Aerodynamic Decelerator System Design

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the Process: Requirements and Design

- Requirements
  - Key driving requirements are flowed down from vehicle.
    - Derived requirements mature with design and integration concepts.
      - Better definition of derived requirements once an architecture is chosen.
    - Interdependencies make interfaces difficult to define initially.
  - Identification of risks.
    - Generic to the basic requirements.
    - Specific to the architecture chosen.
    - Outside of our control (changes in requirements and/or interfaces).
- Design and Analysis
  - Analysis tools are heritage with limited capability.
    - No tool today to predict if a canopy will inflate or remain inflated.
    - Industry confidence is grounded in past experience.
  - Trajectory analysis is critical to designing the ADS.
  - The design and manufacture process for parachutes can take 6-8 months or longer (material lead times alone can be 3-4 months).

the Process: Testing

- Testing
  - Ground testing (when possible) is favorable early (prior to PDR) in order to have a chance to influence the ADS design.
    - Materials, seam and joint, retention of parachutes, routing of risers and harnesses, extraction or deployment of ADS (including mortars).
  - Flight testing in particular is very labor, schedule, & cost intensive.
    - Required to validate the performance models .
    - Test articles, buildup facility, availability of test range(s), test operations, data analysis, comparison and updates to models.
  - May require developing new or application specific test techniques.
    - Additional risks will be identified as the design matures and development testing is performed.
      - Need for additional tests will likely be identified.
  - Dealing with test failures.
    - Often resulting from the test setup and not the test hardware itself.
    - Unpredictable but potentially huge risk to schedule and cost.

