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High Speed/Hypersonic Test (HSHT) Science & Technology (S&T) FY09 BAA White Paper

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Title: Development of Wind Tunnel Testing Capability for Hypersonic Weather Encounters

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Technology Overview

Hypersonic flight vehicles such as re-entry bodies or future scramjet-propelled aircraft will inevitably have to fly through adverse weather such as clouds, rain, snow, and ice. A typical flight profile of a re-entry vehicle is shown in Figure 1, as it traverses different weather effects that are, in part, a function of altitude. Of course, other types of high-speed or hypersonic (HSH) vehicles, such as cruise missiles or interceptors, will follow different flight profiles through the same weather. These weather encounters are known to have significant effects on the vehicle aerodynamically and structurally. Most intuitive is the increased erosion of a thermal protection system due to particle impact, such as sketched in Figure 2. The resulting ablative shape change may lead to detrimental and unanticipated aerodynamic effects that could make the vehicle impossible to control. Particle impact also is a principal source of induced vibration, which can have a profound influence on internal component response and structural integrity. Figure 3 displays the dramatic increase in vibration on a re-entry vehicle as it passes through an ice cloud, in contrast with flight through clear air. Additionally, the passage of particles through a bow shock has been shown to augment vehicle surface heating and pressure loading. The summation of all these concerns becomes particularly acute given that new hypersonic vehicle concepts depart markedly from the traditional sphere-cone re-entry body shape for which most past knowledge has been obtained.

The effects of weather encounters are difficult to simulate through ground testing. Historically, some limited testing has been accomplished by introducing dust particles into a wind tunnel flow, but such particle fields do not well represent actual weather conditions or particle breakup after passage through a vehicle's bow shock. Other testing involving firing particles at a test body are much less representative of real flight conditions. Most knowledge of weather encounters has been provided by flight testing, which have numerous shortcomings including expense, limited data fidelity, and uncertain characterization of the weather environment. As a result, the predictive capability is unreliable even for known vehicle geometries passing through weather encounters, and is likely to be poorer yet for developmental HSH aircraft.

The present project proposes to develop a capability to recreate adverse weather conditions in Sandia's Hypersonic Wind Tunnel (HWT) at Mach 5, 8, and 14. Because the HWT is a blowdown wind tunnel, those particles introduced to the flowfield will not recirculate to pass through compressors, heaters, or other fragile machinery, thus providing an advantage to testing weather encounters. Atomizing spray nozzles will be installed in the wind tunnel's stagnation chamber downstream of the electric resistance heaters but upstream of honeycomb and screens that will remove any perturbations associated with the introduction of the seeding apparatus. The spray nozzles will be fed with supercooled water or ethanol and atomized using air or nitrogen; adjusting the supply pressures and the spray nozzle heads will permit a range of droplet sizes and densities to be tested. Clouds of fine particles may be created by allowing water (or more likely, ethanol) to evaporate immediately after injection from a fine-spray configuration, then condense during the cooling of the nozzle expansion. Conversely, larger particles simulating rain or snow are possible by injecting greater quantities of liquid at spray settings intended for coarser droplets, which may not fully freeze during the nozzle expansion. Nevertheless, adequate nozzle length is available for even large droplets to attain hypersonic velocities.

A complementary component of the project will develop a capability for *in situ* measurement of the particle size distribution and density introduced into the hypersonic flow. This probably can best be accomplished using a laser diffraction system for particle characterization, although imaging methods will be explored as well. Sandia's aerosol research group has substantial experience with such measurement techniques and even much of the hardware needed to apply them to a droplet-seeded hypersonic flow. Once a successful diagnostic is available for droplet sizing and density, it will be used to fine tune the design of the spray nozzles to better replicate those atmospheric conditions through which HSH vehicles can be expected to fly.

T&E Benefit

Successful development of a means of simulating weather encounters in HSH ground testing would represent a capability not possessed by any facility in the nation, and therefore can significantly aid the recent surge for developing innovative hypersonic vehicles. Current and future programs are trending towards new flight vehicle shapes for which data do not exist to adequately predict how weather would influence the aerodynamics and structural response. Therefore the availability of a reliable ground-test technique to measure weather effects may prove critical to the successful development of new hypersonic flight geometries.

