NNA09302073Q-WEH

STATEMENT OF WORK

Supersonic Stacked Toroid Inflatable Decelerator Model

NASA Fundamental Aeronautics Program
Supersonics and Hypersonic Projects

June 29, 2009

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TABLE OF CONTENTS

1.0 Introduction 3
2.0 Scope 3
3.0 Model Requirements 3
3.1 Test Description and Objectives 3
3.2 Model Description 4
3.2.1 Model 4
3.2.2 Balance and Instrumentation 7
3.2.3 Model Supports 7
3.2.4 Air Services 7
3.3 Model Stress Requirements 8
3.4 Test Facility 8
3.5 Model Material Properties 9
4.0 Model Development Reviews and Schedule 9
4.1 Reviews and Meetings 9
4.2 Schedule 10
5.0 Deliverables 10
5.1 Hardware 10
5.2 Documentation, Drawings, and Electronic Files 10
5.3 Model Acceptance 11
6.0 Security 11

DRAFT

1.0 INTRODUCTION

The Supersonics and Hypersonics Projects of NASA's Fundamental Aeronautics Program are engaged in research on aerodynamic and propulsive decelerator concepts for slowing down large spacecraft in the supersonic speed regime as they enter planetary atmospheres. Various aerodynamic decelerator concepts have been or are currently being studied: tension cone, iso-tensoid, and stacked toroid (sphere cone). Supersonic test data are needed for the stacked toroid concept, and are the subject of this acquisition.

2.0 SCOPE

This Statement of Work (SOW) presents requirements for a stacked toroid inflatable decelerator model to be tested at speeds from Mach 1.6 to 2.4 in the NASA Ames 9- by 7-Ft Supersonic Wind Tunnel, or from Mach 2 to 2.5 in the Glenn 10- by 10-Ft Supersonic Wind Tunnel if the minimum pressure requirements for the 9x7 are too high for the model. The Government expects that the model *can* be made to withstand the loads in the 9x7 tunnel, therefore only model requirements related to operating in the 9x7 tunnel are included. If during the design process it becomes apparent that the model cannot be made to handle the high dynamic pressures of the 9x7, then a modification with revised requirements for the 10x10 will be negotiated.

The Contractor shall interface and coordinate with NASA engineers in designing the model to meet the requirements. The Contractor shall fabricate one model and deliver to Ames by the required delivery date. A backup model is included as an option to this requirement.

The Contractor shall provide manufacturer support up to a week prior to or during the start of the test of the model in the wind tunnel, as directed by the Contracting Officer.

3.0 MODEL REQUIREMENTS

3.1 Test Description and Objectives

The primary goal of the test of this model is to build an aerodynamic database for a stacked-toroid, sphere-cone inflatable decelerator. The secondary goal of this test is to examine the fluid-structure interactions (FSI) of the supersonic flow and the flexible model. This aerodynamic database will consist of measured force and moment data. Flow visualization by particle image velocimetry (PIV), Schlieren imaging, and photogrammetric shape/time histories for the model in steady-state fully-inflated conditions as well as during partially-inflated conditions will be included in the overall test data set. Also, if it is feasible with the model, aerodynamic and flow visualization data will be acquired for full inflations from a stowed position.

The test will be run at Mach numbers within the range of tunnel capabilities and at minimum tunnel pressures so as to obtain dynamic pressures as close as possible to the Mars entry conditions and to minimize model loads.

The model will be a multiple-inflation-chamber stacked-toroid sphere-cone decelerator up to a maximum of two feet in overall diameter, the size being limited by maximum allowable

DRAFT

axial force, tunnel blockage, and model PIV and photogrammetric viewing considerations. Individual control of each of the inflation chambers is required to allow for selective partial or full inflations of the chambers while the tunnel is running.

The specific objectives of this test are as follows:

Primary objective

- Measure aerodynamic performance and stability of the decelerator under full inflation, and during buckled or wrinkled conditions under partial inflation, using a 6-component internal strain gage balance for static forces and moments

Secondary objectives

- Record Schlieren and particle image velocimetry (PIV) images of flow field surrounding the decelerator during the above conditions, so as to characterize shock wave positions and regions of flow separation
- Measure the shape history of the decelerator during the above conditions using photogrammetry
- All of the above measurements are to be acquired at high frame rates (500 frames/sec or greater) and synchronized with each other using an IRIG (or similar) time controller
- If the model can be designed and fabricated in such a way that would allow for full inflation of the toroids from a stowed position, then it would be desired to acquire the above measurements during such deployments while the tunnel is running (though repacking of the model between deployments would be done manually between runs with the wind off)

3.2 Model Description

3.2.1 Model

The Contractor shall provide a model consisting of both rigid and flexible parts. The rigid parts will include a spacecraft heat shield, clamping rings for securing the inner fabric rings of the stacked toroid assembly, and a balance sleeve attached to the rear of these clamping rings. The model will be held in the tunnel by a sting in which the balance taper will be mounted, and the sting in turn will be secured to the wind tunnel strut by an adapter or adapters in the Ames Wind Tunnel Operations Division inventory.

