

# **Research Campaign White Paper: Physical Sciences Ground-Based Research Campaign**

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Successful completion of the tasks identified by the Decadal Survey within 10 years will require a robust ground-based program to identify, define and support the spaceflight experiments and to nurture the next generation's scientific talents (graduate students and faculty) that will lead these efforts in the latter half of the decadal effort. This white paper identifies specific research areas that the authors consider the most important of those submitted to the topical decadal review and recommends a strong incubator program for ground-based research over the next decade. The transformative science objective is to enhance access and engage researchers for disciplinary research progress, technology development, and nurture of new ideas for flight investigations. An important underlying thesis of this white paper is that, just as you expect to produce much less corn if plant only one cornstalk (they depend on other plants for support and pollination) you cannot expect vigorous scientific production from a narrowly defined, small cadre of investigations and investigators. It is only in the crucible of a dynamic, critical, and supportive community that great science is born. To this end, this white paper proposes a broad ground-based ecosystem that challenges and incubates selected research themes and then provides a fertile training and collaborative environment for the researchers. Furthermore, this ecosystem will enable the discovery of the future research programs that will be the focus of the next 2033 decadal review. It is our contention that without the existence of a vibrant ecosystem of microgravity investigators, the outcome of the themes selected by the decadal review will have compromised success.

Although we have been fortunate to have a healthy group of spaceflight investigations over the past decade and a strong set proposed for the current Decadal review, it is clear that the breadth and novelty of new investigation concepts have been limited by the very small number of active investigations and investigators in the field. This deficit in both talent and ideas will only grow in the absence of a far-reaching, multi-discipline, ground-based program to identify new research areas and foster the talent to perform the work. Some of the most consequential microgravity discoveries in the physical sciences in the past decade have been serendipitous (quasi-steady cool flame regime, formation of hedgehog structures using elliptical particles, explosive boiling in capillary-driven heat pipes). Although some important programs are identifiable without the benefit of ground-based low-gravity testing, the vast majority have been identified, grown, and refined through initial small exploratory efforts. This is in large part because initial exploration in ground-based testing is the most cost-effective way to perform high risk, high reward research efforts. Beyond the benefit of the initial exploration, ground-based programs are necessary to define the test matrix and refine science requirements; assess the viability of hardware concepts; and mature necessary technologies.

Just as a corn plant needs soil, this ecosystem cannot be nurtured by only investing in research investigations without an equally intense investment in the "soil" i.e. ground-based reduced gravity testing capability. When the PI and project community suffered from the severe funding reductions of 2005-2006, the ground-based test capability investment plummeted to below maintenance levels. The successful spaceflight programs in the years after these reductions were a direct result of the more hidden investment in the ground-based program in the years prior to the reductions. To support an active ground-based reduced gravity program, reliable, cost effective access to ground-based testing is essential. This will require investment in a range of systems from drop towers, aircraft, suborbital vehicles to centrifuges. At this point the situation has degraded to the point that US investigators do not have access to a research grade aircraft and the NASA drop towers are falling so far behind the advances in the discipline [1-3] that they will no longer meet the research needs of the decadal review by the end of the decade. Although the additional

investigators and ground facilities will be costly, the collective input of hundreds of investigators will be a very cost effective force multiplier compared to merely expanding the flight program.

Another part of the ecosystem that is neglected in a narrowly-defined, flight-only research model is public and student engagement. Our collective success depends on the continued engagement of students, faculty, and the public at large. In this regard we have three recommendations: (1) through STEM programs and public engagement educate the public at large about the importance of gravity-induced phenomena and reduced-gravity research, (2) increase the number of students studying gravity related physical sciences in higher education, and (3) maximize utilization of existing ground-based facilities. In the discussion below we identify the leading ideas presented by our disciplines and discuss the impact of ground-based testing on these projects. Proposed test facilities improvements in support of these ideas are also identified.

### **Combustion Science:**

NASA has a long history of combustion research in reduced-gravity facilities including drop towers, sub-orbital vehicles, the Space Shuttle and now the International Space Station (ISS). Historically NASA used a vigorous ground-based program, [4] built through the periodic release of research solicitations (NRAs), to build the program from the ground investigations up. The vibrant ground program helped: train hundreds of graduate students, build NASA's reputation as a leader in fundamental combustion science and guided the selection and development of the most promising ideas for spaceflight experiments. All of the ISS combustion experiments (conducted and planned) can trace their roots back to this ground program.

A 2014 workshop helped identify priorities for the combustion science program. The participants included academia, industry, and other government agencies. The panels identified several topics as priority areas moving forward: high pressure transcritical phenomena, low temperature and/or weak flames, and material flammability, all of which have White Papers submitted for consideration by the NASEM [5-11]. The topical area of high pressure represents a new research thrust (in microgravity) and has immense practical and theoretical relevance. Transcritical refers to the condition where reactants enter the combustor at subcritical conditions but undergo heating and mixing and can transition to supercritical conditions.