Current technology for analysis of weather encounters affecting HSH vehicles is limited at best. Ground testing capability is virtually nonexistent. Historically, some limited testing was accomplished by introducing dust or liquid droplets into wind tunnel flows, but these results did not well represent true flight conditions. Regardless, even these capabilities appear to have been abandoned and no known current weather testing is available. Of course, icing wind tunnels have been in routine use for decades, but these are low-speed or transonic in nature and do not recreate the weather environments and flow conditions that will be encountered by HSH systems. A different ground testing approach has used pneumatic guns to fire particles at test bodies, but clearly this evaluates particle impact without making any attempt to reproduce the aerothermodynamics of flight.

Predictive capability for HSH weather encounters is based upon analytical approaches of limited fidelity and narrow results. Shape change codes for re-entry systems can include the effects of ice and rain upon nosetip erosion, but suffer from significant accuracy concerns and it is unclear to what extent these predictions have been validated against flight tests. They are a mix of analytical and empirical approaches based upon experience with sphere-cone re-entry bodies and cannot be reasonably applied to other HSH systems that fly different vehicle shapes on different trajectories. Furthermore, such algorithms do not address other crucial physical consequences of weather encounters such as localized heating augmentation and induced structural vibration.

In the absence of a viable ground testing capability and computational predictions tailored to a specific type of re-entry body (and even then of uncertain accuracy), the only viable means of T&E for future HSH systems is flight testing. The drawbacks of such an approach to qualifying flight through adverse weather are numerous; obviously, flight testing is enormously expensive and produces limited data fidelity in comparison with ground testing, but furthermore it is difficult to accurately characterize the weather environment through which the flight vehicle will fly, and the conditions experienced are selected by nature rather than a test engineer.

If weather encounters can be replicated in a hypersonic wind tunnel, then this phenomenon can be treated in ground testing just as any other aspect of flight systems engineering. Different weather conditions could be created to reflect particle size, particle density, liquid water content, or other key parameters in defining weather conditions. The actual flowfield conditions can be measured *in situ* using an appropriate diagnostic such as laser diffraction particle characterization, superior to the meteorological description achieved during flight testing. Moreover, the wind tunnel weather conditions would be reproducible and stable, in comparison to the temporally and spatially variable conditions found in nature. Though some wind tunnel model instrumentation will need to be hardened against the impact of weather particles (surface pressure gages, heat flux sensors, etc.), the response of the model to the weather conditions becomes measurable in a way flight tests can never attain.

An additional enticing possibility for ground testing is the combination of simulated weather encounters with low-temperature ablators. Fabrication of wind tunnel model components from volatile materials for measurement of thermal shape change is not new, although previous efforts employing water ice, dry ice, or fiberglass-reinforced ice were troubled due to difficulties with machining flight vehicle shapes, fracturing of ice surfaces, and producing physically unrealistic ablated shapes. Better data were obtained using camphor due to favorable sublimation characteristics, but this appears not to have been used by any wind tunnel facility in nearly 30 years. However, if such a capability were to be reactivated, using camphor or some modern substitute, it might also be feasible to replicate the shape change of weather-induced erosion. Substantial work would be necessary to establish that the erosion of a material such as camphor would be representative of that which would occur on actual thermal protection systems, but marrying these two ground test technologies would open a whole new realm for exploring the effects of weather encounters on HSH systems.

S&T Technology Challenges

If simulating weather effects in ground testing is so valuable, why has it not previously been accomplished? Although the present authors cannot speak for all other hypersonic wind tunnel operators, the likely reason is potential damage to wind tunnel components. The large-scale supersonic and hypersonic wind tunnels used for ground testing within the DoD complex generally are closed-circuit facilities, which means that any particles introduced into the tunnel will be recirculated through the facility. This presents two difficulties, the first of which is that the condensed particles or evaporated moisture cannot realistically be removed before it recirculates, and therefore the thermodynamic cycle of the seed through the wind tunnel circuit will probably result in weather conditions quite different from that intended. The second problem, of greater concern, is potential damage to wind tunnel components. Hypersonic wind tunnels invariably have flow heaters to ensure that the expanded gas remains above the condensation point, which are unlikely to react favorably to particle impacts; the same can be said of the rotating machinery inherent to the compressors.

