JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 36, No. 4, July–August 1999

Atmospheric Reentry Demonstrator Balloon Flight Test

Maurizio De Giorgis,* Giorgio Borriello,† Andrea Allasio,‡ and Raffaele Vavala§
Alenia, 10146 Turin, Italy
Thierry Leveugle¶
Aerospatiale, 33165 Saint Medard en Jalle CEDEX, France
and
Orazio Cosentino**
Italian Space Agency, 00198 Rome, Italy

The Atmospheric Reentry Demonstrator, a 2800-kg Apollo-shaped experimental capsule, managed by Aerospatiale Space and Defence as a prime contractor, is part of the technological activities of the European Space Agency in the framework of the Manned Space Transportation Program. The descent and recovery subsystem, which is under Alenia Aerospazio responsibility, is the subsystem devoted to decelerating and stabilizing the capsule at the end of the reentry phase for a proper splash-down, to ensure the capsule flotation and localization help for the recovery in the Pacific Ocean. A major milestone in the development of the descent and recovery subsystem was reached successfully on 14 July 1996 with a full-scale qualification test performed at the Italian Space Agency Base of Trapani, Sicily. The balloon flight test mission aroused great interest inasmuch as it was the first time that such an experiment had been performed in Europe, especially with respect to the complexity of the test article and balloon mission profile.

Introduction

THE scope of the balloon flight test was to qualify the descent and recovery subsystem (DRS) to be used on the Atmospheric Reentry Demonstrator capsule (ARD).

This test consisted of lifting a qualification model of the ARD capsule (same shape and mass properties) under a 104,500-m^3 helium-filled stratospheric balloon, up to an altitude that allows the capsule to reach flight representative conditions after it has been released from the balloon gondola.

DRS qualification imposed a drop altitude range between 23 and 24 km, which led to operation in a marginal range for an uncontrolled vehicle, as experimented in a previous, unsuccessful test.

Against these constraints, dedicated tools, rules and mission management requirements were specifically developed to account for balloon performance variation, meteorological conditions, and potential wind instability during ascent and altitude flight, and worst cases were identified and simulated.

The reason for a test drop from a stratospheric balloon of a DRS flight standard, installed on a mock-up capsule, was to reproduce as closely as possible the capsule reentry conditions, i.e., dynamic pressure and Mach number, for a complete and representative qualification test data achievement. Because of the representative conditions (flight simulation and test article similarity with the capsule), this test permitted data on the capsule dynamic behavior to be obtained as a secondary objective.

The DRS qualification test was performed at the Italian Space Agency (ASI), Stratospheric Balloon Launch Base of Trapani Milo, located on the west point of the island of Sicily (geographic coordinates: 38°01′N, 12°35′E). Because of the favorable geographical position of Trapani, stratospheric balloon launch within an appropriate window allows reaching a westerly position in the sea, off shore of Marettimo Island, in a safe area for the capsule drop.

A first balloon launch for the DRS qualification was performed on 20 August 1995, at this base, with a negative result. In fact, after a normal ascent phase, and beginning of coasting at nominal flotation altitude, the balloon presented an anomalous behavior, which led it to descend and take an easterly direction, instead of continuing westward toward the sea. It flew over Sicily, slowly losing altitude, all day long, and the mission was terminated in the late afternoon, off Sicily's east coast in the Ionian Sea.

Because of the great interest in this test, another balloon flight test was planned, after an in-depth investigation on the possible causes of the first balloon behavior. The investigation touched on various subjects of the event, reconstructing the flight path with the recorded data, simulating thermal-dynamic effects with dedicated numerical tools, and analyzing the balloon design and all of the mission management against the stringent DRS qualification constraints. As a conclusion of the investigation it appeared that a self-lifting behavior of the balloon venting ducts was the most probable hypothesis to explain the flight anomalies and failure.

Nevertheless, the investigation confirmed that this kind of mission was extremely sensitive to a great number of parameters, due to the altitude and atmospheric uncertainty, i.e., the largest daily range variation of the altitude of the wind direction inversion, that leads to operation in marginal conditions. For this reason, the second balloon flight test was implemented with stringent requirements at design and operating procedure levels, to control the Balloon mission as much as possible.

