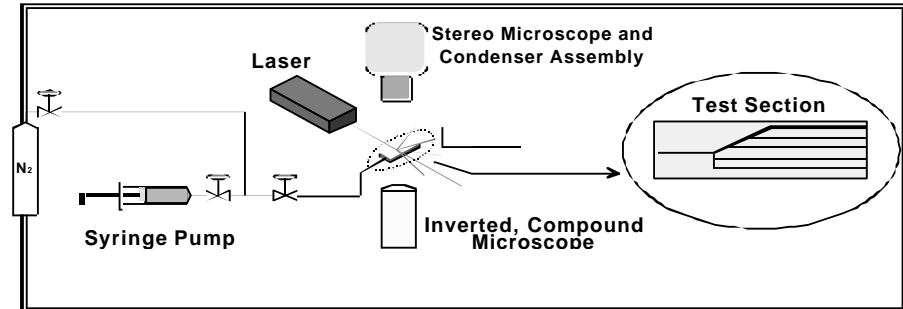
Primary Customer: William Hoffman/JSC

post doctoral researcher: S. Son/NCMR

contracted diagnostics: Prof. K. Kihm/Texas A&M and 2 graduate students

summer faculty fellow: Prof. L. Sumner/Mercer Univ.

undergraduate students: E. Driscoll/ Univ. Dayton, S. Wood/Texas Tech



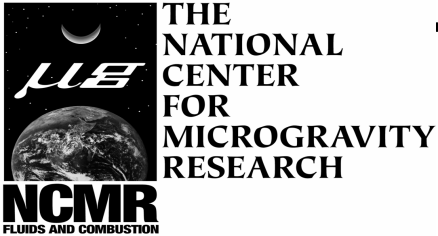
Task Schedule

- Microchannel Studies
- KC-135 Macrochannel Studies
- Develop/Validate Two-Phase CFD Model
- Design Tools for Fuel Cell Optimization
 - phase separation/mixing in microchannels
 - two-phase flow scaling analysis
 - video library of two-phase flow transients
 - two-phase flow in manifolds

		FY02				FY03				FY04			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Microchannel Studies													
KC-135 Macrochannel Studies													
Develop/Validate Two-Phase CFD Model													
Design Tools for Fuel Cell Optimization													
• phase separation/mixing in microchannels													
• two-phase flow scaling analysis													
• video library of two-phase flow transients													
• two-phase flow in manifolds													

Accomplishments to Date:

- collaborations established with Texas A&M, Texas Tech, Mercer Univ. & Univ. Dayton
- new diagnostic techniques developed for studying two-phase flow in microchannels:
 - » micro-particle image velocimetry (μ PIV)
 - » molecular tagging fluorescence velocimetry (MTFV)
 - » Fizeau interferometry for measuring liquid film profile around a gas bubble in microchannels
 - » backscattering interferometer for non-intrusive pressure measurements
- developing technique for inexpensive fabrication of complex microchannel passages



Research for Design (R4D)

“NASA has long recognized the need to use its scientific resources to advance the technology it needs for the space program”