In this regard, blowdown wind tunnels such as those operated by Sandia present a distinct advantage – once seeded, particles will simply be dumped with the gas flow in the tunnel exhaust. This becomes clear by examining the sketch of Sandia's Hypersonic Wind Tunnel (HWT) in Figure 4. The seeding injectors may be installed downstream of the HWT's heater, but still upstream of flow conditioning screens and honeycomb so that any disturbances related to injection are removed. (The existing screens may need to be modified if they prevent achievement of the desired droplet size.) With such a design, the only way droplets can reach the heater is if gas is drawn upstream during the tunnel shutdown process, but this possibility can be minimized by closing the seeder well before tunnel shutdown and purging the lines of any remaining liquid. Construction of protective hardware for the tunnel's pitching mechanism should protect it from damage, and repeated purging of the vacuum spheres into which the wind tunnel exhausts should remove excess moisture before it can do any long-term damage to the interior. Still, the potential exists for some unexpected occurrence, and therefore the present proposal includes schedule and funding for wind tunnel inspection and maintenance. Nevertheless, a blowdown wind tunnel is far more amenable to the introduction of weather simulation than a closed-circuit tunnel.

Another challenge is to produce particle size distributions and densities that are consistent with actual weather encountered by a HSH system. The desired weather conditions are known from historical meteorological data acquired in support of DoD and DOE flight tests, used to define storm profiles and environmental severity. Representative conditions must be matched to the greatest degree possible by the weather simulator. A wide variety of commercially available atomizing spray nozzles are available that can achieve different droplet sizes and densities based upon the gas and liquid pressures applied and the design of the nozzle head. Although the manufacturer characterizes the nozzle performance based upon the applied settings, the thermodynamics of flow through the wind tunnel nozzle will play a dramatic role. If atomizers are used to spray a fine mist into the tunnel stagnation chamber, the droplets will evaporate rapidly and later condense into a fog of ice crystals as the flow cools through the nozzle expansion, especially if ethanol is employed rather than water. This will produce weather conditions similar to high-altitude ice. Conversely, if the spray nozzles are adjusted to produce much larger droplets, these will not appreciably evaporate prior to the nozzle expansion, and in fact may not even fully freeze during the cooling process. Such a seeding approach will yield weather representative of rain. Effects of the wind tunnel screens and honeycomb for flow conditioning also will be important, especially when large particles are desired, and in fact may need to be altered for the purposes of weather simulation.

A final technical challenge to address will be measurement of the particle size distribution and density, which clearly is needed to assess the characteristics of the weather conditions produced and to provide feedback to the design of the weather simulator. At least two approaches will be considered. One is to directly image the particle field, either using backlighting to illuminate the volume of the flow much like shadowgraphy, or to employ laser-illumination of a streamwise plane. The backlighting method is better suited to measuring a range of particle sizes but the volume integration may produce poorer results for particle density estimation. On the other hand, laser-illumination may struggle with a broad distribution of particle diameters because this will create a troublesomely large range of scattered light intensities, but it is well-suited to determining particle densities. A more robust diagnostic is laser diffraction particle characterization, in which a low-power laser beam is directed through the test section, then the scattered laser light is captured by a linear or annular photodetector array. The light's scattering angle is a function of the particle size, and particle density may be determined from the count rate of scattering sources. The principal challenge of such a system is the sensitivity of its alignment to density gradients; estimates suggest that this problem is mild for freestream density gradients, but will be problematic principally for measurements through a shock wave, such as the bow shock of a flight vehicle. This will require some innovative modification of the measurement system, yet it is important due to the need to study particulate breakup after passing through the shock. Nevertheless, Sandia has extensive experience with all of the aforementioned diagnostics and is well-equipped to overcome the challenges that inevitably will arise.

Although much of the hardware needed to implement the weather simulator is commercial off-the-shelf products, achieving a viable and realistic weather environment will require innovation and iteration in the design of the system. Assembly of a system of atomizing spray nozzles is reasonably straightforward, and in fact can leverage from prior experience with flow seeding for laser-based diagnostics, but the difficulty lies in achieving conditions that are representative of actual weather encounters. The challenge is not somehow introducing moisture into the wind tunnel flow, but in constructing a system that can produce a variety of simulated weather with a few small adjustments, and in doing so in a manner that minimizes the risk of damage to the wind tunnel and its sub-systems. From this perspective, the technology readiness level (TRL) of the existing capability is about a 3, because the fundamentals of the technology are readily available even though an implementation of it has never been attempted in a hypersonic environment for the purposes of weather encounters. A complete weather simulator functioning in the HWT would represent a TRL of 6 if it realistically reproduces weather encounters for production testing at hypersonic conditions; a partially successful weather simulator that offers a range of particle characteristics even if not entirely representative of flight conditions and requiring frequent wind tunnel maintenance would still be a TRL of 5 owing to the successful component integration. The diagnostic tools for particle characterization presently would be considered a TRL of 4 because the instrumentation is fundamentally sound for other types of flow conditions; overcoming the challenges associated with their use in hypersonic flow would advance the TRL to a level of 6.