An event-tree analysis was initially conducted to identify the mission criticality associated to hardware design requirements and environmental conditions. The outcome of this analysis identified several aspects, where single failure, procedures, and human error, could have developed into unplanned events leading to hazards to people and/or jeopardization of the test mission. To counteract these critical areas, specific analyses, simulation, and test procedure reviews were conducted within the project team to define feasible improvements in the design and operations.

Areas of the avionics design have been modified to overcome loss of mission and safety hazards induced by unwanted commands to pyrotechnical actuators in the balloon flight chain and test article.

Test Phases Description

The balloon flight test was composed of the DRS qualification drop itself and all of the phases aimed at the achievement of the suitable start conditions. For this reason, the overall phases represent a complex mission scenario to be defined and controlled for the final DRS qualification drop.

Received 16 May 1997; revision received 12 November 1998; accepted for publication 21 November 1998.

*System Engineer, Advanced Systems Unit, Corso Marche 41.
†Program Manager, Future Launchers, Corso Marche 41.
‡System Engineer, Avionics Systems Unit, Corso Marche 41.
§Engineer, Thermo-Mechanical Systems Unit, Corso Marche 41.
¶ARD Program Manager, Space Business Unit, Space and Defence.
**Base Responsible, Stratospheric Balloon Trapani Base.

The global scenario has been divided into the following eight phases. A brief description of each phase is given for a better mission understanding.

Prelaunch

This phase includes all of the on-ground activities for mechanical and electrical interfaces connections between flight chain–gondola, gondola–test article, pyro connections, final telemetry check outs, balloon extraction from container and preparation, capsule power activation, and rotation of the safe and arm in the arm position.

Balloon Inflation

This phase is dedicated to the balloon inflation with the required helium gas mass for the mission altitude. The gas mass parameters (pressure, temperature) needed for the mission altitude and for the lifting force are predetermined on the base of the test article and flight chain masses.

During this phase no other activities were allowed at the start of the inflation, neither on the capsule nor on the flight chain.

Launch

This phase covers the launch operations from the end of balloon inflation to the balloon (attached to the flight chain, gondola and test article) separation from the support crane.

Ascent

This phase covers the balloon ascent, with attached load, up to the foreseen mission altitude and stabilization at this altitude.

Steady Flotation and Drop Point Achievement

In this phase, the balloon is free floating, carried away by the stratospheric wind toward the foreseen drop point. In the drop point proximity, at about 30 min before the separation, the countdown begins for the capsule separation, with the start of the relevant drop test procedures.

Capsule Drop and Free Fall

The test article free fall phase allows achieving the desired conditions of dynamic pressure and Mach number as predetermined for the qualification.

DRS Operative Sequence

During this phase, all of the DRS subassemblies are operated, driven by the onboard electronic timing commands (sequence command generator), simulating the capsule mission. In the meantime all of the monitors were transmitted to ground and/or recorded in the capsule recorders for the qualification data processing.

Sea Recovery

This phase covers all of the recovery operations for searching, approaching, hooking, and hoisting the capsule by the recovery ship.

Test Article Description

The balloon flight model, which represents the test article to be lifted by the stratospheric balloon, was composed of the DRS qualification model and the mock-up capsule. The DRS qualification model was fully representative of the DRS flight model now installed on the ARD capsule.

Briefly, the DRS was composed of the canister assembly with the parachutes chain, the floating bags system, and the localization system; the flight model mortar and pilot parachute, installed on the apex cover mock-up; sets of retention and release pyronuts and pyroitems for the apex cover separation; and a mortar safe and arm device and through bulkhead initiators flight standard.

The mock-up capsule was a metallic structure, covered by fiberglass shells, representing in shape, mass, and dimensions the ARD capsule, containing the DRS qualification model and the equipment used for the mission actuation, monitoring, and data acquisition. The mock-up capsule also was equipped with a stabilization device, consisting of a deployable suspended mass below the capsule, which ensured the correct capsule attitude during the free fall phase. This mass was released from the capsule just before the DRS parachutes sequence initiation.

