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Experimental Parachute Validation Research Program and Status Report on Indoor Drop Tests

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The US Army Natick Soldier Research Development and Engineering Center (NSRDEC) is currently developing coupled fluid/structure computer codes to simulate the performance of parachutes and airdrop systems. Concurrently, NSRDEC is leading and managing an experimental parachute research program to obtain parachute performance data for validation of the computer codes. This program consists of detailed measurements of the aerodynamics and structural dynamics of small-, medium- and full-scale parachutes. Currently, measurements and instrumentation development are focused on the first two scale parachutes. These measurements include spatial canopy position and motion, the three-dimensional geometry of the canopy, canopy fabric strain, suspension line forces, air velocity, and pressure. For the small- and medium-scale parachutes, a test program has been developed in which flat round 3.5-ft., 7.0-ft., and 9.0-ft. diameter model parachutes are vertically dropped in an indoor controlled environment to obtain the measurements. The tests consist of dropping the parachutes in a large enclosed structure with a highly instrumented payload. To obtain repeatable and consistent data, a guided vertical drop system is being used. A thin steel guide wire is anchored at the floor of the structure and extends vertically through the centerline of the payload and the vent of the canopy to the ceiling. Such a test setup restricts the opening and the descent trajectory of the parachute to be on the vertical path of the guide wire. Repeatable and consistent parachute performance data have been obtained.

I. Introduction

THE US Army Natick Soldier Research, Development and Engineering Center (NSRDEC) as well as other groups in the parachute community are currently developing advanced numerical simulations of parachutes and airdrop systems[1-3]. These simulations use complex fluid/structure interactions (FSI) algorithms and methodologies to predict the performance of the flexible canopies. The FSI methodologies being developed should allow for more accurate simulation results of the behavior of airdrop systems, particularly the parachutes. However, to ensure the simulations will accurately model the parachute behavior and provide correct results, it is necessary to validate the simulations against experimental data.

The design of experiments needed to acquire data to be used in the validation of simulations has different requirements than those traditionally used in the development of parachutes[4]. In addition to the typical data acquired during the airdrop of parachute systems, such as position in three-dimensional space, payload dynamics and riser or sling forces, much more data need to be gathered about the system, including the environment where the experiment is being conducted. Numerical simulations require initial conditions and boundary conditions as input

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parameters. The validation of the simulations requires the direct comparison between the simulation and experimental data sets. This implies that it is necessary to generate a simulation of the actual tests used to acquire the experimental validation data and it also means that experimental data about the initial conditions and boundary conditions must be gathered at the same time during the tests. This can be a difficult endeavor with an airdrop from an aircraft given the difficulty in measuring wind data as well as other environmental conditions in addition to the data collection about the test article itself. The technique the NSRDEC parachute simulation uses has multiple components to model the physics of the parachute[3]. These components comprise modules which model the canopy structural dynamics, the fluid dynamics surround the parachute, and a module which allows interaction between these other components. Each component of the simulation should be validated separately in addition to the complete simulation tool.

The type of data to be acquired in the experimental validation studies covers a large amount of measurements. These measurements include spatial canopy position, motion and geometry of the canopy, fabric strain, opening force, flow field characterizations, and pressure distribution over the canopy. Basic material properties (such as Young's modulus of elasticity) are needed for the fabric. Instrumentation and measurement techniques for some of these measurements are well established, e.g., canopy position and opening force. However, measurement methodology for some other measurements have not been well developed, e.g., fabric strain and canopy geometry. In general, measurement methodology is more advanced and well developed for small-scale parachutes than for full-scale parachutes.

Examination of the types of data which could be collected from full-scale aircraft airdrops revealed that a limited amount of data could be collected about the parachute (not the entire airdrop system) in addition to the limited information about the environment for the tests. With the current state of experimental methods and measurement techniques available for full-scale airdrop, the data which could be acquired in these tests was limited to tracking the position of the parachute system, obtaining the sling forces, and monitoring the payload dynamics (e.g. acceleration, pitch dynamics, etc.). Based on this assessment, a three-prong plan was developed by the NSRDEC to acquire experimental data for validation of numerical parachute simulations. The plan consisted of conducting experiments in three primary scale regions for flat circular parachutes, namely small-scale laboratory based experiments, medium-scale parachute experiments, and full-scale parachute experiments (we have defined personnel sized parachute and larger as full-scale since the simulation codes being developed at NSRDEC are primarily for personnel and cargo airdrop). The small-scales laboratory based experiments allow for high fidelity experiments to acquire detailed data on the flow fields around parachute related objects and structural data on the objects. These results are useful for the validation of both the fluid dynamic portions of the numerical simulations as well as the structural dynamic portions. However, there are scaling concerns about these laboratory based experiments. The medium-scale parachute (diameters ~3-ft to ~15-ft) allows us to address some of the concerns about scaling but will still allow for testing in a controlled environment such as wind tunnels or inside a tall building where environmental effects, such as wind, are either controlled or minimized. By going to these larger scales though, the amount and types of data which can be acquired are reduced in comparison to those achievable at the small-scales. Finally, it is still necessary to acquire data from full-scale airdrop testing. The efforts pursued by the NSRDEC at these scales focuses primarily on the development of new sensors and measurement techniques for acquiring data. In addition to obtaining validation test data for the computer codes, it is also a long-term goal of this experimental program to develop new sensors and measurement methodology to advance the state-of-the-art of parachute performance measurement technology. In the near future, these efforts will focus on steady descent first.

The objectives of this paper are twofold, to present a brief overview of the overall experimental validation effort and secondly to present some preliminary results from a set of medium-scale parachutes testing being conducted by the NSRDEC.

II. Overall Validation Efforts

The experimental research program developed for acquiring validation data of parachute simulations focuses on three primary areas, namely laboratory based experiments, medium-scale parachute experiments, and full-scale parachute experimental techniques and sensor development. This section briefly describes the individual research efforts being pursed by the NSRDEC and its research partners to support the validation initiative.

1. Laboratory based experiments

The numerical parachute simulations contain a portion of the code which handles modeling the structural mechanics of the canopy. Data for the validation of this portion of the simulation is being obtained using a variety of textile based objects by the University of Massachusetts Lowell[5]. These experiments measured the shape and strain of inflated fabric structures such as pressurized cylinders and pillows using a three-dimensional image

correlation system. Additionally, a polymer high strain sensor was examined as a potential strain sensor for larger parachutes.

Detailed flow field data is useful for validating the fluid dynamic portions of the parachute simulations. An effort was initiated with Worcester Polytechnic Institute (WPI) to obtain flow field and other data from small-scale parachutes and related rigid objects. There were three objects pursed in this study, three-dimensional velocity field mapping of the water tunnel facility located at WPI in order to characterize the boundary conditions of the tunnels test section, measurement of velocity fields around a rigid disk and cup, and development of methods for making shape measurements of flexible moving parachutes mounted in the water tunnel. The rigid models of the disk and cup were utilized in this study to provide a well defined model geometry which would allow for validation of the computational fluid dynamic portion of the parachute simulations without having to deal with structural and fluid/structure modules of the simulation. The results of the rigid model experiments will be presented at a later time. The shape measurement experiments were conducted to examine methods for obtaining instantaneous geometry data of a parachute at initially small-scales[6] and possibly at larger scales.

The fundamental material properties of the nylon fabrics, cordage, and webbings used in the construction of parachutes are not well defined. The NSRDEC is currently measuring these properties and the results will be published in the future[**].