Technical Approach

The proposed project will be divided into two sequential phases, of which the development of the weather simulator is phase 1. This phase, planned for two years duration, will begin with a design of the spray system that will be capable of injecting a variety of liquids into the HWT's stagnation chamber under a range of atomization parameters. Key aspects to be considered in the design include the size and density of the atomized droplets, drag forces on the spray apparatus, their fatigue lifetime, and limitation of droplet propagation upstream into the flow heaters. Construction of the weather simulator will require more than simply installing spray bars and pressure sources; the stagnation chamber will require alterations to permit potential modification of the flow conditioning section and to simplify removal and re-installation of this portion of the HWT to allow frequent access. A warning system sensitive to impending hardware failure also is envisioned, based upon strain gages installed at key points of the spray apparatus. Wind tunnel flow calibrations may be performed with the spray hardware installed to ascertain the effects upon the flow quality.

Simultaneously, a means of particle sizing will begin implementation in the HWT, using either an imaging method or laser diffraction, or both, depending upon the available equipment. Using the resulting particle size and density measurements, the developing weather simulator can be adjusted or even extensively rebuilt to achieve conditions more representative of actual weather encounters. This will create a feedback loop where both the weather simulator and the particle characterizer can be improved in tandem with each other; repeated iterations almost certainly will be necessary. This portion of the project will form the bulk of the developmental effort of the technology, in which the TRL of both the weather simulator and the particle characterizer(s) will be gradually advanced, one component and one challenge at a time. Additional time and budget will be reserved for inspection of the HWT and associated support hardware, and of course, potential repair of any damage that is discovered.

If phase 1 is sufficiently successful in developing the weather simulator, phase 2 may be initiated as the third year of the program. At this point, an instrumented wind tunnel model of a representative HSH system will be designed and fabricated to operate and evaluate the weather simulator for realistic testing conditions. In particular, the performance of wind tunnel instrumentation will be examined in a weather environment to determine if it can function without great risk of failure or returning erroneous measurements. Data additionally can show some of the effects of weather encounters on vehicle aerodynamics and establish the importance of such testing for HSH system development. If phase 1 proceeds well, phase 2 potentially could be approved early and the design of the wind tunnel model would overlap the conclusion of phase 1 so that it would be available sooner in the final year of the project. Phase 2 will not advance the TRL's of the weather simulator and particle characterizer themselves so much as it will establish their utility and how best to integrate them with existing standard wind tunnel testing technology; in this regard, phase 2 would address the TRL for a broader scope of wind tunnel testing technology pertaining to weather encounters.

At the conclusion of phase 1, the two deliverables will be a functional weather simulator that can meaningfully reproduce flow conditions of hypersonic weather encounters, and a flow characterizer that can measure the particle size distribution and density of the *in situ* weather conditions in the HWT. Phase 2 will deliver quantitative data and an experience base with usage of standard wind tunnel models and instrumentation in a flow environment potentially damaging to the model and sensors.

Transition

Once successful, the proposed project would provide the only known capability for simulating weather effects in hypersonic ground testing. If desired, the technologies developed herein could be modified and transitioned to other hypersonic wind tunnels including those at the Von Karman Facility at AEDC. However, differences in wind tunnel design may render simulated weather environments undesirable in other tunnels; for example, continuous wind tunnels such as those at VKF as opposed to the blowdown facilities used at Sandia might be vulnerable to the recirculation of ice particles and high moisture content. As such, it may be preferable to conduct testing for hypersonic weather encounters at Sandia's facilities rather than replicate the capability elsewhere. Alternatively, DoD may have other blowdown wind tunnels suitable for the transition of the weather simulator. Regardless, the development of a ground testing capability for hypersonic weather encounters would provide an unprecedented opportunity to investigate these effects on HSH flight systems, and therefore the existence of this new ground testing technology would benefit such DoD programs even if testing did not occur within a DoD facility.