An automatic sequence command generator, specifically developed by Alenia for this test, commanded all of the sequence, after capsule separation from the balloon. In addition, the following instrumentation and units were installed on the capsule to accomplish and monitor the mission: 1) sequence command generator; 2) data recorder; 3) vibration, inclinometers, and separation sensors; 4) accelerometers and g-switches; 5) pressure and temperature sensors; 6) triaxial gyrometers; 7) radio transmitter and antenna; 8) telecommand unit; 9) heaters; and 10) batteries and harness set.

Balloon and Flight Chain Description

The balloon was a polyethylene stratospheric natural shape, zero-pressure-type balloon of 104,500 m^3, manufactured by Raven specifically for the ARD DRS balloon flight mission, according to a dedicated specification. The design was implemented with the recommendations of the investigation and was manufactured with attached venting ducts.

The flight chain is the set of structural and electrical I/Fs and equipment that are not parts of the test article, and that are used to link the balloon to the test article itself and to manage the mission phases 3, 4, and 5, allowing the test article separation.

The gondola is the major structural part of the flight chain charged with supporting the avionics equipment, as well as the ballast and the ballast release device. The gondola was equipped with the following units: 1) delivery ballast equipment; 2) telemetry unit, decoder, and antenna; 3) Vaisala sounding equipment; 4) Omega navigator system equipment and antenna; 5) global positioning system transponder; 6) separation systems; 7) radar transponder; and 8) battery set.

Test Requirements and Constraints

The balloon flight test was a functional test, performed on a full-scale model of the ARD capsule reproducing as closely as possible flight dynamic conditions encountered in the flight mission, compatibly with the constraints imposed by a free drop from the stratospheric balloon starting from 0-m/s velocity, and by the structural stiffness of the mock-up that makes exceeding high subsonic regimes unfeasible, and without attitude control.

The minimum values to be reproduced and the test differences from the flight due to the constraints mentioned earlier are minimum dynamic pressure $Q \geq 5000$ Pa (target was 5500 Pa), maximum Mach number $M \leq 0.8$, angle of attack 0-deg initial conditions, pitch rate $\leq$1-deg/s initial conditions, and maximum angle of incidence $\leq$40 deg at mortar firing.

The main differences from the flight unit were as follows. There was no active attitude control (stabilization mass implemented due to the calculated instability during the free fall phase). The mock-up capsule center of gravity was on the symmetry axis to facilitate the stability. Thermal conditions differed from the reentry ARD. (Heaters have been implemented on the pyronuts to have more representative thermal conditions on this critical part). No mechanical loads at the qualification level (static, quasistatic, vibration, shocks) were applied to the DRS during the test. During the sea recovery it was not expected to validate the "sea state 4" after splashdown, but at a much lower level.

To achieve the flight representative qualification values for the DRS, the balloon mission limits have been calculated to be drop altitude range within 23 and 24 km, with stable initial conditions, i.e., 0-deg angle of attack and pitch rate $\leq$1 deg/s. Altitude lower than 23 km would have lead to a degraded DRS qualification, due to the values lower than the expected ones. The 24-km altitude was considered as a limit threshold not to be exceeded because of the risk of going over the Mach number limit (nearly Mach 1), with possible structure and component hazardous conditions.

According to the statistical wind measurements, and to ASI actual sounding data over several years in the Trapani area, the most favorable launch window was estimated to be July. Great efforts were made to maintain the schedule compatible with this window.

Test Execution and Control

To account for balloon performance variation, meteorological conditions, and potential wind instability during ascent and altitude flight, the worst cases were identified and simulated. Meteorological sounding balloons were launched starting several days before the envisaged launch date, for wind profile control. Alenia appositely developed a mathematical thermodynamic model with the aim of investigating the acceptable meteorological conditions envelope and to support the mission control (predicting the balloon trajectory in real time). This model, developed for the study of the anomalous behavior of the first balloon flight, has been upgraded for the balloon mission prediction.