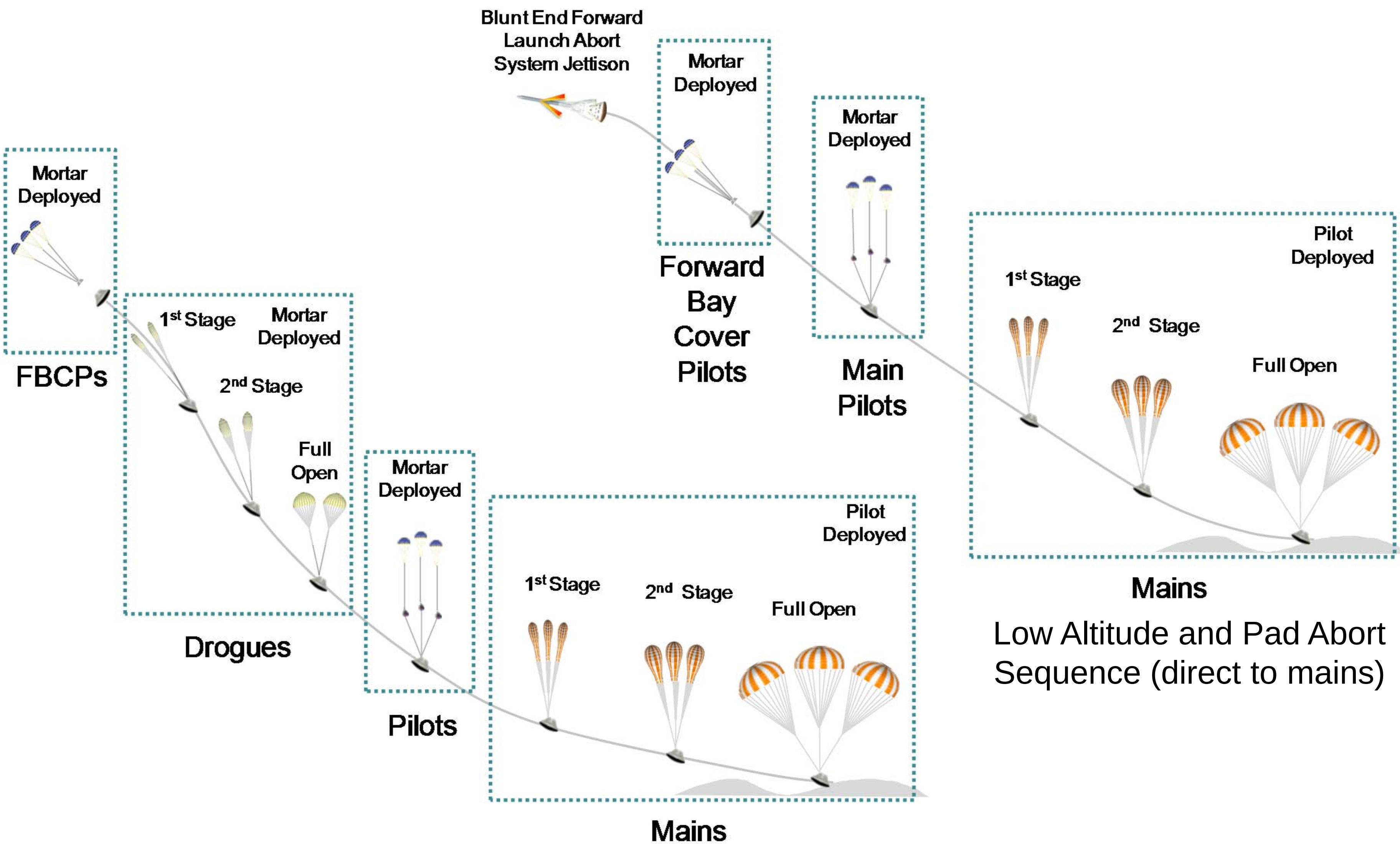
Margin and Verification

- Critical to carry margin in early ADS definition and design
  - The ability of the ADS to react to changes is limited due to length of design/manufacture/test cycle.
    - The design of the vehicle will mature around the ADS as the preliminary design is worked.
  - The engineering development testing will drive down the known risks going into the Preliminary Design Review.
  - Ideally the ADS will 'return' the margin at CDR.
    - Maturation of vehicle design and requirements could reset the ADS.
- Limited experience in human rating large multi-chute ADS
  - Most parachute failures occur either during deployment, as a result of being implemented outside the intended environment, or due to an unidentified coupling of to the recovered mass.
  - Full scale flight testing is the key to Human Rating an ADS.
    - Coupled multi-body simulations have promise for exploring how well the design meets the vehicle level requirements, they will not replace testing the deployment and inflation of the flight hardware.

Capsule Parachute Assembly System (CPAS)

- The Capsule Parachute Assembly System (CPAS) project is a Government Furnished Equipment (GFE) project responsible for: the design, development testing, performance modeling, fabrication, qualification, and delivery of the CEV parachute system to support the pad/ascent abort tests and the first three orbital flight tests (including first human flight)
- CPAS has three basic operational phases
  - Mortar deployed Forward Bay Cover parachutes to assist removal
  - Mortar deployed drogues to decelerate and stabilize the capsule
  - Mains to achieve the steady state landing velocity and hang angle
    - Mains are individually deployed by mortar deployed pilot parachutes following drogue release or possibly (in a low altitude abort) directly to mains (skip drogues)
- First Order Drivers to CPAS design
  - Drogue deploy: dynamic pressure and Mach number
  - Touchdown: landed vehicle weight, landing rate of descent, minimum deploy altitude (from a Pad Abort)
  - Additional critical design drivers:
    - Fault tolerance, system mass (both total and mortar ejected masses), volume/shape for each parachute, environments (temperature, vibration), maximum load into structure

Orion CPAS Concept of Operations



Low Altitude and Pad Abort Sequence (direct to mains)