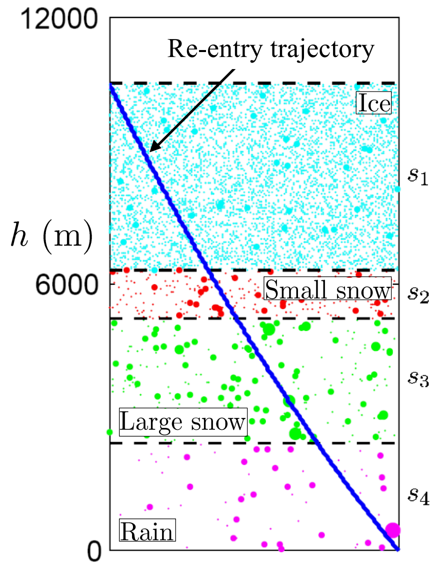


Figure 1: Typical trajectory of a re-entry body through a weather encounter.

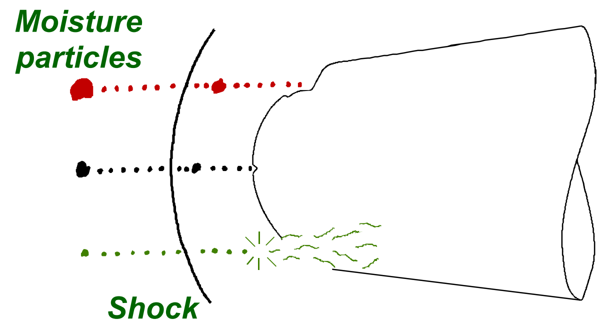


Figure 2: Nosetip erosion due to impact of weather particles.

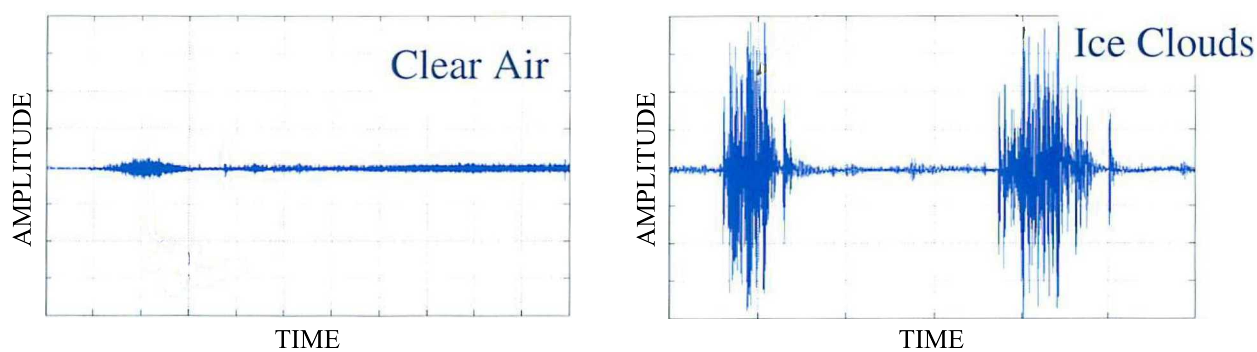


Figure 3: Vibrational response of an HSH system in clear air and through a weather encounter.