The model assumes the balloon as a spherical shape and takes into account both the thermal and dynamic aspects. In particular, the elements considered are 1) solar flux (calculated taking into account the time, position, and altitude of the balloon), 2) terrestrial albedo, 3) convection heat exchange (both the forced and natural convection between the air and balloon skin, and natural convection between the helium and balloon skin), 4) infrared radiant heat exchange with the Earth and with the sky (taking into account the balloon characteristics and instantaneous dimension), 5) ascent force (depending on the helium and air condition and on the helium mass), 6) weight (the change in mass of ballast and helium mass), 7) drag force (calculated assuming a spherical shape and considering the velocity vector resulting from ascent velocity and relative air velocity), and 8) inertial force. The model, written in FORTRAN and running on a portable personal computer, was structured with a high degree of flexibility in inputting the data, with the aim of reducing the time necessary to perform the simulations.

The model was validated using the first flight trajectory data; Fig. 1 shows the first mission flight data against the code mission simulation.

A main input file contains the balloon and payload description and the name of the other input and output files. The file used for inputting atmospheric and wind conditions vs the altitude was produced in real time by a decoder program (also developed by Alenia) directly linked with the meteorological data acquisition system (Vaisala sound).

The output of the model is in table form to permit the use of a commercial tool (electronic sheet) for the postprocessing of the data. Furthermore, an output file describing atmospheric conditions in a format agreed to with Aerospatiale Space and Defence has been produced; this file is the input of the free fall phase simulation code developed by Aerospatiale Space and Defence to ensure the use of the same input data for the different analyses performed by Alenia and Aerospatiale.

The output of the Alenia model comprises altitude and trajectory data, ascent speed, and thermal conditions. Analyses were performed with the aim of defining the key mission parameters, using Trapani site historical data. Simulations with the data measured by the sounding vehicles, launched during the days before the mission, were also performed, as support to the mission control.

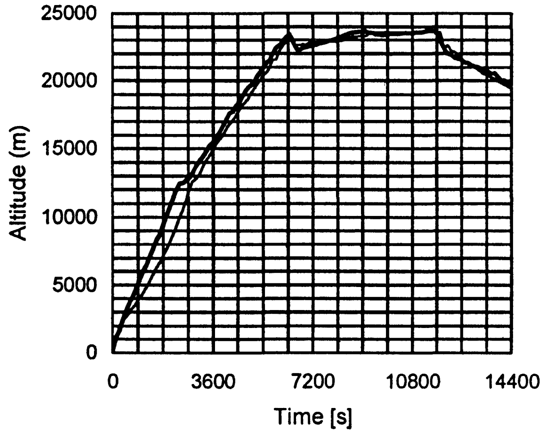

Fig. 1 Model validation with first balloon altitude profile: ——, simulation, and ——, BFT 1.

The simulation performed with the last meteorological measured conditions was used as a reference line during the mission, comparing the measured behavior of the balloon, with the intent to speed up recognition of eventual problems. This comparison was performed using a tool developed by Alenia for the mission, able to acquire the mission data in real time and to produce different charts representing horizontal and vertical trajectories, vertical speed, wind conditions (speed and direction), altitude, and radio signal visibility.

To evaluate the balloon behavior in nonnominal conditions and to predict the consequent mission profile, several cases were simulated with this tool before the launch, also considering the necessity to individuate the extreme acceptable conditions for the balloon launch.

ASI has furnished atmospheric data for July 1990, 1991, and 1992. These available data were sampled and sorted, selecting the atmospheric conditions leading to different degraded missions (with respect to the nominal one, corresponding to the average July atmospheric conditions). To permit the comparison between different cases, all of the analyses were performed without discharging ballast. The test configuration adopted for the analyses was representative of the flight, and took into account the known masses distribution.

The considered cases were as follows: nominal (average July condition), longest mission duration, shortest mission duration, maximum trajectory deviation toward north, and maximum trajectory deviation toward south.