Nominal Mission and High Altitude Abort Deployment Sequence

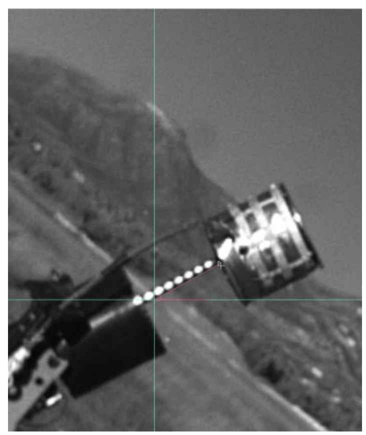
Orion CPAS: Design Status

- The Engineering Development Unit (EDU) design is based upon Apollo heritage, CPAS Gen-1 design, and the development test program begun in 2007
  - 20 drop tests performed to date, evaluating performance of single and clusters of parachutes for various environment and design iterations
  - Numerous ground tests including vibe, off angle extraction, long term bag growth, materials contamination, scaled model wind tunnel, and mortar firings
  - Successfully deployed Gen-1 design on Pad Abort-1 (May 2010)
  - Preliminary Design Review for the EDU design (Nov 2010)
  - Two test failures, both due to test technique failure (not CPAS hardware)
- Currently, NASA and LM are jointly maturing the landing system design for integration into Entry Flight Test-1 (EFT-1) and subsequent crewed missions
  - Chutes are Government Furnished Equipment, Lockheed provides mortars
  - CPAS has completed 4 of 18 EDU drop tests planned to demonstrate repeatable system performance, anchor performance modeling, and buy down risk prior to EFT-1 and CDR
- CPAS Critical Design Review (CDR) currently scheduled for 2015
  - Formal qualification testing aligned with spaceflight Orion 2

12/11 Two Main EDU Test
(pilots deploying mains)

7/10 Gen-1 Test
Main Line Length Ratio

4/11 Off Angle Main
Extraction Test



7/11 Pneumatic Mortar
Test of EDU Drogue

2/12 first Engineering
Development Unit (EDU)
Parachute Test Vehicle (PTV)
airdrop test
(C-17 extraction and landing)

JSC Unique Skills in Aerodynamic Decelerators

- Decelerator Systems Simulation (DSS)
  - A multi-body 6-dof simulation based on the analysis code that was used to design the SRB recovery system.
  - Modified extensively during X-38, Pad Abort Demonstrator, and Orion programs.
  - Uses: design flight tests (predicting not only the parachute loads but the dynamics of the coupled system), flight test data reduction, Monte Carlo analysis to aid in designing the parachutes and spacecraft attach structure, trade studies for design options, response to atmospheric perturbations such as gusts (and more).
- Core team with decades experience simulating, designing, integrating, and testing large parachute systems.
  - Analysis and design experience with both ballistic and steerable ram air parachutes (including modeling databases and guidance algorithms).
  - Testing encompassing: design of the test, design and manufacture of the test articles, instrumentation, integration and procedures, execution of the test, data reduction and analysis.
  - Systems integration: from negotiating interface control documents, to defining achievable requirements, to working with the spacecraft designers to solve integrated spacecraft level problems.

Things to Look For

- Complexity of design and fault tolerance (including the retention and deployment concepts)
  - Never has it been truer than with ADS that simple is better.
- Technical risk (readiness level of technology)
  - Tightly coupled to experience, it's not that low TRL is unachievable, just not achievable quickly and/or for little money/schedule.
- Contractor experience (parachute vendor specifically)
  - Related to technical risk, is the design/architecture within the contractors experience or is it driving the development of new hardware and/or analysis capability?
- Maturity of vehicle design (wrt/requirements changes)
  - What about the vehicle design has the potential to both invalidate the ADS design and is likely to change?