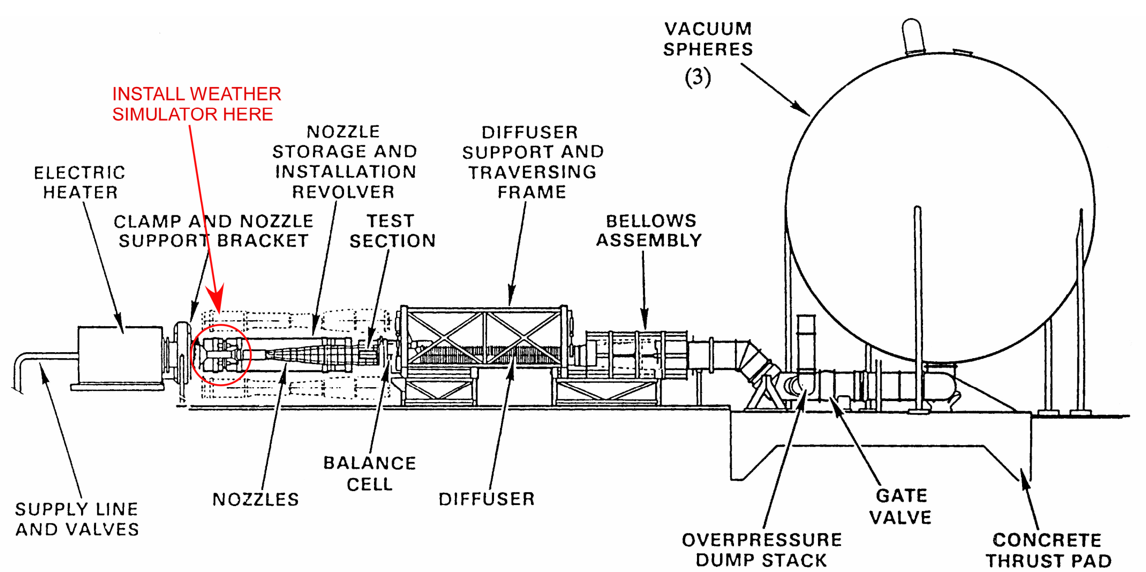


Figure 4: Sketch of Sandia's Hypersonic Wind Tunnel.

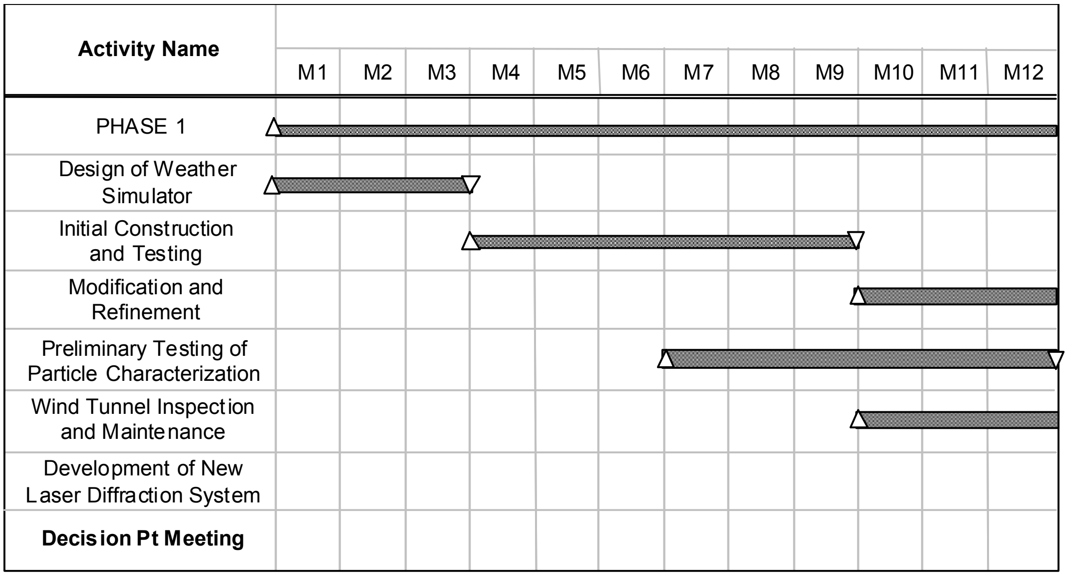
Schedule and Total Price Rough Order of Magnitude