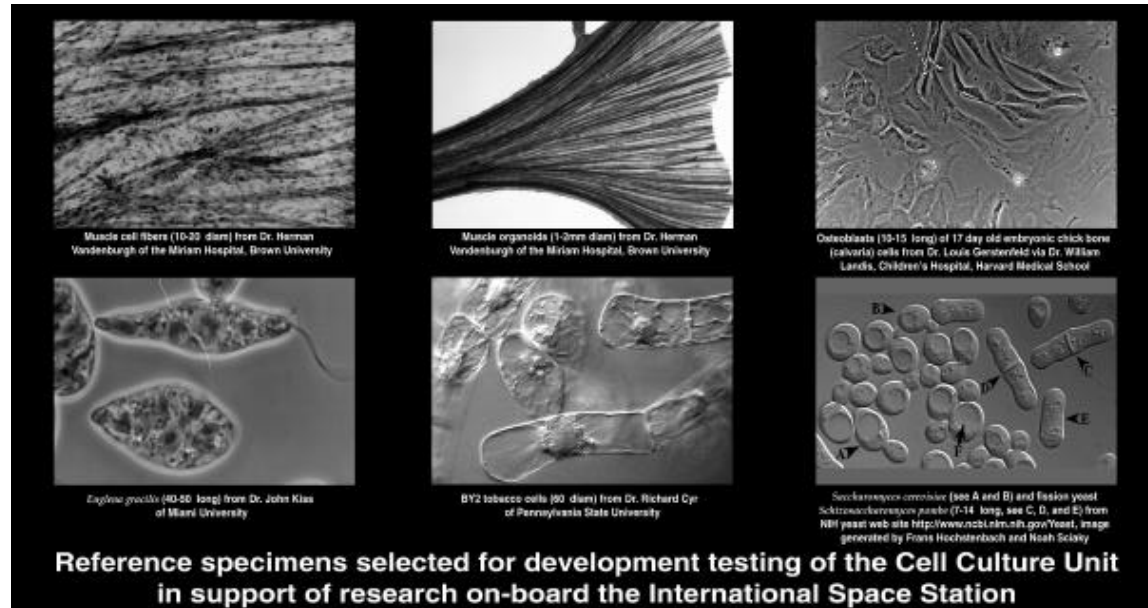
“However, there was no institutional method for proceeding with specific cooperative investigations”

“The NCMR, through its R4D effort is reminding NASA how this can be done. NASA should strongly encourage this initiative by the NCMR--- because the basic method is right, and will surely help NASA learn how to develop the science-technology connection which it lacks, but which may well be the key to NASA’s future success”

“The Administrator should recognize the agency-wide significance of R4D and support it directly” (not from the research budget)

Cell Culture Unit design goals

CCU must accommodate diverse cell types, diverse responses to gravity changes, diverse needs of scientific community



- Can this culture system provide the nutrient and gas exchange required for optimal growth without exposing the cells to forces greater than the microgravity?
- How do we develop systems with comparable mass transport in different gravitational environments (1-g Earth control, *m*-g, centrifuged CCUs up to 2-g on ISS)?

Other NASA Technologies

Conduct other research in direct support of NASA's technology programs.

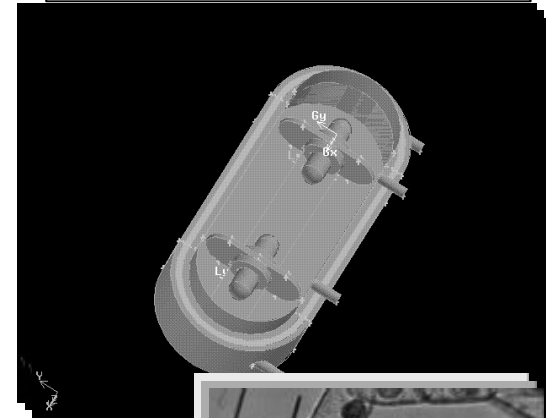
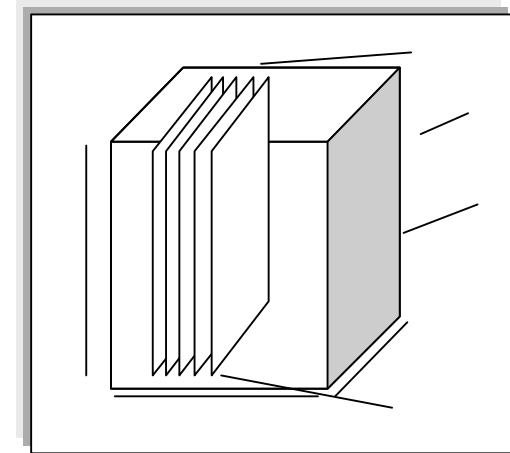
- **Lithium-Based Polymer Battery Program Funding Source (NASA GRC)**
 - Analytically demonstrate that thermal dissipation (Joule heating) is a limiting factor in terms of predicting life cycles in polymer based battery
- **Cell Culture Unit Funding Source (NASA ARC)**