Observations on Human Rating

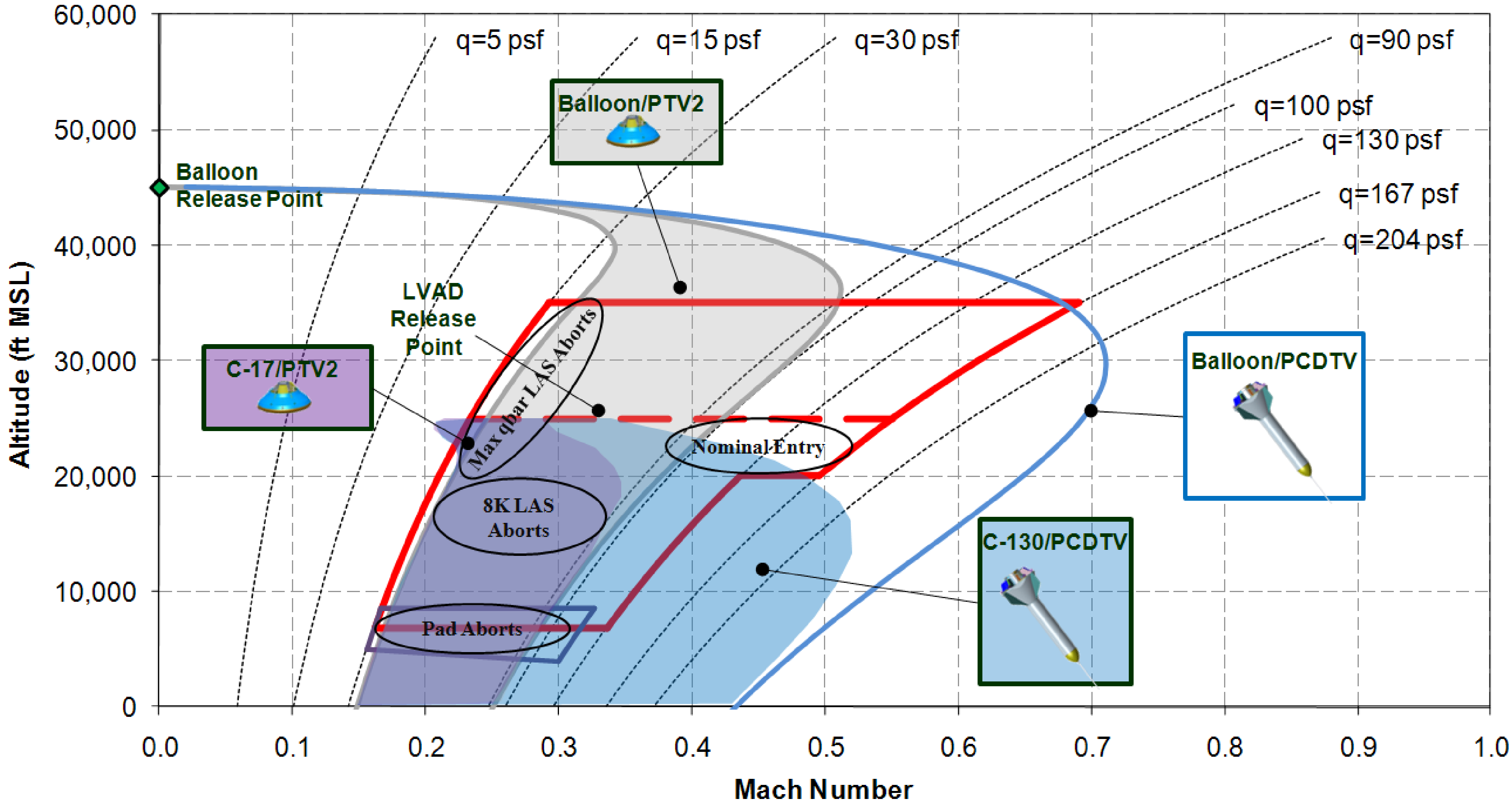
- Verification and Validation by testing alone is prohibitively expensive
  - Traceability of requirements to parent specifications is critical to system certification
- Every design is different, there is no document that dictates what tests or how many to run
  - Early risk assessment can guide not only where to focus the development of models and testing, but also architectural decisions at and above the parachute system
- Careful development of the models, understanding their limitations & assumptions, and how they are dispersed, is mandatory to demonstrate confidence in results
  - Models must be anchored to test data
- Testing cannot be entirely replaced by analysis
  - Some aspects of the system performance and interaction with the spacecraft can only be learned through testing
    - Latent failure modes, coupled dependencies that are not obvious or identified with the models
  - Throughout the CPAS project, we have strived to explore those risks where we could not demonstrate a solid physics model for simulations
- Ultimately human rating relies on human judgment, to optimize the design within the resources available (mass, funding, & schedule)

Conclusion

- Parachutes systems generally fail for 1of 3 reasons:
  - Failed to deploy properly
  - Deployed outside the intended envelope, or
  - A fundamental error in predicting the physics
- Parachute modeling is almost exclusively empirical
  - Parachutes are bounded random events, the skill is in determining where to draw the bounds
    - Some predictions, like loads, torque, and terminal rate of descent, are physics based models anchored to test reconstructions
    - Other aspects, like packaging, deployment, and inflation, are not modeled with enough confidence to verify with analysis alone
- The CPAS is an extremely lightweight, delicate collection of pieces that absolutely must act together simultaneously or fail with disastrous results
  - Alone among the robust pieces of equipment on the spacecraft, the parachute system must assemble itself in midair at a wide variety of possible velocities and orientations
  - Successful designs are simple and ‘given the opportunity to fail’ with repeated demands during development testing
- At the system level; test early, test often!

