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Topical White Paper: High Throughput Ground-Based Reduced-Gravity testing

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Development of a high-throughput 10-second, variable gravity drop facility would provide NASA with breakthrough capability that will enable important new fundamental research opportunities in both physical sciences and life sciences in addition to providing the ability to support exploration needs for partial gravity testing. This Keystone Capability would establish a new world class resource that would not be easily matched and would dramatically exceed capabilities elsewhere.

NASA has long benefitted from two drop-tower facilities built at what was then the NASA Lewis Research Center (now the Glenn Research Center (GRC)). The 2.2 second drop tower was built in 1959 by converting an old jet fuel distillation tower and the 5.2 second Zero-Gravity Research Facility (ZGRF) was completed in 1966. Both of these facilities were initially constructed to solve engineering problems at the dawn of the space age but over time, they became very heavily used by the fundamental research community. At its peak, the 2.2 second tower had 1480 drops/year driven primarily by ground-based research projects. Historically the majority of tests in the NASA drop towers have been combustion investigations. This has been driven in part by the lower characteristic time for many combustion processes but also arguably due to historical precedent. The tremendous productivity seen at the Portland State University 2.1 s drop tower in capillary fluid behavior[1] and the broad range of disciplines making use of the 4.7 s ZARM drop tower in Bremen, Germany demonstrate that other disciplines could make good use of drop tower testing.

Although it is relatively simple to build a 2 second drop tower, aerodynamic drag quickly becomes a major constraint for longer durations. This has been addressed by dropping in a vacuum (GRC[2] and ZARM[3]) or with gas thrusters (JAMIC (now closed)[4]). These approaches have high upfront costs in addition to very high operational costs and slow turnaround. Recently two facilities have been completed (Hannover[5] and Bremen[6]) that offer more rapid test turnaround through propelling the drop capsule either with a winch or linear synchronous motors. There is evidence that design projects are underway for a similar facility in China so there is substantial interest world-wide in this type of capability. A recent design study has confirmed that the NASA ZGRF could be upgraded to provide approximately 10 seconds of reduced (zero or partial) gravity. This would be accomplished by a linear synchronous motor system similar to that used in the Einstein Elevator in Hannover. The facility at NASA GRC provides unique opportunities due to the existence of a 509-foot concrete lined excavation, a workforce with long experience in reduced gravity testing, and located at a NASA Research Center with all of the resources it provides.

The proposed facility (ElectroMotive Drop Tower (EMDT)) capabilities include vibration levels below 10^{-4} m/s^2/Hz$^{1/2}$ for low-gravity tests; acceleration levels controllable to 0.01 g for the partial-gravity tests; peak accelerations and decelerations of 6 g (lower levels available for reduced test time). The facility schematic is depicted in Figure 1. The test article is loaded into the drag shield at ground level. Once it is configured, the drag shield rides down the rails at arbitrary speed to the bottom. During launch it accelerates over 30 m to approximately 50 m/s with an average acceleration of 4 g. It then travels at the desired acceleration profile up and down the 120 m flight section before it decelerates over the 30 m launch section. The flight time is

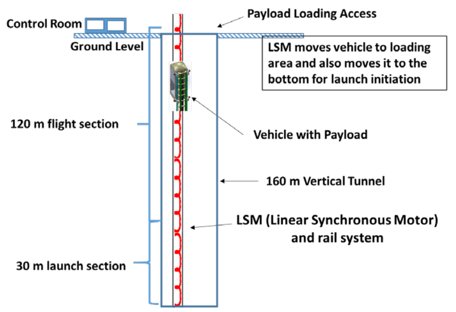

Figure 1: Schematic drawing of the proposed ElectroMotive Drop Tower

approximately 10 s and the system can operate at g-levels from 0.01 g to 0.5 g (partial-gravity) or at “zero” g (low-gravity). For the low-gravity tests, the payload would float inside the drop capsule providing very low disturbance levels. For the partial-gravity tests, the payload would necessarily sit on the floor of the drop capsule, however the disturbances would have less impact given the constant partial-g baseline.