Research Scientist: John Kizito

Application Area: Fluid physics, Computational Fluid Dynamics, Fundamental Space Biology

Impact

- NASA is about to spend \$1.0 Billion dollars on Biology and Biotechnology in space. We are assisting in designing meaningful interdisciplinary biological space experiments by offering predictive tools related to transport issues in Microgravity



Rodent Urine Management for the Advanced Animal Habitat in Microgravity

Application Area

Veterinary services in microgravity

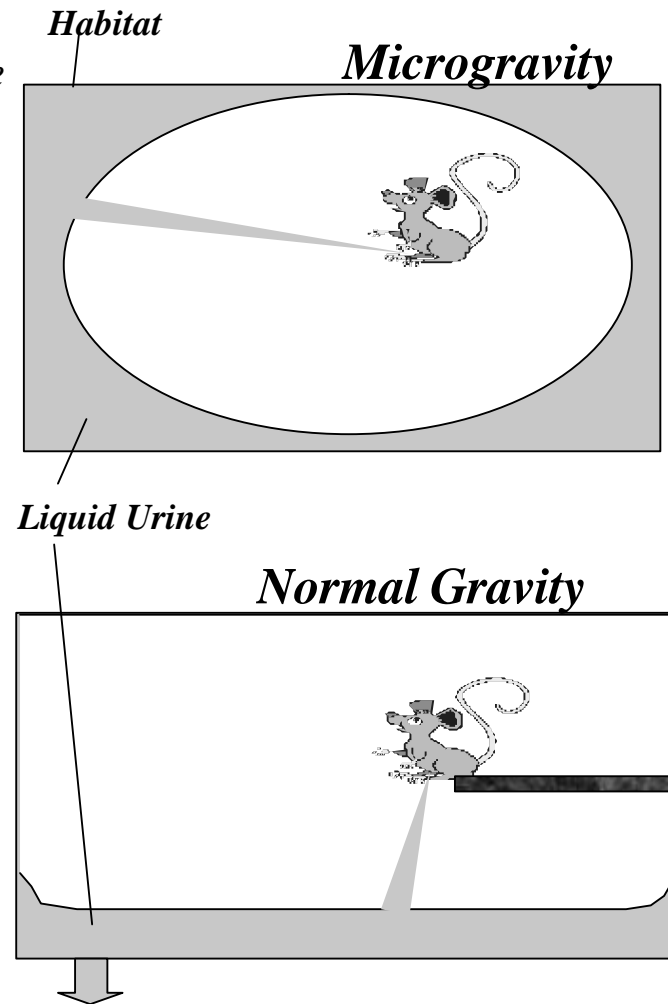
- render expert advice to *STAR Enterprises, Inc.* and *Space Hardware Optimization Technology, Inc.* to the design of the Advanced Animal Habitat-Centrifuge for *NASA Ames Research Center* which will house rats and mice on the International Space Station.

Nature of the Problem

- Existing habitat design results in accumulation of rodent urine on walls
 - Rodent proximity to the wall result in wicking the urine onto the fur or hair causing hypothermia
 - Existing fan design causes liquid evaporation and urea crystallization resulting in pungent smell
- Rodent mother and baby interaction

Impact

- Animal tests are essential for experimental and medical trials a prerequisite long duration manned exploration missions