Back-up

CPAS Deploy and Flight Test Capability Envelopes



Flight Test Articles and Target Carrier Aircraft

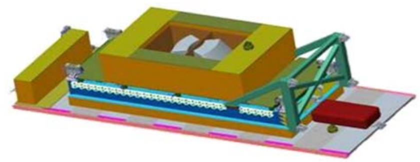
<u>SDTV</u>: Low velocity deployment of ~500 lb test article to test a single Pilot parachute.

UH-1

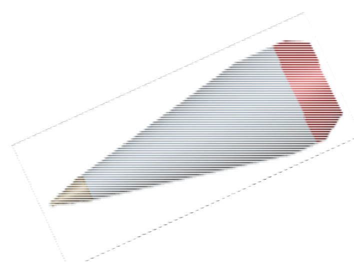
<u>MDTV</u>: Med velocity deployment of single Drogue and/or single Main with ~7-10 Klb suspended weight.

CH-47 or C-130

<u>Weight Tub/Platform</u>: Med velocity deployment up to the full Orion vehicle weight. Test parachute configuration may include a Cluster of Mains, Drogues, and/or Pilots.

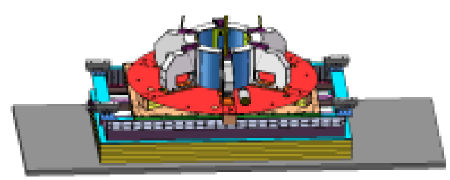


<u>Parachute Compartment on a MDTV</u>: Designed to provide full system and/or main cluster tests from a C-130 without pallet effects. Provides a stable single point attach.



or

<u>Parachute Compartment on weight tub/platform</u>: Designed to provide full system and/or main cluster tests from a C-130. Includes pallet effects. Does not provide a stable single point attach.



C-130

Medium Drop Test Vehicle (MDTV) capability

MDTV on Carriage Monorail System (CMS) being placed on K-loader

LVAD pallet deployment

mid-air separation MDTV from CMS

Drogue deploy

Main static line deployed by drogue

2nd stage main (15’ stabilization parachutes 2 ea)