The four most significant advances that would be provided by this facility are access to repeated low-cost drop tests; increased test duration; access to partial-g and reduced launch and landing accelerations. The increased test frequency is expected to have a dramatic effect on the approach to ground-based, reduced gravity testing. The ability to pursue large statistics, risk failed tests and the opportunity for inexpensive testing can all be expected to drive innovation. The two most important discoveries of the droplet combustion program[7-9] (radiative extinction and cool flames) would likely have been discovered on the ground had such a facility been available. Much of the work performed using low-g aircraft on pool boiling and verified through the MABE experiments on the ISS could have been performed in the proposed facility. The experience at the Dryden Drop Tower[1,10] at Portland State University has demonstrated the dramatic innovation that can occur in system design and discovery through rapid access to drop testing. Increased test duration should not be considered as a mere doubling of the test time but rather a tripling or nearly quadrupling. For most tests, there is an overhead of 1 to 3 seconds needed to damp out the structural response to the change in acceleration and to establish the test conditions. Going from a 5 second drop to a 10 second drop extends the actual test time by as much as a factor of 3.5. The access to partial-g testing will be game changing for exploration life-support research and risk mitigation for partial-g systems. The other opportunities for partial-g testing may provide longer durations but are much more expensive (rotating suborbital flights and aircraft), have much higher vibration levels (aircraft) and are not able to scan as many g-levels as the proposed EMDT. Reduced acceleration levels make more advanced diagnostics possible in addition to opening up the test environment to a wide range of other disciplines for which 30 to 60 g decelerations were unacceptable.

Fundamental Combustion Research: the near term thrust area for low-gravity combustion research is very high pressure transcritical systems. These conditions are of interest because all future engine concepts are pursuing operation at these conditions. Designing a facility to conduct this testing in a spacecraft is daunting due to the high pressures (> 100 atm) and high temperatures (>400 °C). Ground-based testing in a high throughput facility offers huge advantages. Other thrust areas include very low-stretch flames for study of Low Global Warming Potential (LGWP) refrigerants[11]. These refrigerants are very important to reduce global warming but are substantially more flammable than prior refrigerants. Understanding the kinetics requires study of very weak flames. This testing would be challenging on an occupied spacecraft due to the high fluorine content of the fuels and the prevalence of HF as a reactant. Study of emerging topics such as metals combustion[12] would also be substantially facilitated in the proposed EMDT.

Spacecraft Fire Safety: plans for habitation on the surface of the moon (and eventually Mars) raise important new considerations in fire safety. To date, study of material flammability in partial gravity has been limited to studies of thin fuels during low-gravity aircraft trajectories[13] and in the GRC ZGRF using a centrifuge drop capsule[14]. Both of these studies observed an extended flammability zone where materials were flammable at lower oxygen concentrations at partial gravity conditions near lunar gravity levels compared to both normal gravity and microgravity conditions. These results suggest that flammability limits determined in normal gravity may not be conservative however, the data set collected to date is very limited. Low gravity conditions also enable fires to persist in conditions where they are less likely to survive in low gravity e.g. inside narrow channels between fuel surfaces, smoldering in porous media, and deep-seated fires. These various configurations can have a significant effect on material flammability but the extent of this impact as a function of g-level is not readily predicted and is an important area of future study. Plans are in place to conduct test using other partial gravity platforms (rotating centrifuge in the 5.2 second drop tower, the Blue Origin rotating capsule centrifuge, and a lunar lander experiment). However, these test platforms are constrained by cost (suborbital and lunar) or by limitations such as the Coriolis effect and the test duration (drop tower centrifuge). Inexpensive, repeated access to partial gravity without disturbances such as Coriolis induced acceleration would provide a truly extensive improvement in our test capability and would facilitate exploration of many of these issues.