In addition, eight cases have been considered, using the Vaisala sounding data of 4 July, to evaluate the possibility of the worst conditions: 1) reference case, for comparison (considered as nominal with the condition of 4 July); 2) nominal case with ballast discharge; 3) maximum balloon inflation (maximum positive error during helium charge: nominal ascent force +6%); 4) minimum balloon inflation without ballast discharge (maximum negative error during helium charge: nominal ascent force −6%); 5) minimum balloon inflation with ballast discharge (maximum negative error during helium charge: nominal ascent force −6%); 6) gas leakage, with ballast discharge to recover the failure; 7) infrared (IR) leakage: 20°C decrease in the IR heat sink temperature for 4 h during the floatation phase, without ballast discharge; and 8) IR leakage: 20°C decrease in the IR heat sink temperature for 4 h during the flotation phase, with ballast discharge.

The analysis results show that it was possible to perform the balloon flight test with a variety of atmospheric wind conditions. To effect the test with the best probability of success some considerations were taken into account: 1) The shorter the mission duration, the lower was the possibility of a balloon failure due to a change in atmospheric wind conditions. 2) It was preferable to have the shortest part of the trajectory above the ground (lower risks of flying above high-density population zone). 3) The only possible action to recover a balloon failure was to discharge the ballast. 4) With the objective of maintaining the maximum amount of ballast, an ascent rate lower than the nominal was considered acceptable (it was suggested to discharge a small amount of the ballast only if strictly necessary when crossing the tropopause). 5) In case of flotation at an altitude stable but lower than desired, it was suggested to wait for the balloon to approach the drop zone and then discharge the ballast necessary to obtain the correct altitude (taking into account the speed of the balloon to permit a stabilization at the new altitude). 6) A delay of the launch of the balloon should be considered if after the wind direction inversion (from east to west, at an altitude higher than 18–19 km) the wind speed does not increase (condition indicating wind instability).

The date envisaged was around 10 July 1996. The launch campaign was postponed twice due to unfavorable weather conditions revealed by soundings and mission simulation. The test campaign started on 13 July 1996 with the meteorological briefing in the evening, after the Test Readiness Review Board had declared the test article ready for the mission. The favorable meteorological conditions allowed authorization of the start of launch preparation. All of the prelaunch operations occurred nominally according to the prepared procedures.

Meteorological conditions were under control with launch of two soundings, and the mission simulation was updated with the new

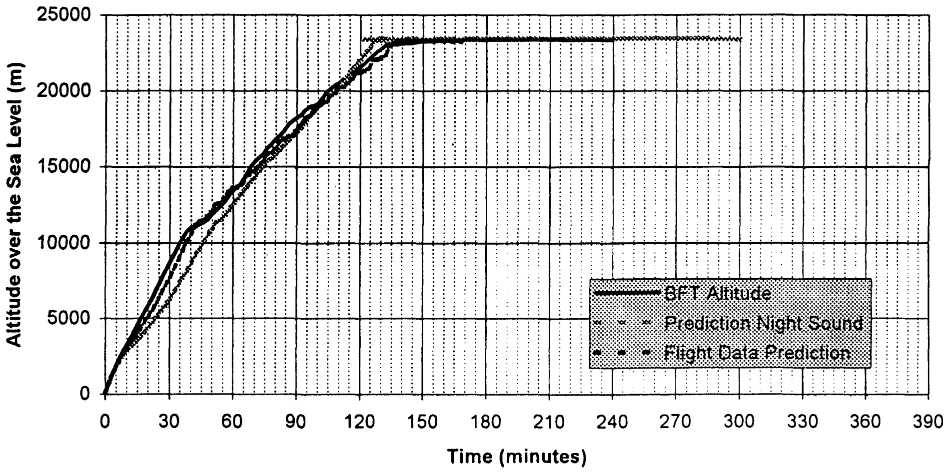

Fig. 2 Balloon flight mission altitude profile.