CMS Recovered using GFE G-11 cluster

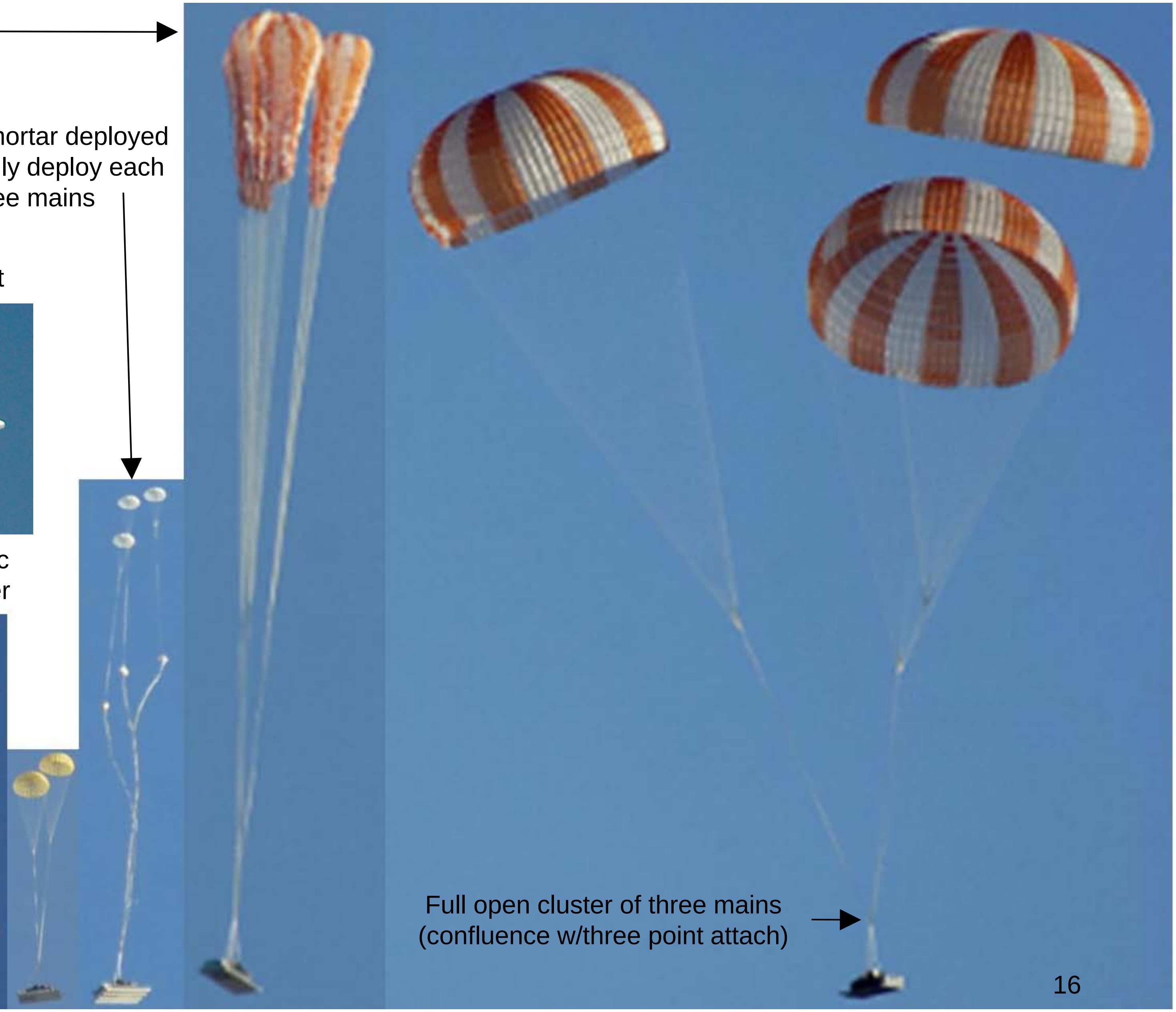
Low Velocity Air Drop Test of the Gen-1 CPAS design

Three mains inflated
in first stage

Independently mortar deployed
pilots, individually deploy each
of the three mains

LVAD pallet deployment

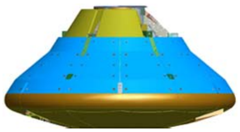
Extraction parachute static
line deploys drogue cluster



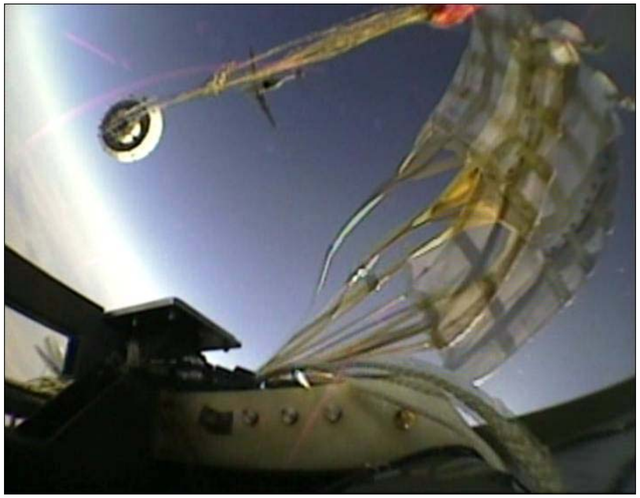
Full open cluster of three mains
(confluence w/three point attach)

Higher Altitude Flight Test Articles

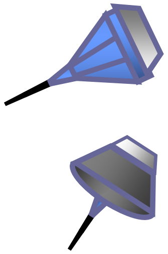
PTV2: Representative parachute compartment for CPAS system deployment sequence, representative wake at low dynamic pressure, representative capsule mass, low drogue dynamic pressure, reduced capsule height, center of gravity and moments of inertia.



C-17



LDTV: Representative Parachute Compartment deployment sequence at high altitude and Mach number. The option to add an inflatable feature to perform high altitude, high mach testing in the presence of a wake.



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