Fluid Physics:

A high-rate drop facility with accompanying automated imaging, data collection, and archive will provide a watershed of exposure to unearthly low-g fluid phenomena that are in the critical path of NASA’s exploration mission. Such a timely drop facility would be enabling to NASA’s goals in space and would serve to accelerate progress to expanding our fundamental and applied science database from which to design robust fluid systems for spacecraft. Such systems are myriad and cross-cutting, touching on fields from fluids to combustion to material science, biology, plant animal and human physiology, food production, medical procedures, hygiene, power generation, propulsion, fuels, propellants, coolants, and much more.

The highest rate drop tower in the USA is capable of approximately 100 drop tests per 8 hr. day for only 2.1 s per drop[1,10]. A NASA 10-second-high-rate facility represents a quantum change in capability. Giant data files collected from such a facility addressing critical fluids subjects such as multiphase flow regime mapping and device certification would provide a database capable of confidently establishing predictive theoretical analyses, numerical benchmarking, and high TRL for fluid systems designed for spacecraft. Based on the performance of other high rate drop towers it is defensible that such a tower could increase productivity by an order of magnitude well in excess of 6000 drops per year in the fluids fields alone, with unique capability of varied initial conditions, and Martian, lunar, and other g-levels. Particular advances are expected in the field of multiphase flows such a droplet and bubble flows, wall-bound droplet and rivulet flows, and special gas-liquid phase separations phenomena and devices, with windows into full system operation—not just single component performance.

Drop towers can potentially perform low-gravity flow boiling experiments at much lower cost than aircraft and are usually much more accessible, but the 2-5 second drop time of current towers is often a limitation to obtaining steady state data. Longer duration (~10 seconds) drop facilities that provide high quality low-gravity and fractional gravity conditions would be a relatively low-cost way to explore boiling behavior over a wide range of conditions that would quickly advance our understanding and will be crucial to understanding and validating the conditions under which two-phase system instabilities occur under terrestrial, Martian, Lunar, and μ-gravity experiments.

Ground based systems also allow the use of more advanced instrumentation and data acquisition systems than can be used on the ISS with its space and power limitations. Fundamental aspects of these experiments will greatly enhance the body of scientific knowledge regarding boiling, and the improved modeling that results from them will aid in the design of engineering systems utilizing phase-change fluids that range from liquid metal to cryogenic fluids.

Biology: While drop towers are typically considered realms in which to explore physical phenomena, modern molecular tools and sophisticated imaging technology have come together to enable drop towers to help fulfill the high scientific demand for partial gravity in biological experiments. While the sustained microgravity of orbital environments is ideal for many biological investigations, not all questions require sustained microgravity, and many experiments benefit greatly from rapid and repeated access to a microgravity environment that can be assayed in real time by the investigator directly. The easy access and reproducibility of drop tower experiments provides a powerful approach for many biological investigations. Further, the typical quality of drop tower microgravity tends to exceed that attainable by most other terrestrial platforms, such as parabolic flight aircraft[15]. The primary drawback of the drop tower for biological investigations is the short duration, and the limited space in which to mount an experiment. Yet it is recognized by the research community that expanded capabilities for drop towers such as the EMDT will greatly enhance the breadth of experiments that can utilize these platforms to answer fundamental questions[16]. The types of biological questions that have been addressed include capturing the signal transduction associated with gravity-sensing in plants and cell cultures [15,17], motility in microorganisms (ZARM Biology Project list), and even the effect of the transition to microarray in fish orientation[18]. In all cases, the ability to do real-time analyses of the transition into microgravity is a powerful tool for understanding how biological organisms adjust to this novel environment.