2. Medium-scale parachute experiments

Medium-scale parachute testing provides a reasonable compromise between scaling effects while still testing under controlled conditions. A comprehensive medium-scale parachute testing program was initiated by the NSRDEC. The program provides an opportunity to conduct a variety of tests for obtaining an array of validation data including basic parachute/payload system performance data (e.g. acceleration, suspension line forces, and descent velocity), detailed canopy shape measurements, possible flow field measurements, and a test bed for new canopy sensors. The concept of these tests is to drop a highly instrumented payload under a medium-scale parachute (3.5-ft to 9-ft diameter) inside a tall enclosed environmentally controlled structure. The trajectory of the parachute system was controlled by dropping the system along a vertical guide wire thereby restricting the lateral motion of the system. Additional instrumentation can also be placed around the parachute descent path or on the floor of the test facility to monitor the parachute system. The details of this program and some preliminary results are presented in the next section of this paper.

NASA Langley Research Center (LaRC) has developed a shape measurement technique for measuring the three-dimensional canopy shape in these vertical parachute drop tests[7]. The method uses a photogrammetry technique which tracks the position of small markers attached to the canopy surface using cameras mounted on both the payload and from a ground based camera array system. It is anticipated that the onboard camera system can scale up to support future full-scale airdrop testing as well.

This test program is also examining methods of performing flow field measurements around the parachute canopy as it descends. The method of Stereo Particle Image Velocimetry (SPIV) provides detailed flow field measurements around a body in a plane but has the limitation of being able to measure only in an area approximately (2×2) ft^2. A small imaging area of this size requires either testing with small parachutes or making multiple measurement areas around larger parachutes and then connecting the areas together to create a composite flow field measurement. To overcome these limitations of SPIV, efforts are being pursued using other techniques which are better for making measurements over larger areas. The technique of Stereoscopic Tracking Velocimetry (STV) is being investigated by the University of Illinois at Chicago as a possible method for obtaining flow field over large areas[8]. This technique uses multiple cameras to track the motion of seeding particles introduced into the flow to infer the velocity of the fluid. Similarly, an effort is underway through a Small Business Innovative Research (SBIR) program for the development of a Planar Doppler Velocimeter[9] (PDV) capable of measuring flow fields over large areas at speeds as low as 1 ft/s.

The limitation of indoor vertical drop testing is the height of the building which in turn limits the size of the parachute due to the distances need for the parachute to inflate. Wind tunnel testing is an alternative testing venue which could support similar sized parachutes. However, since the wind tunnel air flow is maintained at constant speeds, only steady descent or infinite-mass inflation could be studied in wind tunnels. In an effort to provide another option for finite-mass inflation studies, the US Naval Academy is investigating the possibility of performing parachute testing in their tow tanks beginning with infinite-mass testing[10] and then proceeding to finite-mass testing using pre-programmed motion control.

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3. Full-scale parachute experimental methods development

The full-scale parachute testing program involves the continued evolution of the onboard payload photogrammetry system developed by NASA LaRC. The current testing plan is to test the system on 28-ft. diameter C-9 personnel parachutes and then proceed to 64-ft. and 100-ft. diameter cargo parachutes. This plan will provide a full spectrum of geometric shape validation data covering the full range of test environments.

Beyond the basic parachute and payload system performance data obtained in most parachute research and development programs, almost no data exists on the aerodynamic and structural performance of full-scale parachutes[11,12]. Given the significant advances recently in electronic and wireless communications, the NSRDEC has supported the development of new pressure sensors to support aerodynamic studies of parachutes[13,††]. Similarly, the developments of new strain measurement sensors or techniques are also being pursued[‡‡].

III. Indoor Vertical Tests

As briefly outlined in the last section, a comprehensive an indoor vertical parachute drop test program was developed to support the collection of validation data in addition to studying the physics of parachute dynamics. This section describes the specifics of the development of the experimental test program, presents some preliminary results obtained from testing to-date, and future plans of the program.

A. Experimental Setup

1. Test facility

The facility being used for the drop tests is the Space Power Facility (SPF) at the NASA Glenn Research Center (GRC) Plum Brook Station in Sandusky, Ohio[15,§§]. A photograph of the facility and schematics of the facility are shown in Fig. 1. The test chamber of the SPF is a circular dome-shaped structure designed for high vacuum conditions to test space hardware in a simulated Low-Earth-Orbiting environment, although for the parachute drop tests, the test chamber was maintained at ambient atmospheric conditions. The schematic view of the test chamber in Fig. 1b shows the substantial structure of the facility which makes it an attractive environment to conduct parachute testing. The test chamber is constructed from 1-in. thick (or thicker) aluminum floor, walls, and ceiling which is surrounded by a 6-ft thick outer concrete structure. The combination of these two structures has a modulating effect on the environment inside the test chamber, creating a quiescent air space ideal for detailed parachute studies. Inside the structure, the air velocity has been estimated to be extremely, low at less than 0.33 ft/sec. The test chamber is 100-ft. in diameter and 120-ft. high at the center of the chamber. The test chamber is accessible from two 50-ft. × 50-ft. equipment doors, an 8-ft. × 8-ft. personnel door, and a 6-ft. diameter manhole port at the top of the chamber. The two large doors were closed and the personnel door and manhole port were covered with temporary plastic covers during testing to minimize air currents inside the chamber. Given the height of the facility and lack of forced convection inside the chamber, there was a concern a natural convective currents would be established due to temperature stratification. Measurements of the temperature at both the floor and near the ceiling of the chamber showed a temperature variation of less than 1°F.

2. Vertical guide wire and support equipment

In order to obtain consistent and repeatable test data, a 0.093-in. diameter piano wire was secured from the ceiling to the floor of the chamber. A schematic of the experimental setup is shown in Fig. 1c. The guide wire passed through the center of the payload and through the vent of the parachute. Such a set-up restricts the opening and the descent trajectory of the parachute to be on the vertical path of the guide wire. A tensioning mechanism (ratchet puller) on the floor applied a force on the guide wire to minimize the horizontal movement of the parachute and the payload during their vertical descent. A dynamometer was used to monitor and set the tension of the guide wire at a value of 200 ± 20 lbs. Foam cushions and paper honeycomb were positioned on the floor to attenuate the impact of the payload at landing. The parachute and payload were lifted to the ceiling of the chamber using a lifting line attached to a pulley and electric winch. A remotely activated mechanical release mechanism was used to secure the parachute to the lifting line. The apex of the canopy was attached a pivoting arm on the release mechanism. The release mechanism was remotely activated using a radio frequency (RF) transmission from the floor of the chamber which activated a servomotor causing a mechanical arm to rotate, thereby releasing the parachute. A photograph of

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†† Small Business Innovative Research Solicitation, http://www.acq.osd.mil/osbp/sbir/solicitations/sbir062/army062.htm

‡‡ Small Business Innovative Research Solicitation, http://www.acq.osd.mil/osbp/sbir/solicitations/sbir072/army072.htm

§§ http://facilities.grc.nasa.gov/spf/

the release mechanism with the canopy attached is shown in Fig. 2c. For experiments studying parachute inflation, a static line was also secured between the release mechanism and the parachute sleeve (Fig. 2c).