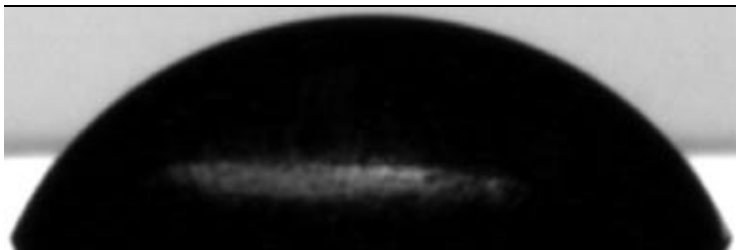
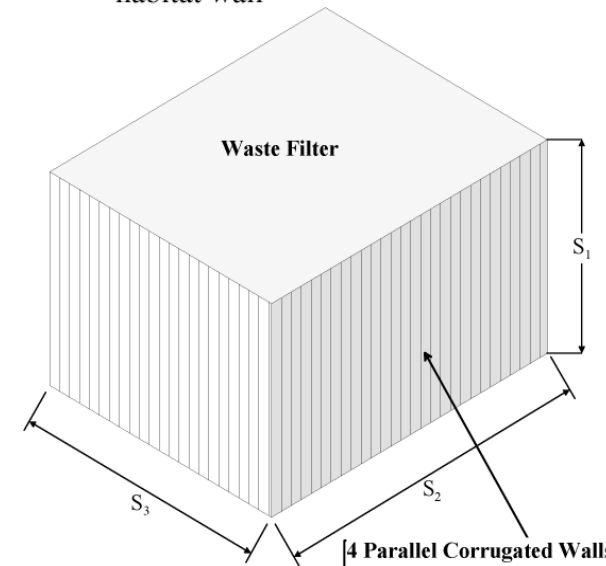
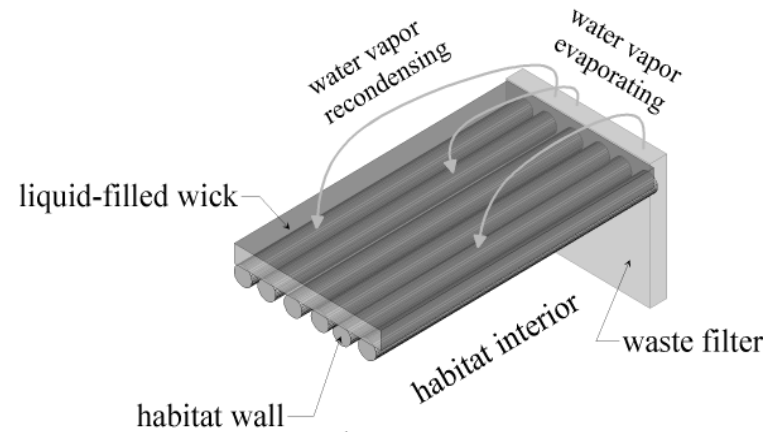


Research Scientists: John Kizito and Jeff Allen

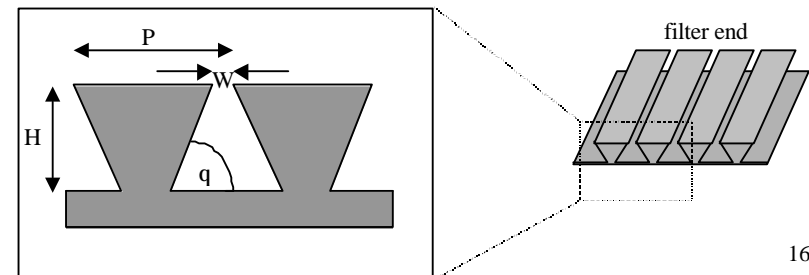
Application Area: Fundamental Space Biology

Results

1. Measured 301 data points of transport properties of rodent urine,
2. Developed concepts of managing fluids within the specimen chamber such that:
 - the animals remain suitably dry,
 - fluids within the specimen chamber are directed to the primary waste filter and/or liner for containment and/or evaporation,
 - fouling of the lighting subsystem, the camera lenses, and sensors within the specimen chamber is minimized,
 - liquid is deterred from entering air outlet, and
3. Developed a plan for concept verification.