The flexible parts of the model will include the toroids, fill tubes, a fabric membrane on the windward side of the toroids that forms a solid surface, and possibly a similar membrane or individual strips on the back side of the toroids to secure them and provide torque resistance (if deemed necessary). The windward-side membrane should be made as smooth as possible with minimal seams or pie-shaped segments, but it is recognized that it may need to be segmented for manufacturability.

Several conceptual views of the model are provided here to illustrate the basic design of the model, but these are not intended as rigid requirements on the model design.

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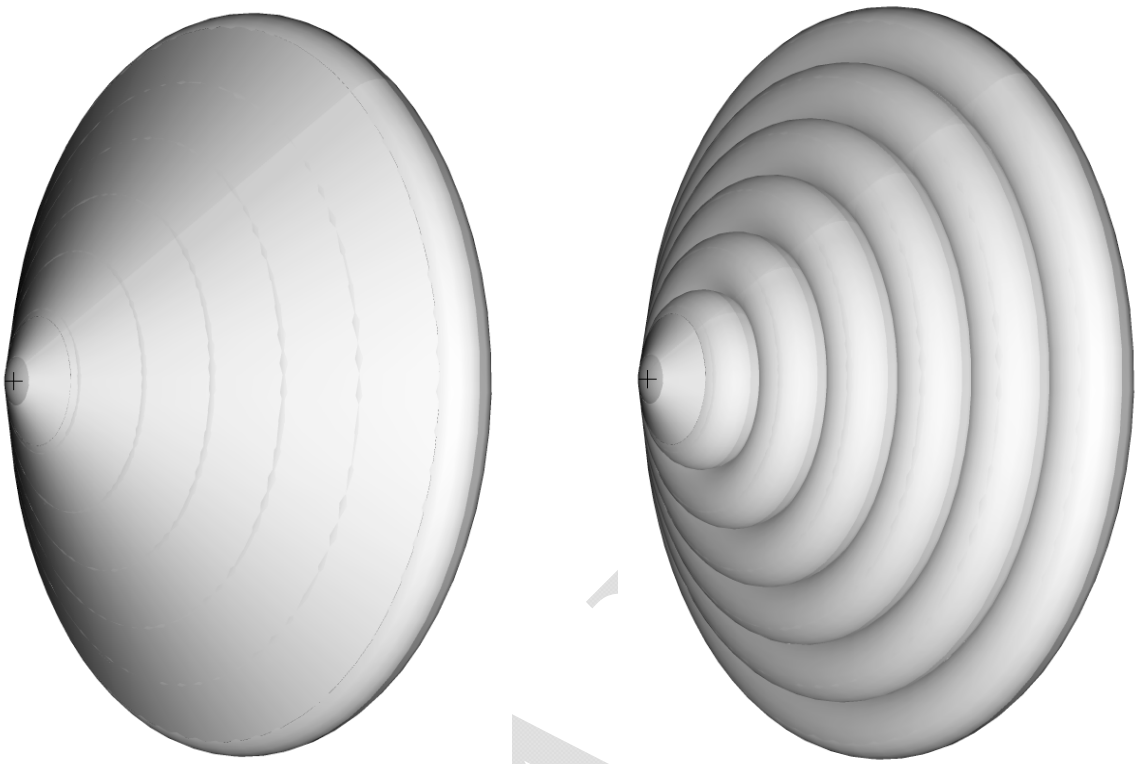
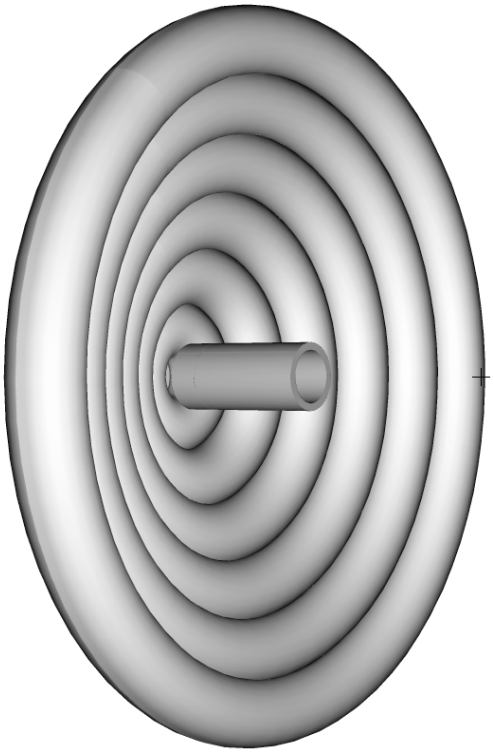
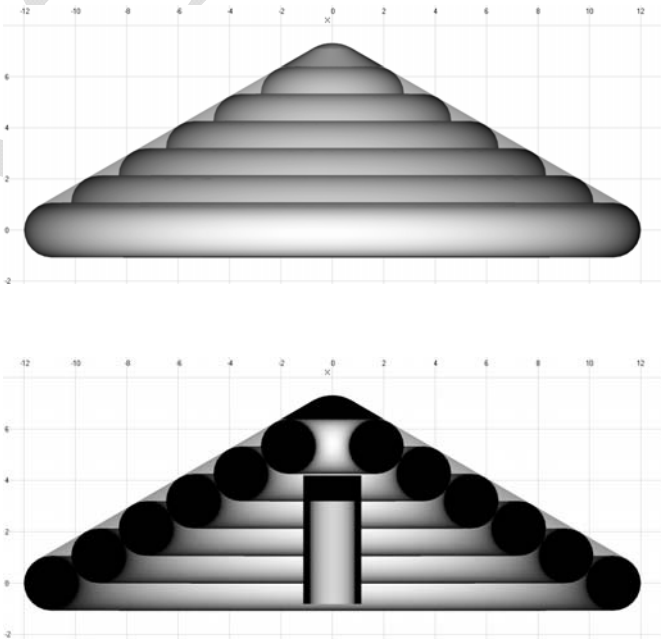