3. Parachutes

The parachutes used in these tests were flat, round parachutes with constructed diameters of 3.5-ft., 7.0-ft., and 9.0-ft. The parachutes had an apex vent with an area 5% of the constructed canopy area. Three groups of porous and non-porous parachutes were constructed for testing using previous design guidelines for model parachutes[14]. The dimensions and other canopy design features are shown in Table 1. All parachutes had 16 suspension lines which were collected into four groups of four suspension lines. Each group was attached to a short riser (~6-in. long) for connecting to the payload using small metal split rings. The fineness ratio of the suspension lines was 1.0 for all the canopies. The 3.5-ft. diameter small-scale parachutes were chosen mainly to establish measurement techniques for the initial set-up and development of three-dimensional canopy flow field measurement techniques being developed separately and to be tested in the future. As these techniques are demonstrated, they will be further developed for the 7.0-ft. medium-scale parachutes. The 7.0-ft. canopy made from 16-gores was established as the baseline canopy for canopy shape measurements. The 9-ft. diameter parachute was constructed to support low mass ratio drops to achieve proper scaling with full-scale parachutes.

Table 1. Properties of Parachutes

canopy diameter	3.5-ft.			7.0-ft.			9.0-ft.	
canopy fabric	(1.1 oz/yd^2)[15]		F111[16]	1.1 oz/yd^2		F111	1.1 oz/yd^2	F111
fabric porosity	porous		non-porous	porous		non-porous	porous	non-porous
number of gores	1	16	16	2	16	16	16	16

Although both porous and non-porous fabrics have long been used for parachute canopies, basic porosity effects on parachute performance are not well understood. The porous and non-porous canopies were chosen to study the effects in this controlled indoor environment. Sleeves, made with the same fabric as that of the canopies, were constructed for the canopies for the opening study (the guide wire design makes it physically impossible to conduct opening study from a deployment bag). Static lines were connected to the sleeves to initiate parachute opening. Parachutes were also dropped from a free hanging position without a sleeve for steady descent study.

4. Payloads

Two payload packages were designed and built for the tests. The payloads were designed to accommodate instrumentation and ballast weights so variations in total payload weights could be achieved. Each payload was cylindrical in shape with a foam spherical nose cone as shown in Fig. 2a. The payload was manufactured from aluminum with thin aerodynamic shields covering the outside of the packages to create a streamlined shape in an effort to minimize the wake profile of the payload. The two payload packages were 4-in. and 6-in. in diameter with an overall length of 12.25-in. (not including the spherical nose). The weight range achievable with the 4-in. payload was 3.4 lbs to 24.7 lbs. The weight range achievable with the 6-in. payload was 6.8 lbs to 42.1 lbs. A pair of linear bearings was mounted along the center of the payload to slide on the vertical guide wire. The payload consisted of upper and lower compartments in which the upper compartment housed the instrumentation and the lower compartment held the ballast weights. The instrumentation package contained in the payloads were comprised of a tri-axial accelerometer, either two or four load cells, a descent velocity probe, and onboard camera systems used to extract canopy shape geometry. Data and digital video recording systems were also incorporated into the instrumentation package. Onboard data was stored on flash memory cards and power to the payload instrumentation came from rechargeable lithium ion batteries. The development of the instrumentation package for the payloads is described in Jones et al.[7] which also describes the methods used to measure the shape of the canopy. The parachutes were attached to the payload through the load cells mounted around the top outer edge of the payload. Either two or four load cells were used in the experiments depending on the testing being performed. The suspension lines were divided into two or four groups to attach to the load cells. A photograph of the payload resting on the impact cushion prior to being lifted to the top of the chamber is shown in Fig. 2b.

5. Drop procedure

The procedure for conducting a test began with attaching the apex of the parachute to the release mechanism when the payload was on the impact cushion. For inflation studies, the parachute was packed into the sleeve and the static line was stowed with rubber bands at the top of the sleeve (Fig. 2c). The bottom of the sleeve was tied shut with thin thread which would easily break when the parachute was released from the sleeve. For free hanging drops, the parachute and suspension lines were allowed to hang freely from the release mechanism and there were no

special procedures taken to organize the canopy or lines beyond ensuring the lines were not tangled (Fig. 2d). For the inflation study, the canopy and suspension lines were organized such that half of the gores and lines were on either side of the guide wire before the sleeve was pulled over the canopy and the thread secured around the bottom of the sleeve and the suspension line groups (Fig. 2e-f). At this point, the release mechanism was powered and the parachute and payload were raised to the top of the chamber using the electric winch. A closed circuit television system was mounted at the top of the chamber near the lifting line pulley to monitor when the payload reached the top of the chamber. Once at the top of the chamber, the payload was remotely powered on. The data acquisition system and video recorders were then activated along with the onboard lighting. A short countdown was commenced after which the release mechanism was activated to drop the parachute. The parachute would open and descend along the guide wire and impact the cushion materials on the floor of the chamber. The data acquisition system and video recorders would be deactivated and then the payload would be powered off. The release mechanism would be lowered and the procedure would begin again for the next drop. Due to video data storage limitations, the onboard video would need to be downloaded from the payload after two consecutive drops. The video data was downloaded using a USB connection to a laptop computer and the other data could be downloaded using a flash memory card. Battery power was adequate for conducting approximately 6-8 drops before needing to be recharged. Figure 2g shows a 7-ft. canopy descending approximately halfway down the guide wire and Fig. 2h shows a 3.5-ft single gore canopy falling with a 4-in. diameter payload.

B. Preliminary Results

The medium-scale parachute drop test program at SPF has conducted a large number of tests covering a spectrum of parachutes and payload configurations. At the time of this publication, over 260 drops have been performed over a four week test schedule. These drops have included detailed parachute performance measurements of acceleration, suspension line forces, descent velocity, and three-dimensional canopy shape measurements for the canopies listed in Table 1 during steady descent and inflation. The payload weights varied from 3.4 lbs to 17.1 lbs for these tests. For the inflation studies, the static line length varied from 5-ft. to 30-ft. Due to time constraints, only some preliminary data will be presented in this paper with future publications being planned to present the full analysis of the data collected.

The data that follows is a sample of the typical data collected during a drop. This sample data is from the drop of a 7.0-ft. canopy with the 6-in. diameter payload and a total weight of 11.9 lbs. The canopy was constructed from 1.1 oz/yd^2 fabric using two gores with the suspension lines divided into four groups attached to four load cells. The parachute was released from a free hanging position at a drop height of 92-ft. measured from the bottom of the payload to the top of the impact cushion.

1. Acceleration

Figure 3 shows the acceleration of the payload as it descends down the guide wire. We have defined time to be zero at the point the parachute is released. The accelerometer was a tri-axial sensor with the vertical component being parallel to the guide wire. Examination of Fig. 3a, which illustrates the vertical component of the acceleration, shows that prior to release, the payload experiences 1g of acceleration. After release, the parachute/payload system free falls approximately 0.5 s at which point the parachute begins to inflate as is evident in the sharp rise in acceleration. During inflation, the acceleration reaches a peak value of 3.2g's and rapidly falls off to a mean value of 1g during steady descent. Observations of the canopy showed that it exhibited significant breathing (the periodic outward and inward movement of the skirt diameter) after inflation. This behavior is also apparent in the acceleration data in which the vertical component of the acceleration shows a periodic behavior from approximately 1.0 s to just prior to impact at 5.5 s. The amplitude of the oscillations is approximately ±0.3g. Figure 3b shows the two lateral axes of the accelerometer. During the drop, these axes sense little motion except a small disturbance during the parachute inflation and just prior to impact when the payload exhibited some lateral motion which was not uncommon during the tests.