Fundamental Physics: Recently, microgravity environments have proven useful for investigation of quantum systems, especially systems of ultracold atoms [19-25]. Here laser cooling and other techniques are used to prepare a dilute gas at temperatures of 10^{-6} K or lower, where quantum effects are exhibited [26]. Ground-based research in this area has been extremely fruitful over the past few decades, but a number of applications are limited by the presence of gravity. These include atom interferometry, where measurement time in gravity is constrained by fall distance [21,27,28]; studies of quantum system in novel geometries, such as bubble-shaped atom traps which are distorted by gravity [29,30]; and cooling to lowest possible temperatures, perhaps only 10^{-15} K [21,31,32]. The Cold Atom Lab (CAL) on the ISS was established in 2018 in an effort to realize some of these benefits, and it has successfully produced ultracold atoms and demonstrated atom interferometry in orbit [24, 33]. An effort by the German DLR has achieved comparable results on a sounding rocket platform [20, 21, 34]. It is expected that these projects will ultimately lead to both fundamental advances and useful applications[35]. Examples include precision tests of Einstein’s equivalence principle [36-38], searches for dark matter [39-41], and improved inertial navigation systems[42-43].

Most of the exciting prospects for ultracold atoms in space rely on true microgravity accelerations which are not easily achieved in the context of a drop tower. However, the proposed EMDT performance is in many cases satisfactory for important supporting efforts. For instance, to produce a sample of ultracold atoms in the CAL apparatus, atoms must be collected with laser beams, confined in a magnetic trap, further cooled via evaporative cooling, and then expanded out of the trap [24,32]. Although it was possible to develop and test some of these procedures in gravity [33], a considerable effort was required to optimize them in the microgravity environment. Future planned experiments will require even more elaborate preparation work. This work could be usefully carried out in the drop tower, with a significant savings in cost and mission time.

This application will benefit significantly from both the long measurement time and the high drop rate of the EMDT facility. On CAL, it takes about 10 s to prepare a cold atom sample for measurement, which is well matched to the proposed capacity. The high drop rate is equally beneficial, since the process of optimizing sample preparation methods requires copious data and benefits from quick turnaround capability. The German DLR effort has made extensive use of the ZARM drop tower for many years, to the benefit of their program [44]. In comparison, the proposed drop rate at the EMDT would permit much faster development of new and more complex experiments. Assuming the NASA quantum physics program continues as currently planned, we expect the cold-atom work to be an important component of the EMDT platform.

Soft Matter/Complex Fluids: The proposed EMDT will provide a variable gravity environment to study soft matter/complex fluid related scientific questions. In addition to being the perfect platform for providing a variable gravity environment, the EMDT will allow us to create a robust, focused, ground-based program that feeds into successful microgravity research on the International Space Station and beyond. Three pillars of soft matter/complex fluids that can be supported by microgravity-based research are: (a) smart reactive materials and systems, (b) self-reliant sustainable/circular ecosystems and (c) active materials and metamaterials. Some examples of research activities that are key to the success of these focus areas follow below. The EMDT facility will allow us to study consolidation mechanisms of foams and other complex fluid under both shear and elongation [45-47]. As an example, on earth, the foam consolidation and rupture are mediated by gravitational field, whereas in microgravity surface forces become a dominant force. However, under partial gravity (e.g. lunar/Martian gravity) the relative impact of different forces is not well understood. This understanding is important for all the key focus research areas. Another example is understanding the stability of gels in variable gravity environment. These gels can be tailored for different end goals ranging from development of smart reactive materials to electrolyte for batteries [48-49]. These gels are critically balanced in earth gravity. However, it is expected that under variable gravity condition, their stability will be hampered and can even lead to complete collapse of gels. While the short tests (~few seconds) that can be obtained in drop tower may not be ideal for long duration processes, it provides important information for the growth of field. Some examples are as following. In elongation rheology, the lifetime of a thread is ~0.1-0.5 sec[46]. In studying the stability of gels aka the phase separation, the timeframe of separation ~L^2/D, where L is the pore length and D is the diffusion co-efficient (~10-5 cm^2/s). For, L~10 μm, the characteristic timeframe of response ~0.1 s. In view of these, we believe that possibility of utilizing drop tower facility for the growth of soft matter/complex fluid is extremely large. Overall, the opportunities raised by the EMDT facility for the growth of soft matter/complex fluid are extremely large.

Development of a high throughput EMDT has the potential to give unprecedented access to reduced gravity testing, provide regular access to partial gravity conditions and foster accelerated progress in a myriad of disciplines that previously have not made extensive use of drop towers.

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