As combustors move to higher operating pressures (increased efficiency) engineers rely increasingly on physics-based computational tools to develop new engine concepts. Unfortunately, there is a dearth of fundamental information near supercritical conditions with the critical point representing a near singularity. Only through the control of boundary conditions and symmetry uniquely provided in a microgravity environment can the link between computation and physical reality be assured. A NASA-led multi-agency microgravity research program in microgravity, offers a unique opportunity. High-pressure conditions represent relatively uncharted territory in microgravity combustion research requiring a broad ground-based program to support the flight testing. A ground program is necessary to identify the research topics that require flight, address other research topics on the ground, develop hardware specifications and mature diagnostic techniques. High pressure research presents new challenges (hardware, diagnostics, modeling) that are not a simple extension of the traditional low-pressure combustion research. Gas flows can be destabilized at high pressures and at supercritical conditions since there is no surface tension to stabilize liquids. Understanding and overcoming these challenges cannot be accomplished with a single flight experiment; they need a large multi-dimensional community of researchers working independently and in teams to make the needed transformational leaps in this area.

While low-temperature and/or weak, low-stretch flames represent more established topics in microgravity combustion, there is no incubator program to identify, develop, and address new

concepts. This is particularly true for high risk, high reward ideas. The prior ground-based program not only helped build the flight program but was scientifically relevant on its own. [12] The success of the combustion flight program was the direct result of a healthy ground program that utilized state-of-the-art facilities. A vigorous ground-based program using updated and state-of-the-art facilities is necessary to ensure the future success of the microgravity combustion program.

#### **Fluid Physics:**

The Topical Investigation Submissions to the Decadal Review identified cryogen management; [13] boiling and multiphase flow [14-19]; capillary behavior; [20] fluid management [21-22]; and heat pipes [23] as critical elements in the next decade of fluid physics research. The success of boiling experiments aboard the space shuttle and ISS were due in large part to ground-based research that preceded the space flight. Research by the individual PIs included comprehensive numerical model development of the phenomena as well as extensive testing in normal gravity and using ground-based reduced gravity facilities. This ground preparation meant that despite limited on-orbit testing of the Microheater Array Boiling Experiment in the Boiling eXperiment Facility, the overall science outcome of the effort could be salvaged by tweaking a previously developed transition criteria for buoyancy dominated boiling vs. surface tension dominated boiling. It should be recognized that these previous experiments were very focused and there is a wide range of other variables that have not been studied in reduced gravity such as fluid types, geometry effects, surface finish, not to mention imposition of flow, electric and acoustic fields. A data set this broad cannot be covered in a flight program and can only be addressed by a coherent ground-based program which would not only mature the research field but would also highlight those research efforts that would benefit the most from long duration microgravity.

Similarly narrow in scope, the Zero Boil Off Tank (ZBOT) experiment is a series of at least three space flight experiments led by a single investigator and his team. Even though there is intense interest from the cryogenic community and an immediate need to increase the fundamental understanding of transfer and long-term storage of volatile fluids in microgravity, a single team's approach limits the pace of obtaining results and also adds risk as a potential single point failure. Surrounding the flight investigation with a vibrant ground-based program would both challenge and bolster the flight investigation.

#### **Fundamental Physics:**

The fundamental physics community submitted white papers that covered a broad range of topics at the forefront of physics where substantial benefits can be gained from conducting experiments in space (e.g. ISS, commercial stations, Gateway, Lunar Surface, Free Flyers.) White papers included research in cold matter physics, physics with optical clocks, physics with atom interferometers, research at the intersection of quantum and gravity, quantum entanglement research, tests of the standard model of physics, Gravitational physics, complex plasma physics, lunar dust/charge/plasma research, and critical technology development.

The focus of research to date in fundamental physics has been on cold atoms and their unique scientific and technological properties. This is well aligned with the National Quantum Initiative enacted into law in 2018 [24]. The key fundamental physics accomplishment in the last decade was launch and successful operation of the NASA Biological and Physical Sciences (BPS) Cold Atom Laboratory (CAL) to the ISS [25]. This pathfinding accomplishment can be followed by dedicated fundamental physics keystone missions to take full advantage of the cold atom technology demonstrated by CAL in addressing today's most challenging physics questions.

Of central importance to most Keystone missions in fundamental physics is the need to further mature the quantum metrology and precision measurement schemes to enable state-of-the-art

performance within tight size, mass, and power constraints required for space implementation. To this end, we argue that significant investment is required by BPS during the early formulation phase of Keystone missions in fundamental physics to reduce the risk and cost of implementation once a mission is selected for flight. We recommend that early development of advanced technology solutions, say up to a Technology Readiness Level (TRL) of 2-3 can be achieved most efficiently by the research community through regular targeted solicitations. To reach a TRL level of 6, as is desired at the Preliminary Design Review (PDR) a combination of community and NASA center development is recommended. The TRL maturity can be used as a selection criterion prior to proceeding into Phase A for a Keystone mission.

As the budget grows, we envision a series of fundamental physics Keystone missions, perhaps eventually at something like 4 to 5-year intervals. It is crucial that the TRL of the Keystone missions' critical technologies are developed early. It is recommended that a sequence of 3-year technology focused NASA Research Announcements (NRAs) is used to competitively select investigators to mature innovative concepts to TRL 2 or 3. Following evaluation by BPS, a smaller number of investigations can continue with increased levels of funding, and with participation by the Keystone mission implementing NASA center, to jointly raise the TRL to 4, at which point formal authority to proceed into Phase A can be given. With this approach, a strong technology starting point is established for the Keystone mission to allow reaching a TRL level of 6 by PDR.