2. Suspension line forces

The total force acting on the canopy is measured by the load cells. Figure 4 shows the sum of the four load cells measurements of the suspension line forces. Prior to release, the total force is equal to the suspended weight of the payload. After release, the force drops to near zero values as the system free falls. As the parachute inflates the force rise rapidly to a peak value of approximately 37 lbs and then rapidly falls to a mean value of ~12 lbs with oscillations with an amplitude of ±3 lbs. The peak measured force value corresponds well with the predicted value from the peak acceleration of 38.1 lbs. The canopy breathing is also seen in the force data.

3. Descent velocity

The velocity probe used in these experiments is based on hot-wire anemometry and was custom designed to measure the descent speed of the payload. The probe protruded from the side of the payload into the freestream flowing past the payload as it descended. A sample of the probe output is shown in Fig. 5. It should be noted that this data was filtered in post processing using a 9th-order Butterworth filter with a cut-off frequency of 50 Hz. The plot shows the speed of the payload rises rapidly to a peak value of 13 ft/s, slows down to a value near 10 ft/s while the parachute inflates and then slowly approaches a steady descent speed of 14 ft/s just prior to impacting the cushion. Pre-drop calculations of the steady descent predicted a descent speed of ~18 ft/s based on a canopy drag coefficient of 0.75. The difference could be caused by a relative rotational motion between the payload and canopy. The velocity probe was designed under the assumption that the flow would be perpendicular to the sensing element however the rotation of the payload would cause the flow to approach the sensing element at an oblique angle thereby skewing the reading. Further analysis of the data and sensor is needed to verify the rotational behavior of the probe. Additional speed verification can be achieved by integration of the acceleration to calculate the descent speed.

4. Canopy skirt diameter

Figure 6 shows the diameter of the canopy skirt over approximately 1 s of the descent. The vertical axis of the plot corresponds to the location of the skirt plane therefore a ring of data points at any given plane would represent the location of the canopy skirt in space. An accumulation of these rings is depicted in Fig. 6. The plot shows the variation in canopy diameter as the parachute falls through the measurement volume which corresponds to the breathing observed. These measurements were made from the ground based camera system mentioned in Jones et al[7]. Synchronization of this data with the other acquired data still needs to be performed.

IV. Conclusions and Future Efforts

A comprehensive experimental parachute validation research program for the validation of the numerical parachute performance simulations has been formulated. Most of the experiments and instrumentation development for the small- and medium-scale are well underway. Progress has been satisfactory in the implementation and set up of test facilities, applications and development of instrumentation, execution of experiments and data acquisition. Preparation and plan for future outdoor full-scale testing is on going.

The indoor guide wire set up inside the Space Power Facility has been shown to be a viable technique to monitor parachute performance and measure the important fluid and structural parameters during opening and descent in a controlled manner. The designed parachutes, payloads and instrumentation for these controlled tests have functioned well with good results. The set up also provides a test bed for developing new instrumentation and measurement methods in preparation for the outdoor full-scale testing. These tests and research activities in the SPF will continue to acquire a complete set of high fidelity measurements for the validation of the numerical parachute performance simulations.

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References

[1]Charles, R., Accorsi, M., Morton, S., Tomaro, R, Stein, K., Sathe, S., and Tezduyar, T, "Overview of Airdrop Systems Modeling Project Within the CST CHSSI Program," Proceedings of the 18th AIAA ADS Technology Conference and Seminar, May 23-26, 2005, Munich, Germany, AIAA Paper 2005-1621.

[2]Tutt, B. and Taylor, A., "The Use of LS-DYNA to Simulate the Inflation of a Parachute canopy," Proceedings of the 18th AIAA Aerodynamic Decelerator Systems Technology Conference, May 23-26, 2005, Munich, Germany, AIAA Paper 2005-1608.

[3]Charles, R.D., "Applications of Airdrop Systems Modeling Software," Proceedings of the 19th AIAA Aerodynamic Decelerator Systems Technology Conference, May 21-24, 2007, Williamsburg, VA, AIAA Paper 2007-2503.

[4]Oberkampf, W. and Roy, C., *Verification and Validation in Computational Simulation*, AIAA Professional Development Short Course, January 7-8, 2006, Reno, NV.

[5]Carney, A., Niezrecki, C., Niemi, E., and Chen, J., "Parachute Strain and Deformation Measurements using Imaging and Polymer Strain Sensors," Proceedings of the 19th AIAA Aerodynamic Decelerator Systems Technology Conference, May 21-24, 2007, Williamsburg, VA, AIAA Paper 2007-2553.

[6]Ghaem-Maghami, E., Desabrais, K.J., and Johari, H., "Measurement of the Geometry of a Parachute Canopy using Image Correlation Photogrammetry," Proceedings of the 19th AIAA Aerodynamic Decelerator Systems Technology Conference, May 21-24, 2007, Williamsburg, VA, AIAA Paper 2007-2568.

[7]Jones, T.W., Downey, J.M., Lunsford, C.B., Desabrais, K.J., and Noetscher, G., "Experimental Methods Using Photogrammetric techniques for Parachute Canopy Shape Measurements," Proceedings of the 19th AIAA Aerodynamic Decelerator Systems Technology Conference, May 21-24, 2007, Williamsburg, VA, AIAA Paper 2007-2550.

[8]Feng, Z., Cha, S., and Ludovisi, D., "Development of the Experimental System for Measuring Three-Dimensional Large-Scale Parachute Flow," Proceedings of the 19th AIAA Aerodynamic Decelerator Systems Technology Conference, May 21-24, 2007, Williamsburg, VA, AIAA Paper 2007-2570.

[9]Jenkins, T.P., Turner, K.I., and McKenzie, R. L., "Planar Doppler Velocimetry for Low-Speed Flows", To be presented at the International Congress on Instrumentation for use in Aerospace Simulation Facilities (ICIASF), Pacific Grove, California, June 10 – 13, 2007.

[10]Holloway, M. and Weber, F., "Infinite Mass Testing of a Scaled Parachute using a Tow Tank Facility," Proceedings of the 19th AIAA Aerodynamic Decelerator Systems Technology Conference, May 21-24, 2007, Williamsburg, VA, AIAA Paper 2007-2565.

[11] Henfling, J. F. and Purvis, J. W., "Pressure Distributions on Parachute Ribbon Shapes," Proceedings of the 8th AIAA Aerodynamics Decelerator and Balloon Technology Conference, April 2-4, 1984, Hyannis, MA, AIAA Paper No. 84-0815.