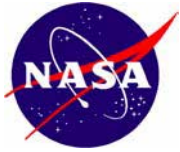
Male rat urine on untreated aluminum. Contact Angle, $\theta \approx 67.0^\circ$





Conclusions

“NCMR is a vital and successful operation, effectively supporting NASA’s program in many ways beyond technical monitoring. NCMR is supplying leadership for certain new initiatives important to NASA’s future. NASA might regard NCMR as kind of a small laboratory of innovative research management, and should support it generously”



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Microgravity Science Division*

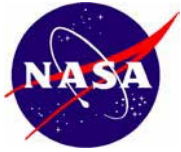
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**Multiphase Flow in Power and
Propulsion Workshop
Fluid Stability and Dynamics
Workshop**

Sponsored by the
Office of Biological and Physical Research,
NASA HQ

Hosted by
NASA Glenn Research Center
15 May 2003



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Fluid Stability and Dynamics Workshop
Microgravity Science Division*

Space Directorate



Workshop Purpose

- Short term: Present a research plan and a “roadmap” developed for strategic research for the Office of Biological and Physical Research.
- Long term: Conduct necessary ground-based and space-flight low gravity experiments, complemented by analyses, resulting in a documented framework for parameter prediction of needed by designers.



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Motivation for this Workshop

- Research Maximization and Prioritization (ReMAP), August 2002.
- NASA Exploration Team (NExT)
- Led to OBPR's Strategic Research Initiative.

Need a Research Plan and Roadmap to
Guide the Strategic Research



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Some Previous Two-phase Flow Workshops & Studies

- 1986 - Microgravity Fluid Management Symposium
- 1989 - Workshop on Two-Phase Fluid Behavior in a Space Environment
- 1990 - The Workshop on the Commercialization of Space Fluid Management
- 2000 - Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies – NRC Report
- 2000 - Workshop on Research Needs in Space Thermal Systems and Processes for Human Exploration of Space
- 2000 - Workshop on Research Needs In Fluids Management for the Human Exploration of Space

These Workshops have emphasized the importance of multiphase flow and phase change for NASA's exploration mission.



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Why are we here?

- We have provided you a “strawman” Research Plan and Roadmap
- Review Priorities and Roadmap
- Provide Feedback
 - Does the plan make sense? If not, then let us change it so it does.
 - Will the proposed space-flight experimental facilities adequately address significant questions?
 - What other facilities & tests are needed to address critical and severely-limiting issues?
 - Are there any other elements missing in the plan?



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Agenda

- 7:30-8:00 AM Continental Breakfast
 8:00- 10:00 AM Opening Plenary
 8:00 -8:10 Opening Welcome (Ostrach - NCMR)
 8:10 - 8:20 Logistics (Kassemi - McQuillen)
 8:20 - 8:35 Overview Roadmap (Singh)
 8:35 – 8:55 Nuclear Propulsion - (Johnson - GRC)
 8:55 - 9:15 Advanced Life Support (Joshi - HQ)
 9:15 - 9:35 Strategic Research (Chiaramonte - HQ)
 9:35 - 9:50 Overview of Draft Document
 9:50 -10:05 Facility Description
 10:05 – 10:15 Charge to the Panels (McQuillen)
- 10:15 - 10:45 Break
 10:45 – 2:30 Parallel Sessions
 Multiphase Flow Session McCreedy
 Stability & Dynamics Hochstein &
- 12:00 - 1:00 Working Lunch
- 2:30 – 4:00 Plenary Technical Discussion
- 4:00 – 5:00 Closing Plenary Session - Panel Reports
- 5:00 Dinner/Adjourn



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Workshop Deliverables

- Revised Research Plan and Roadmap Document to represent “Consensus Best Plan”
- Identified list of spaceflight and ground-based facilities and modeling that are needed to answer the key missing questions (considering limitations of budget and space access).
- Any other consensus recommendations that the community wants to include.

Workshop recommendations will be sent to HQ for their use in formulating and advocating strategic research.

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