¾ front views with and without fabric shell over toroids



¾ rear view without fabric covering, showing balance sleeve



Side views, full and cut-away showing heat shield, toroid cross-sections, and balance sleeve

Detailed requirements and guidance about the model design and construction are as follows:

- Parts needed from model vendor
  - Flexible parts: toroids, fill tubes, fabric membranes around toroids
  - Rigid parts: heat shield, clamping ring assembly, balance sleeve, with the forward end of the sleeve to mate with the back side of the clamping ring assembly.
- Required Dimensions
  - Overall model diameter (D): limited to 22 inch *maximum* by expected axial force. Balance and wind tunnel strut axial force limits are 3000 lb, and based on q = 600 psf and C_A = 1.5 for 22-in. diameter, AF = 2376 lb.
  - Toroid cross-section diameter (d): on the order of 1.5 to 2 in., as dictated by number of toroids and amount of compression between toroids
  - Heat shield diameter: roughly 4 in., may be adjusted up or down slightly for better integration with toroids; spherical tip roughly ¾ in. in diameter
  - Angle of heat shield conical surface outside of spherical tip and angle of toroid assembly: 60 deg from longitudinal axis
  - Number of toroids: nominally 6 (±1 or 2), to give D/d ratio on the order of 10 and to give appropriate stiffness to stacked toroid assembly without becoming too thick
  - Clamping ring assembly thickness: not more than 2.5 in., preferably about 2 in., to permit 4-in. balance to be located approximately in the centroid of the model as viewed from the side
- Design notes
  - In the views of the conceptual model on the previous page, the details of the toroid attachments to one another, the inflation tubes, and the heat shield attachment to the balance sleeve are not shown. The Contractor shall provide these details to the Government during the model design process.
  - The Contractor shall design the flexible parts of the model to be made as light and thin as possible while providing enough structural integrity to survive up to two weeks of testing (estimate about 80 hours of run time on a two-shift-per-day test)
  - The model must have the capability for individual inflation control of the chambers, from zero gage pressure to full inflation
  - Inflation tubes for providing air to toroids are estimated at two lines per toroid. One line, or more than two are acceptable if technically advantageous. If the Contractor expects to use one line, the Contractor shall address mitigation of the risk associated with the probable asymmetric filling of the toroids and potentially unusually high stresses in the toroid structures due to the asymmetric loads.
  - Lines will have to bridge metric gap and thus are required to be as flexible as possible to minimized tares on the model forces and moments—the Contractor shall provide creative solutions for this while still ensuring the lines can be protected from the high-energy, turbulent flow behind the stacked toroids, and that they can carry sufficient mass flow to inflate the tubes within approximately 2 seconds or less. Also, the Contractor shall determine if the inflation chambers can have check valves to seal off the air once inflated, then the inflation lines upstream

DRAFT

of these valves could be depressurized to reduce balance tares while acquiring force data.