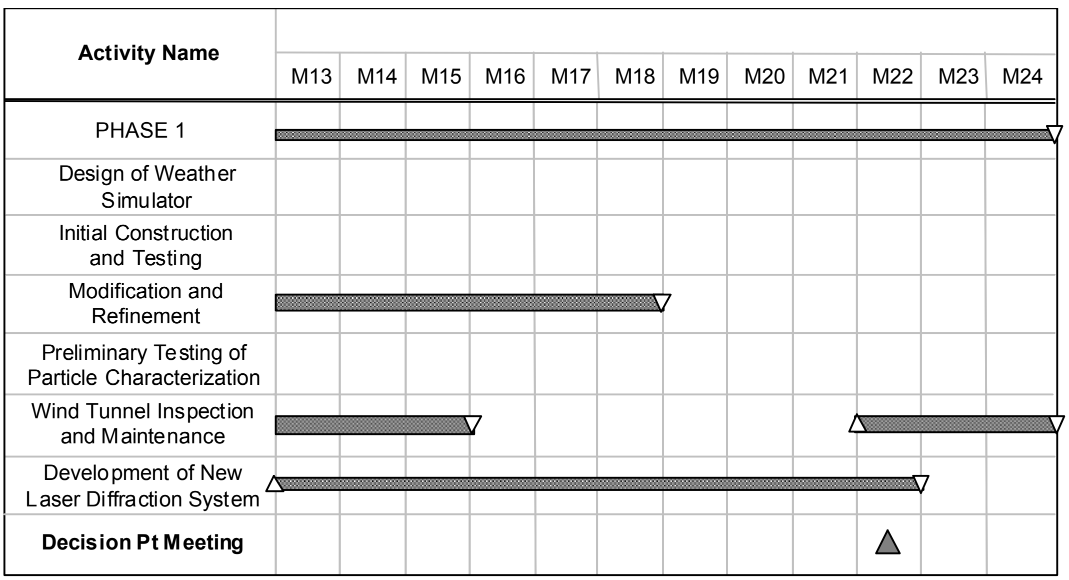
The proposed project will be divided into two phases. Phase 1, covering the first two years, will implement the spray nozzles and associated apparatus for seeding liquids into the wind tunnel stagnation chamber, and it will address particle characterization using the laser diffraction instrument. Development, testing, and modification of the seeding hardware will be concentrated in the first year with additional fine-tuning occurring in the second year. Some preliminary scoping of particle characterizers will occur in the first year, but delivery of this capability is intended for the end of the second year. Costs include substantial contingency funds to repair and modify the wind tunnel and associated support hardware in the event of failures induced by the addition of particle injection.

Phase 2 will be the third year of the program, in which an instrumented wind tunnel model of a representative HSH system will be designed and fabricated.. In addition to demonstrating the capability of the weather simulator and the performance of wind tunnel instrumentation in a weather environment, data from the wind tunnel model can show some of the effects of weather encounters on vehicle aerodynamics and establish the importance of such testing for HSH system development. If phase 2 is approved sufficiently early, it could overlap the conclusion of phase 1 such that design of the model would begin and hence it would be available sooner in the final year of the project.

	ROM ($K)	PoP (mos)
Phase 1	$1300k	24 mos
Phase 2	$700k	12 mos
TOTAL	$2000k	36 mos

(schedule charts located on following page)


Activity Name
M1 M2 M3 M4 M5 M6 M7 M8 M9 M10 M11 M12
PHASE 1
Design of Weather Simulator
Initial Construction and Testing
Modification and Refinement
Preliminary Testing of Particle Characterization
Wind Tunnel Inspection and Maintenance
Development of New Laser Diffraction System
Decision Pt Meeting


Activity Name
M13 M14 M15 M16 M17 M18 M19 M20 M21 M22 M23 M24
PHASE 1
Design of Weather Simulator
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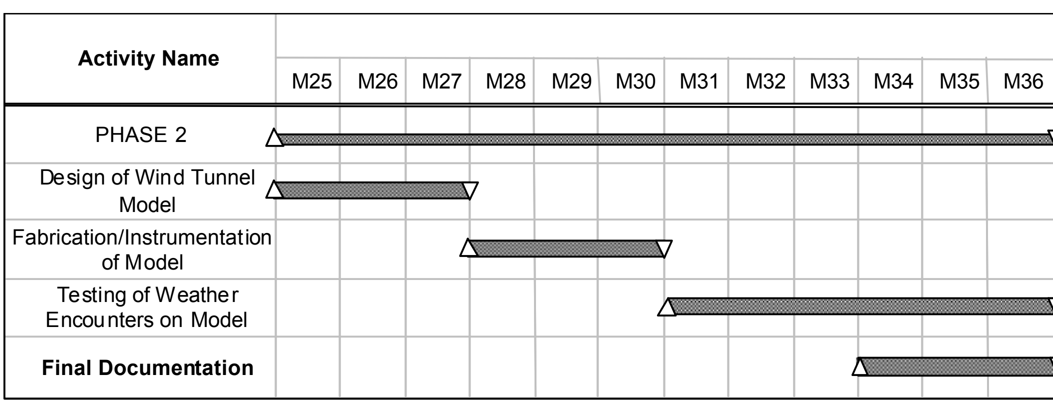
Activity Name
M25 M26 M27 M28 M29 M30 M31 M32 M33 M34 M35 M36
PHASE 2
Design of Wind Tunnel Model
Fabrication/Instrumentation of Model
Testing of Weather Encounters on Model
Final Documentation