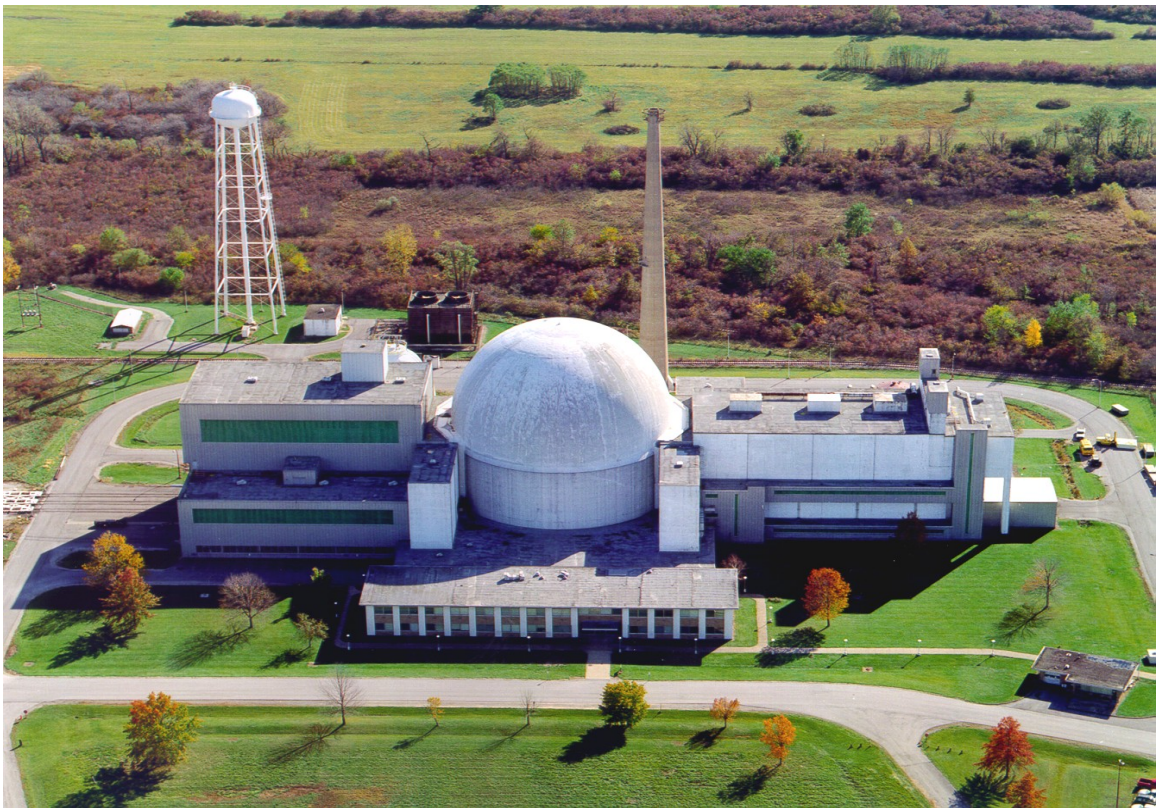
[12]Render, A.B. and Bradley, P.D., "The Development of a Parachute Strain Measurement Technique," Proceedings of the AIAA 9th Aerodynamic Decelerator & Balloon Technology Conference, Oct. 7-9, 1986, Albuquerque, NM, AIAA Paper 86-2469.

[13]Burns, D., Burns, D., Lee, C., and Desabrais, K., "Compact, Lightweight Pressure Sensors for Aerodynamic Parachute Measurements," Proceedings of the 19th AIAA Aerodynamic Decelerator Systems Technology Conference, May 21-24, 2007, Williamsburg, VA, AIAA Paper 2007-2570.

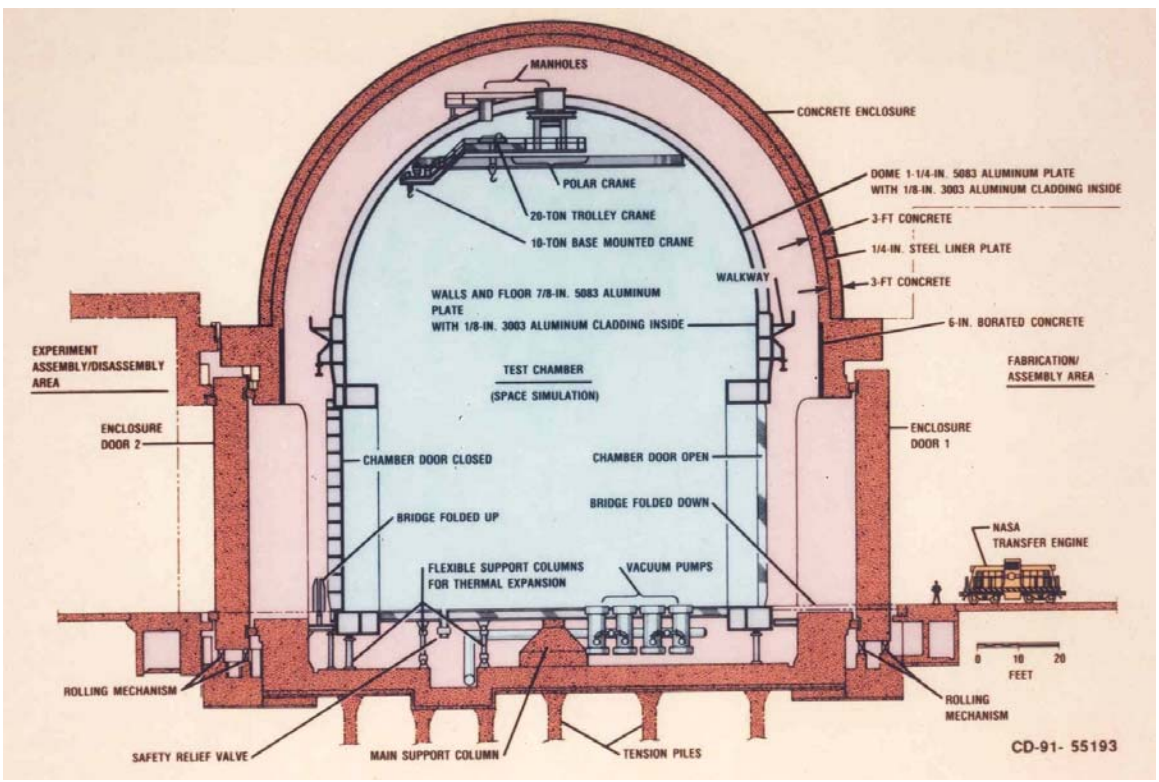
[14]Lee, C.K., "Modeling of parachute Opening: An Experimental Investigation," *Journal of Aircraft*, Vol. 26, No. 5, May 1989.

[15]Parachute Industry Association (PIA) Standard Specification: PIA-C-7020, Cloth, Parachute, Nylon-Rip Stop and Twill Weave, Type I.

[16]Parachute Industry Association (PIA) Standard Specification: PIA-C-44378, Cloth, Parachute, Nylon, Low Permeability, Type I.