- The Contractor shall determine if model can be made such that the deflated toroids can be wrapped tightly around balance sleeve for full-deployment testing. If so, then the Contractor shall provide a means for holding the toroids closely-packed around the sleeve, with removable flow shield (such as a Kapton wrap) that can be unwrapped or unzipped with tunnel running.

3.2.2 Balance and Instrumentation

- Balance: Aerophysics Research Instruments 1.75-in. Mk II internal 6-component force & moment balance (existing at Ames)
  - Balance to be mounted in sleeve behind model heat shield and clamping rings. Balance taper to fit into model sting. Balance is owned by Ames, and sting for subject model does not yet exist.
  - Balance capacities:
    N1 = N2 = 2000 lb Ax = 3000 lb
    S1 = S2 = 2000 lb RM = 1000 in-lb
  - Balance size: 1.75 in. diameter by 4 in. length
- Pressure sensors: to measure inflation chamber pressures
  - Type of sensors and method of data transmission shall be determined at the first Technical Interchange Meeting
- Shape and position measurements: photogrammetry
  - The Contractor shall consider the high-reflectivity fiducial marks on model required for photogrammetry. The Contractor shall consider ways to permanently attach high-reflectivity markings on the model surfaces. Possible options include: (1) dot stickers (1/8 to 1/4 inch in size), but such stickers may not adhere well the model fabric; (2) painting the dots, but paint may flake off after repeated folding of the surfaces or running in the tunnel; and (3) sewn onto the fabric. The number and distribution of the markings will be discussed during model design.
- Flow visualization: PIV and Schlieren
  - Particle image velocimetry uses mineral oil to create micron-size seed particles in the flow for visualization with a laser. Small oil droplets will impact the model and some will stick to the model or be absorbed in any porous materials of the model. The Contractor shall consider impacts of this on the model construction and retention of fiducial marks.

3.2.3 Model Supports

The balance sleeve will be the most aft part of the model, which will encapsulate the balance, which in turn will be mounted to a sting and various adapters as necessary to the tunnel strut. The sting and adapters will be provided by NASA Ames.

3.2.4 Air Services

Wind tunnel “shop air” (less than 150 psi) or bottled air at relatively low pressure is envisioned for use as the inflation gas for the decelerator chambers, depending on the

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requirements for inflating the model toroids. Separate air lines will be run to each chamber. The Contractor shall notify the Government in advance of the decision to use other "air".

3.3 Model Stress Requirements

The Contractor shall submit a stress report for the model and support hardware. Facility requirements for stress analyses are specified in the NASA Ames Test Planning Guide for High Speed Wind Tunnels (http://windtunnels.arc.nasa.gov/HSpeedTestPlanGuide.pdf). The model stress requirements specified in this guide were written for rigid models, but any unique requirements from the Government for a flexible model will be presented at the first Technical Interchange Meeting.

3.4 Test Facility

The model will be tested in the Ames 9- by 7-Ft Supersonic Wind Tunnel, which is described in detail in the aforementioned Test Planning Guide.

The following test conditions are anticipated:

- Mach range: 1.6 to 2.4
  - Tunnel starts and stops at Mach 1.55. Starting and stopping loads, as described in the Test Planning Guide, are often greater than the model running loads. Therefore, the Contractor shall consider this when sizing and analyzing the stresses in the model.
- Total pressure ranges:
  - For tunnel start/stop: 650 psfa
  - For Mach number change: 1400 psfa
  - Overall: 650 psfa
  - Tunnel minimum pressure of 650 psfa will be set for data acquisition, and Mach number changes will be made at 1400 psfa
- Angle of attack and sideslip ranges: ±10°
  Angle of attack and sideslip will be controlled by the wind tunnel strut
- Operating temperature ranges: 70° F to 125° F (normally not controlled; depends on tunnel power level and outside air temperature; high-power running—low Mach and high pressure—generates the most heat)

The following table provides a summary of the wind tunnel flow parameters over the Mach number and total pressure ranges stated above:

DRAFT

Mach	P_T (psfa)	P_T (atm)	P (psfa)	T_T (°F)	T (°F)	q (psf)	Re/L (10^6/ft)	V (fps)
1.55	650	0.31	164.6	100	-81.6	276.9	1.30	1477
1.6	650	0.31	152.9	100	-89.5	274.0	1.28	1509
2	650	0.31	83.1	100	-148.7	232.6	1.10	1729
2.4	650	0.31	44.5	100	-199.6	179.3	0.91	1897
1.55	1400	0.66	354.6	100	-81.6	596.3	2.79	1477
1.6	1400	0.66	329.4	100	-89.5	590.2	2.75	1509
2	1400	0.66	178.9	100	-148.7	501.0	2.37	1729
2.4	1400	0.66	95.8	100	-199.6	386.1	1.96	1897

3.5 Model Material Properties

Structural properties of the materials used in fabrication of the model will need to be measured in various bench tests, and such tests will also be performed on the complete model to characterize its structural behavior under static conditions as much as possible.

The Contractor shall provide, at a minimum, the following material properties to the Government prior to the end of the contract period:

- Tensile strength and elastic modulus
- Shear strength under tensile load
- Thermal elongation
- Any other known material properties

For each of the material tests, the Contractor shall specify the number of plies of material, if applicable, whether the sample is pressure liner and/or weave, under internal pressure or not, temperature for the tests, the kind of fixtures used for tests, etc. The Contractor shall provide the results in a material properties report and submitted to NASA.

4.0 MODEL DEVELOPMENT REVIEWS AND SCHEDULE

4.1 Reviews and Meetings

Technical interchange meeting: There will be a technical interchange meeting (TIM) at the initiation of the work effort to develop an initial plan for the system design and hardware interfaces. This meeting will be held at the contractor's location within about a week after the effective date of the contract. Additional TIMs may be requested by either NASA or the contractor to facilitate model design and development, if necessary.

Reviews: There will be a preliminary design review (PDR) nominally within 6 weeks of the contract initiation and a final design review (FDR) 8 weeks after that (changes in the schedule for these reviews may be suggested by the contractor to better fit the design and fabrication schedule). The PDR will include a review of the preliminary design of the model, anticipated construction methods, risks in model construction and performance, and a

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timeline for the major tasks. The FDR will serve as a final check of the design details and will include a go-ahead for fabrication.

A model acceptance trip shall be conducted just prior to delivery to inspect the completed deliverables and make final adjustments if necessary.

Status update telecons: The Contractor shall participate in weekly telecons with NASA to provide status updates on the design and fabrication tasks. No formal written updates are required for these telecons.

Reporting: The Contractor shall prepare monthly status reports that include a summary of the work completed, percent completion of sub-tasks, and confidence of on-time delivery. The updates are to be submitted via email to NASA. Update reports shall begin at the end of the first month of the work period.

4.2 Schedule

The following schedule assumes a test start date of June 1, 2010. This is not a firm date, but is a reasonable estimate based on the tunnel schedule known at this time. This test date could slip or move forward by a couple of months or more.

• Technical interchange meeting (TIM) at vendor	ASAP after contract award
• Model preliminary design review (PDR) at vendor	TIM + 6 weeks
• Model final design review (FDR) at vendor	PDR + 6 weeks
• Fabrication authorization	FDR (if no significant corrections to be made)
• Model stress report delivery	FDR + 2 weeks (but not later than 6 weeks prior to test)
• Model acceptance trip	End of April 2010
• Model delivery	Early May 2010
• Test support	Early June 2010

5.0 DELIVERABLES

5.1 Hardware

- Assembled model with all flexible and rigid components as identified in section 3.2.1
- Spare fasteners for each type used in model assembly
- Small samples of materials used in model construction, both with and without representative seams

5.2 Documentation, Drawings, and Electronic Files

- Stress analysis for model
- Material and heat treat certifications for all parts

DRAFT

- Drawings of all parts in “C” size hard copies and electronic pdf files
- CAD models of all parts in iges and step formats
- Fastener certifications
- Other Quality Assurance documents as appropriate

5.3 Model Acceptance

The Contractor shall notify the ARC technical lead of the expected shipment of the hardware. Personnel from Ames will then visit the Contractor just prior to shipment of the hardware to inspect the work and ensure that all requirements have been met. Items that will be checked during this visit include, but are not limited to:

- Full assembly and disassembly of model
- Full inflation and deflation of all toroids and individual ones, with time measurements for each
- Check fit of clamping assembly to front end of balance sleeve

6.0 SECURITY

The model will be unclassified, not proprietary, and not “sensitive” (as in SBU—sensitive but unclassified) in any way. The Contractor shall not place restrictive markings on any of the design documents, stress analyses, or drawings, whether in hardcopy or electronic form.

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