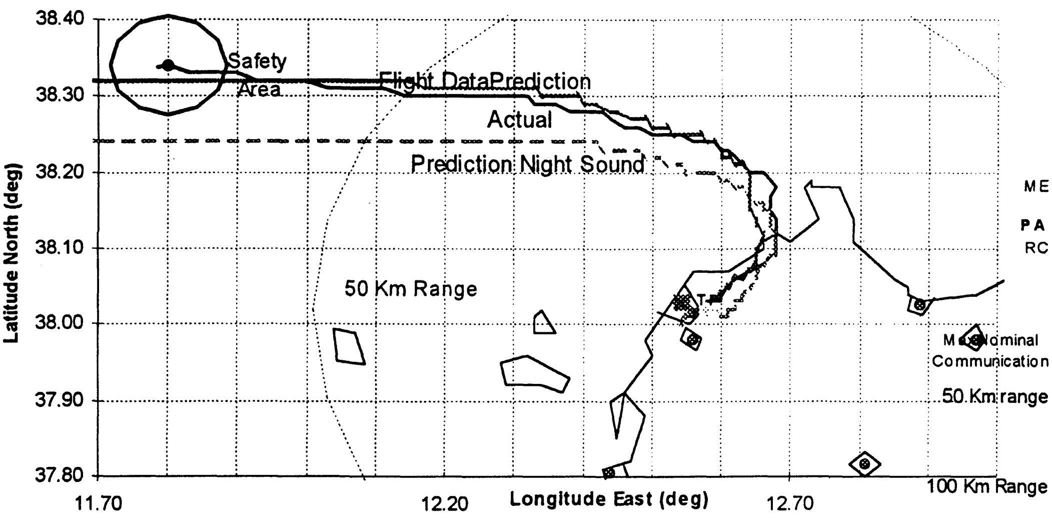

Fig. 3 Balloon flight mission on ground trajectory.

actual data acquired, to have a mission prediction as close as possible to the last meteorological data.

On the morning of 14 July 1996, as the on-ground wind condition was favorable, authorization for balloon unpacking was given, and inflation started at 6:30 a.m. At 8:02 the balloon launch occurred. Ascent was within the expected profile, comparable with mission prediction, and within the safe area limits. The ascent rate was slightly higher than the simulation, and the sea was reached in less than 1-h flight. At 10:30 the ceiling altitude was reached, but at the lower threshold; for this reason, the decision was taken to release 130 kg of ballast. At 10:50, the flight altitude being stabilized and all of the drop conditions reached, the mock-up capsule was released, and the descent and recovery test qualification performed.

The SARSAT beacon signal was detected by the Flight Measurement and Control Centre of the Centre National d'Etudes Spatiales of Toulouse, after capsule splashdown and the identification data communicated to the recovery ship, so that at 12:35 p.m. on 14 July 1996 the capsule was localized and recovered.

The gondola, equipped with its own floatation system, was recovered as well, although it was not possible to recover the balloon envelope, which had already sunk prior to the arrival of the ship.

Actual balloon flight mission data are shown in Figs. 2 and 3. Figure 2 shows the balloon altitude profile and Fig. 3 shows the actual mission on-ground trajectory, both compared with the prediction based on Vaisala data of the last sounding launched during the night of 13 July 1996, and with the flight mission prediction, calculated with the Alenia mathematical model.

Conclusions

The balloon flight mission was perfectly within the required limits, i.e., drop occurred at 23,200 m; this ensured, according to the flight predictions, the desired parameters to achieve the DRS qualification values. The DRS qualification test was performed in accordance with the foreseen sequence, the capsule was recovered, and telemetry data and video recording were collected as planned. Postflight inspection revealed no damages to the recovered test article.

Review of the data recorded in flight showed compliance with the expected predictions, with the exception of minor anomalies not affecting the qualification and were surmounted with suitable design recovery changes.

The balloon flight test, which was only the test means to reach the DRS qualification, was actually a complex flight mission. There is, therefore, reason for satisfaction in that this is the first time in Europe that such a mission with this payload mass has been accomplished by a stratospheric balloon.

The harmonized combination of the whole method and the cooperation between the Aerospatiale, ASI, and Alenia integrated team resulted in a successful mission.

I. E. Vas
Associate Editor