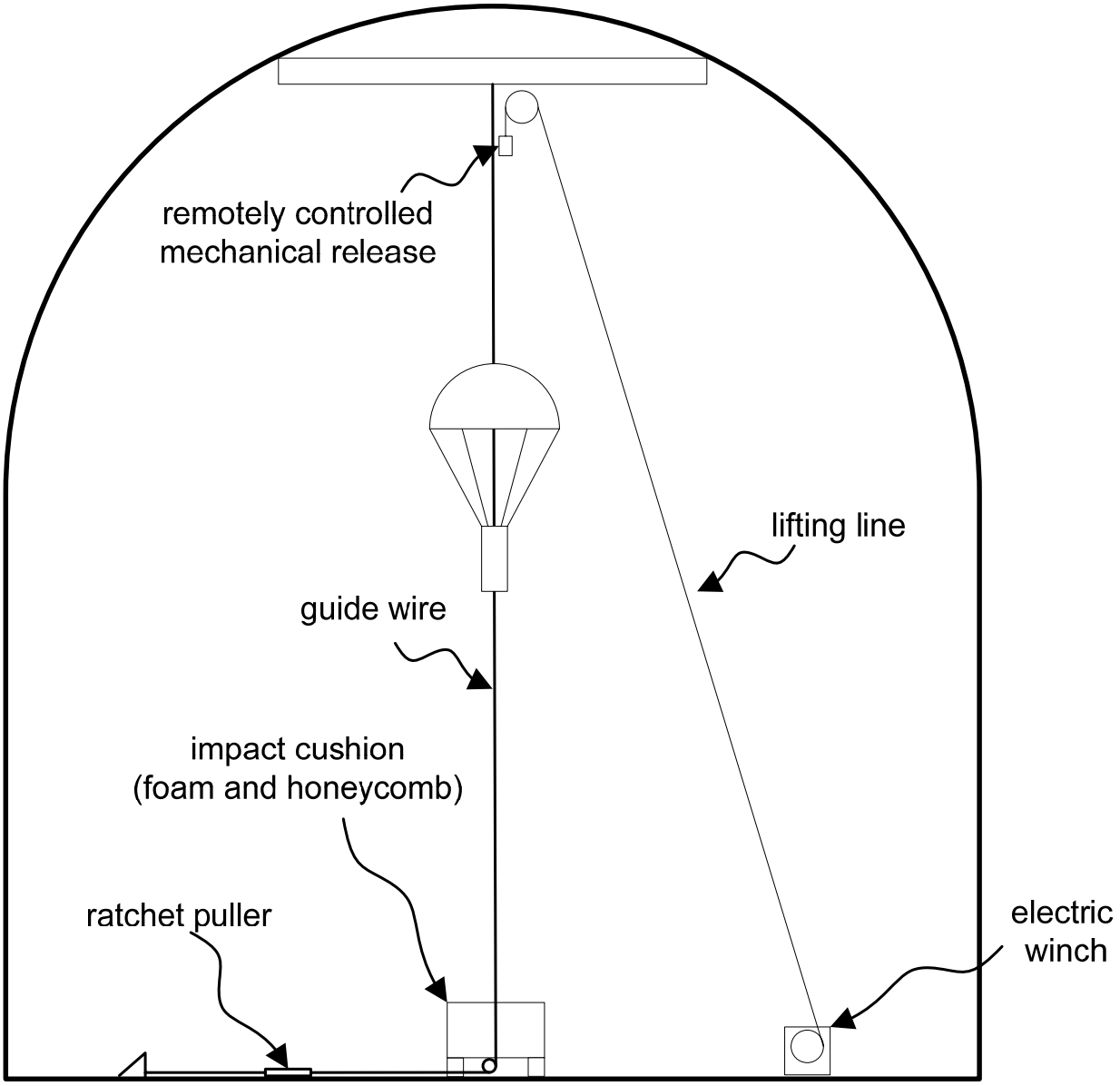


a)



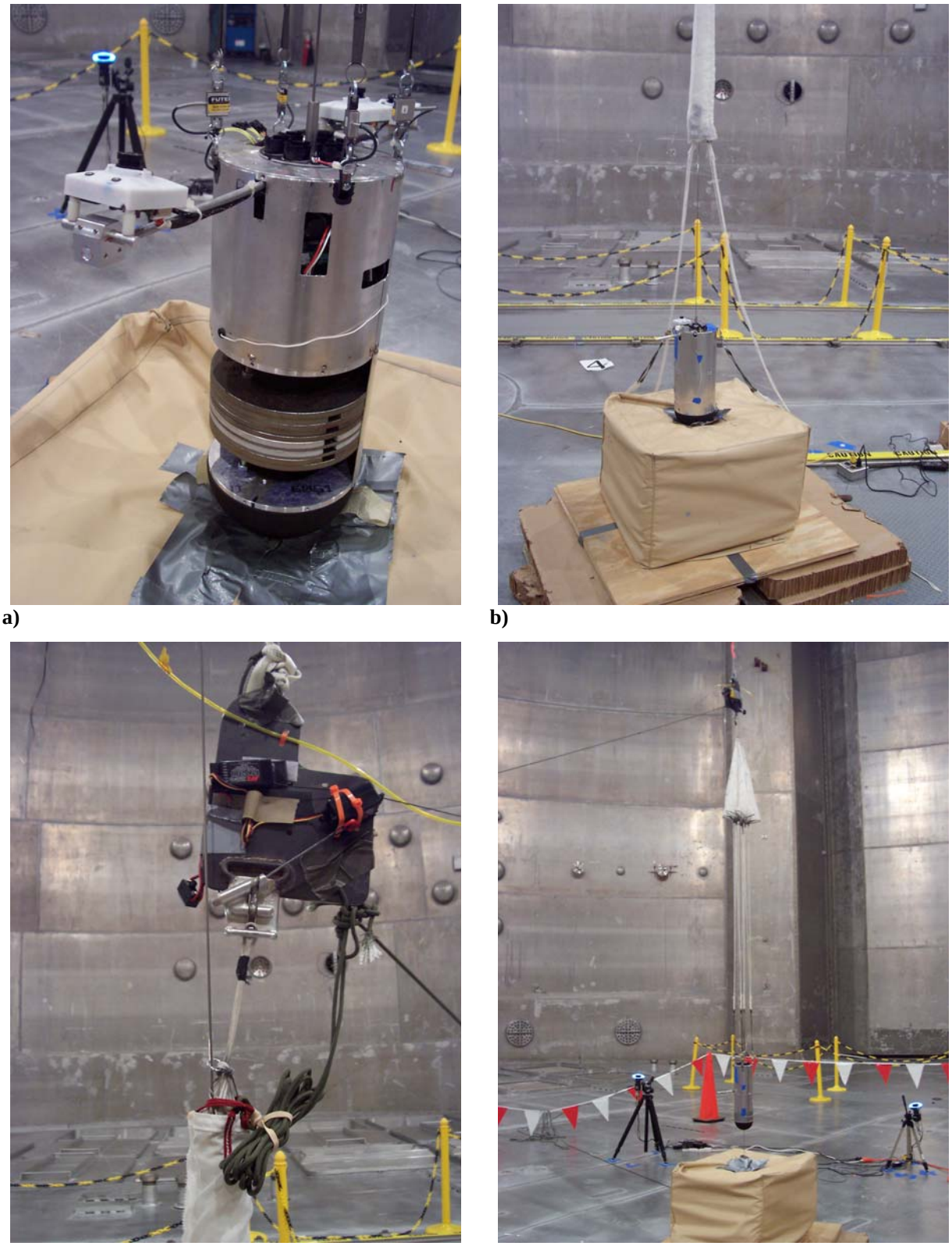
b)

Figure 1. a) Photograph of the SPF facility; b) cross-sectional view of the SPF chamber; (continued)



c)

Figure 1 (continued). c) schematic of the experimental setup inside the SPF chamber.