#### **Materials Science:**

High priority areas identified in the recent Decadal Review Topical White papers include, welding, additive manufacturing, nucleation control, and thermophysical properties [26-30]. These topical areas comprise a body of work that would revolutionize material science both for exploration and for terrestrial applications. Much of the final stages of this work requires long term reduced gravity access but a large portion of the research would also benefit immensely from a vibrant ground-based research program conducting supporting modeling, 1-g testing and ground-based reduced gravity testing. As with the other disciplines above, a robust ground-based program is needed to address these topics as there are too many issues to resolve through flight testing alone. The ground program is necessary to identify the research topics that require flight, address other research topics on the ground, develop hardware specifications and mature diagnostic techniques. The ground-based program is also necessary to energize and challenge the flight program. Welding, joining, and additive manufacturing processes are enabling in-space manufacturing technologies for sustained and deep space exploration since they allow realization of novel metallic vehicles and structures. Such processes, however, induce significant metallurgical changes to parent material that can degrade properties and introduce defects. Information on in-space welding is very limited as there have been few experiments (e.g., Soyuz-6 USSR 1969, Skylab NASA 1973, Salyut-7 USSR 1984). The last (and only) NASA experiments on Skylab were nearly 50 years ago. To enable in-space welding and allied processes, experimental data are needed, especially those that will identify and elucidate the physical phenomena associated with the microgravity environment. In particular, the absence of convection as the primary mixing phenomenon in a weld pool, and the subsequent solidification and development of weld shape and properties need to be studied to inform ground-based process modeling efforts. Drop towers are ideally suited for generating empirical conditions to study such phenomena, particularly for highly transient beam-welding processes such as laser and electron beam welding where physics occur at the millisecond time scale. Drop tower data will inform and validate computational models for predicting critical one-shot space welds since extensive in-space process development studies are not possible. Likewise, ground-based programs will be a very effective

means to address topics such as nucleation phenomena and additive manufacturing as ground-based facilities can be used to address transient phenomena and many of the processes have relatively short time scales.

### **Soft Matter/Complex Fluids:**

The most important goal, with regard to soft matter is to understand, control, and use complex soft matter dynamical systems [31-37] to improve the understanding of nonequilibrium phenomena from nano- to large- scale systems. Present complex fluid and soft matter-based materials and systems lack the ability to learn, communicate and react to outside stimuli. This is extremely important for successful long term deep-space exploration and habitation. Smart reactive materials and systems can help us understand and develop complex dynamics and cooperativity that we lack. Soft matter-based self-sustaining ecosystems require the knowledge to impart flexibility to overcome various challenges, namely hydrodynamic interactions, gravity, friction, charging, and hysteretic effects [38-41]. Complex fluid and soft matter can show very different performance between micro-scale properties and macro-scale performance under different gravity conditions, which can have significant impact on the goal of self-sustainable ecosystems. In the recently concluded Grand Challenge Workshop for soft matter, 3 key questions were identified that need to be studied in the next decade through a combination of flight experiments and a robust ground-based program: (a) How do dynamics and cooperativity influence smart reactive materials and systems? (b) How can we develop a nonliving self-reliant sustainable/circular ecosystem via better understanding of fundamental dynamical organizational principles of its constituents? (c) How can we tailor the microstructure to develop active materials and metamaterials? [42]

### **Recommendations**

To achieve success and conduct successful flight programs, a graduated approach is required, where a ground level research program includes a large pool of investigations (>20-30/year/discipline), support for multiple postdocs (>10/discipline) and interns (>20/discipline). This will create a strong backbone for Physical Science research under microgravity (LEO) and partial gravity (Lunar and Martian surfaces) in future. **Specific recommendations are below.**

1. Utilize the ROSES NRA and the Established Program to Stimulate Competitive Research (EPSCoR) programs to build a ground-based research program that is scaled to address the critical issues in the Physical Sciences identified above. This would be a 10-year program spanning several NRA selections that would expand the reduced gravity research community and adapt to address the new findings that will be uncovered in the behavior of physical process in partial gravity.
2. Greatly improve student access to NASA research facilities. One of NASA's core missions is to inspire and educate the next generation of scientists and engineers. Providing students with access to state-of-the-art NASA facilities is a remarkable educational opportunity, as they work side-by-side with NASA scientists and engineers, and students from other institutions.
3. Maximize utilization and upgrade NASA's reduced gravity facilities. This should include investments to increase the drop tower throughput (number of tests per day, week, year), the size of the payload, the capabilities of the payload (e.g., advanced laser diagnostic techniques) and duration and quality of the reduced gravity time. This should also include the capability for partial gravity research to facilitate research to enable NASA's exploration efforts. For larger scale and longer duration experiments, this also includes the need for a research grade, low-gravity aircraft in the United States in addition to regular access to suborbital flights.

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