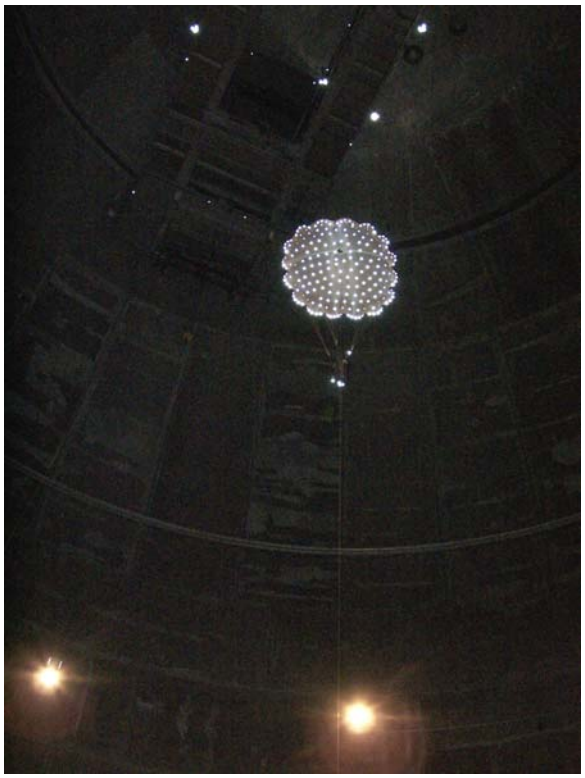


a) b) c) d)

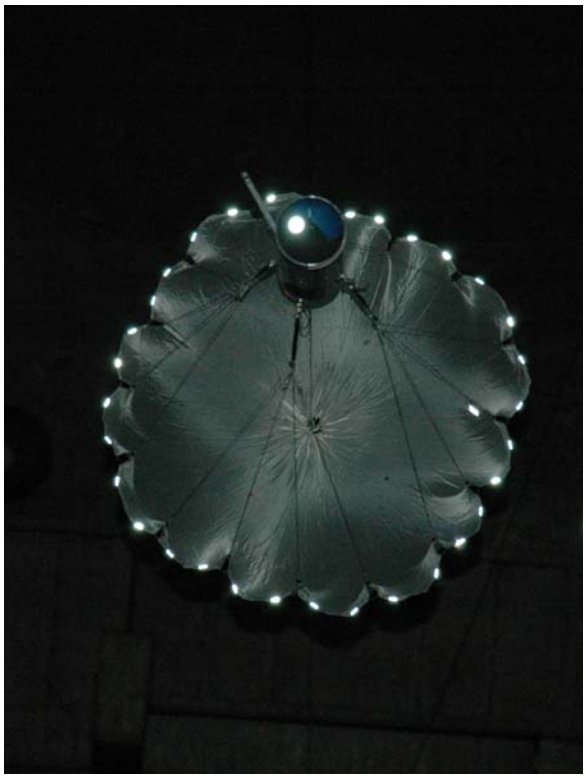
Figure 2. Photograph of a) the payload mounted on the guide wire; b) landing cushion; c) the remotely controlled mechanical parachute release holding a static line deployed parachute packed in a sleeve; d) a 3.5-ft canopy with the 4-in. diameter payload free hanging; (continued)

e)

f)

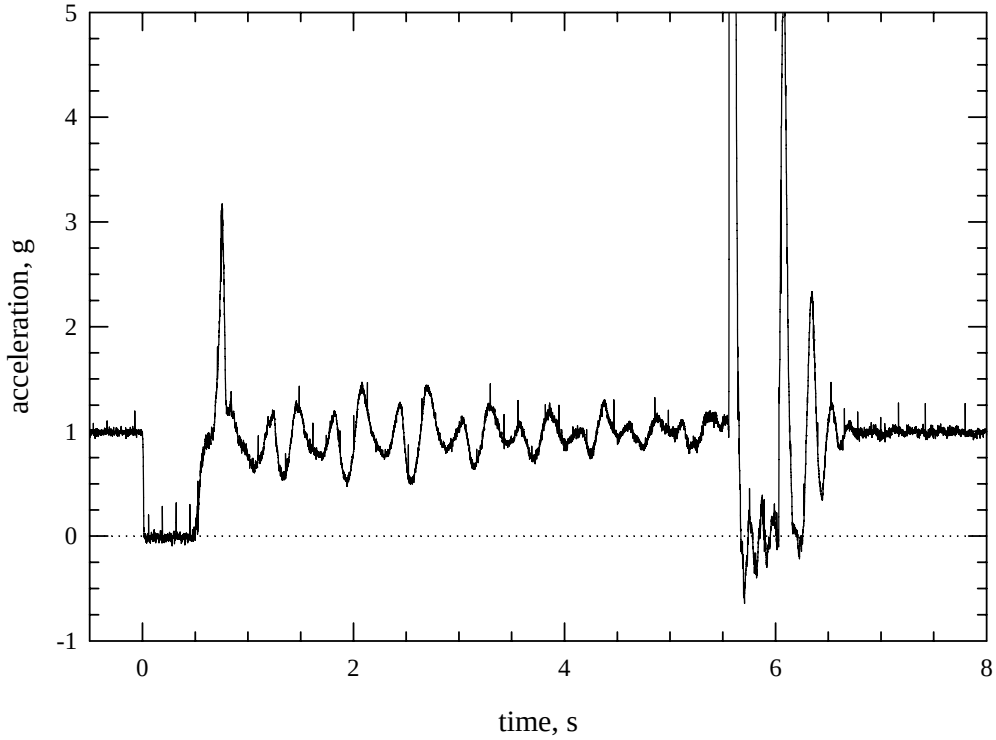


g)

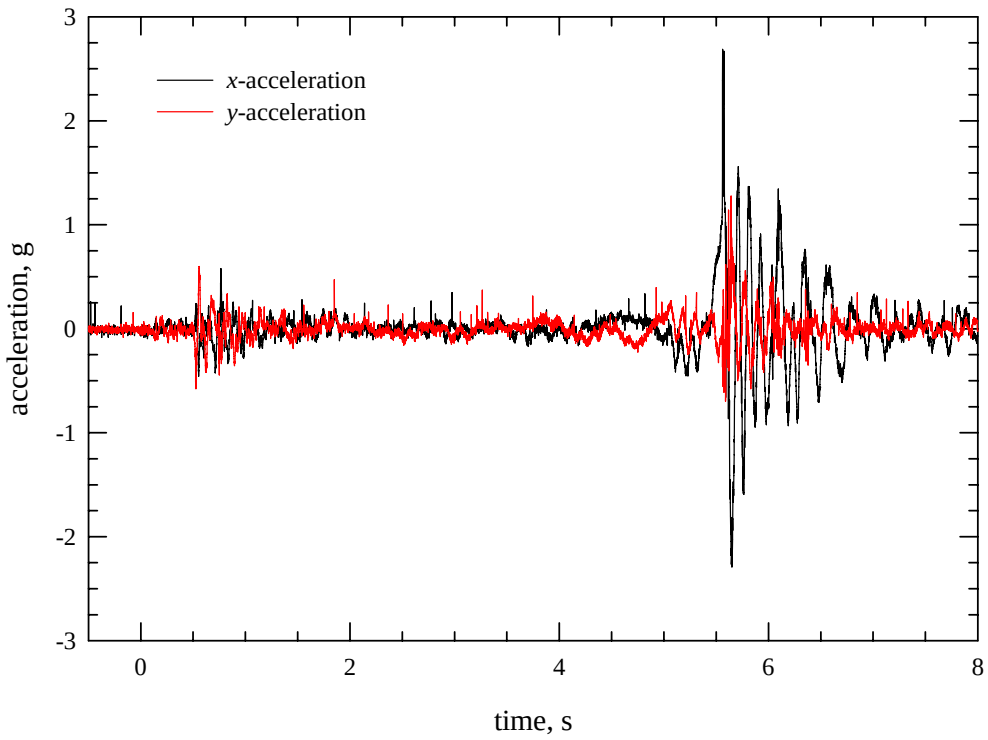


h)

Figure 2 (continued). e) 7-ft. canopy packed in a sleeve; f) close-up of the bottom of sleeve and suspension line grouping; g) the payload falling under a 7-ft. canopy with retro reflective targets on the canopy; and h) 3.5-ft. single gore, canopy falling with the 4-in. diameter payload.



a)



b)

Figure 3. Sample acceleration data plots for a) the vertical axis; b) the two lateral axes (*x*- and *y*-axes) for a payload weight of 11.9 lbs and a 7-ft. diameter canopy.

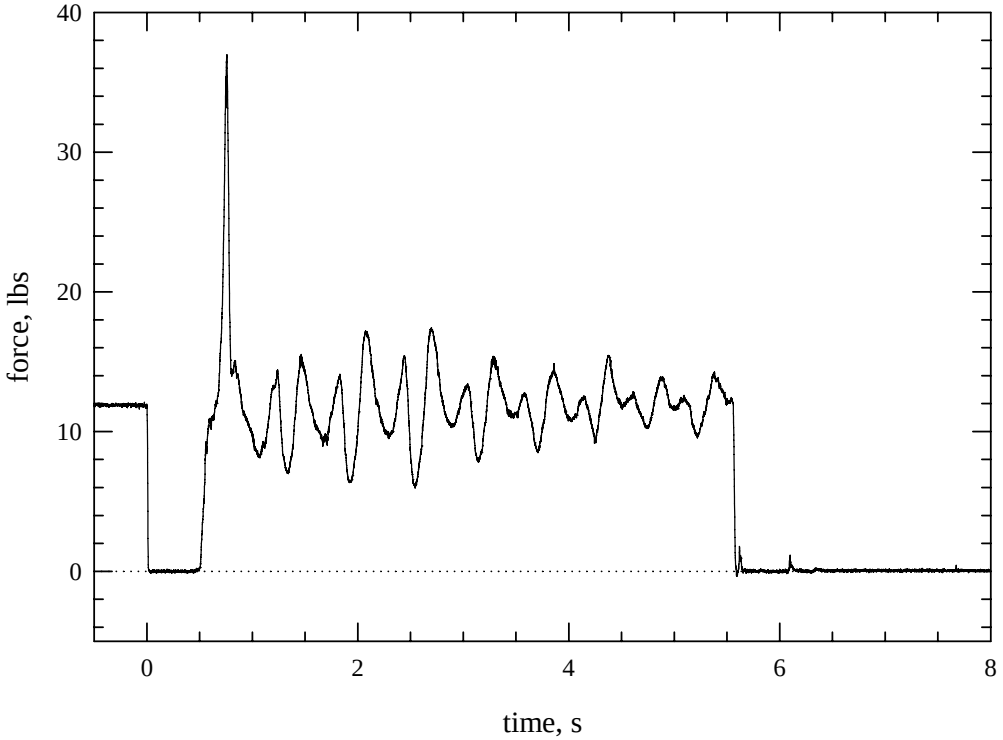


Figure 4. Sample of total suspension line force for a payload weight of 11.9 lbs and a 7-ft. diameter canopy.

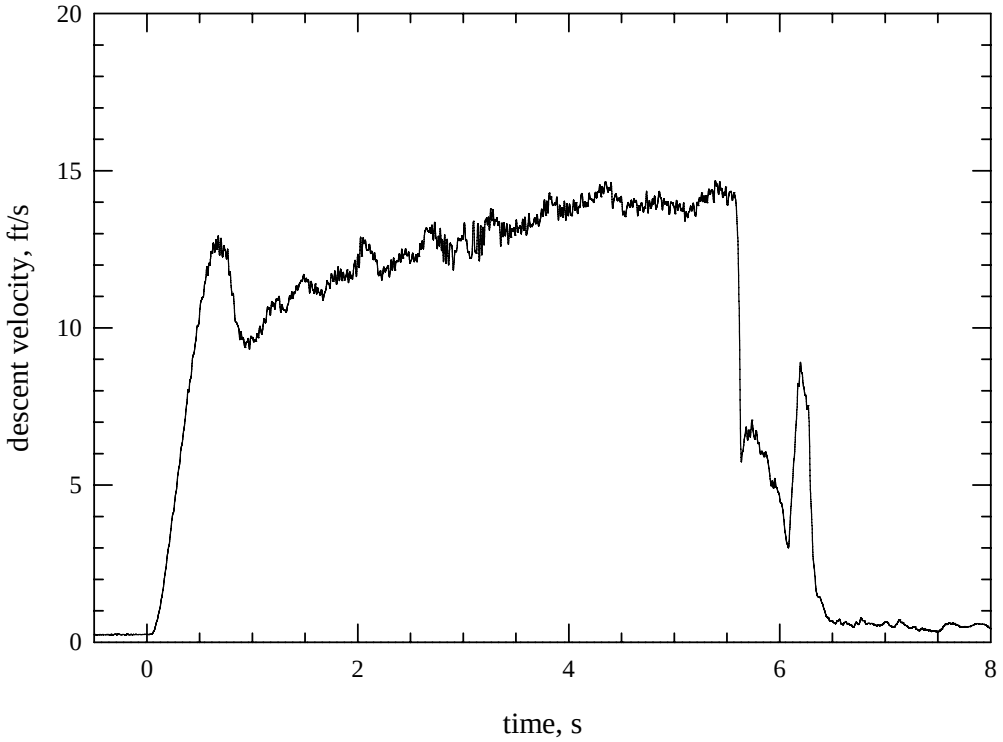


Figure 5. Sample of descent velocity for a payload weight of 11.9 lbs and a 7-ft. diameter canopy.

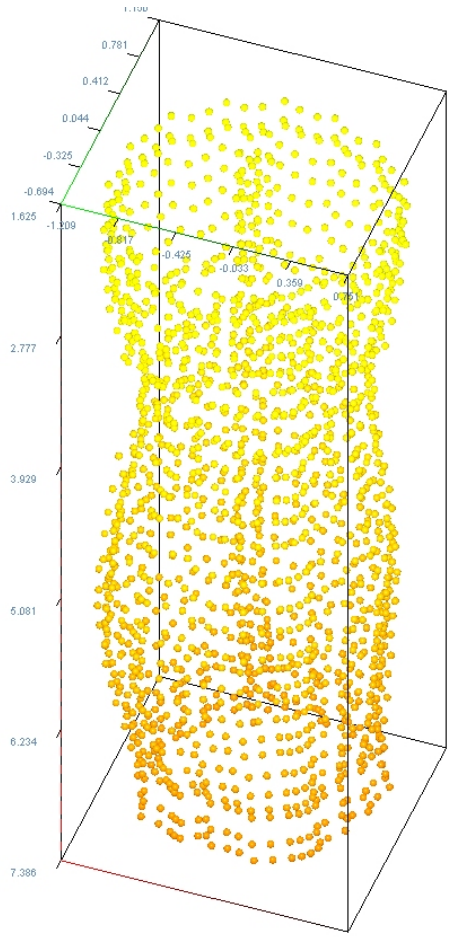


Figure 6. Sample of canopy skirt diameter for a payload weight of 11.9 lbs and a 7-ft. diameter canopy.