# How to Maintain Flight Testing in Human Spaceflight Programs

## PM Challenge

**February 9-10, 2011**

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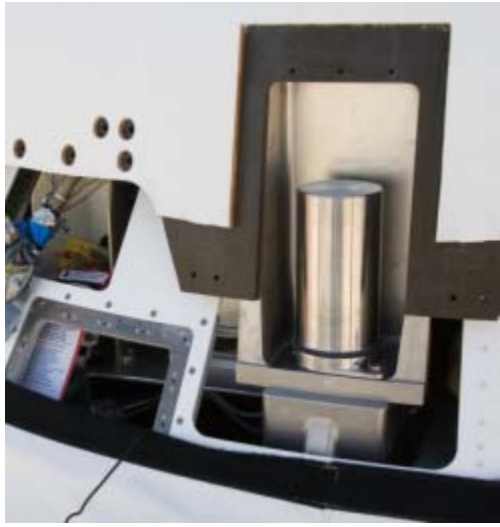
# Outline

- Importance of FT in Human development
- PA-1 Highlights
- Ares I-X Highlights
- Common Themes between PA-1 and I-X
- Challenges to Flight Testing
- Conclusions

# Importance of Flight Testing for Development of Human-Rated Spacecraft

- Failure of ships ferrying humans to/from earth must be virtually non-existent
- Ground testing cannot replicate stacked-environs for integrated systems well
  - If available it is very expensive
  - Usually only simulated effects for many aspects
  - Much easier to do verification testing (corners of the box), Flight test is about validation (all systems work together to perform a selected trajectory/mission)
- Component testing on ground cannot eliminate integrated system "blind-spots"
  - Ex. Shuttle foam debris, Hubble aberration
- Development of complex systems is spread across many suppliers, with independent functions
  - Operate with different mind-sets, different ways of thinking (**coordinate frames**, analysis techniques, uncertainty factors, testing rigor)
  - Interfacing of these systems always has inherent risks, and potential blind-spots (ICDs and IRDs wont catch everything)
- Integrated testing of full-scale systems in the right environment is the most-valuable kind of design validation that exists - proof is in the performance



# Development Flight Testing

- "Early" flight tests to assure that Engineering team is on the right track and to anchor analyses and tests
- Often planned at beginning of a Program/Project
- Often deleted due to budget and schedule challenges
  - Budget challenges can be driven by "expected full rigor" from your discipline teams
- One of the most significant benefits is the entire production machine (production "throughput", procurement, drawing release, configuration control, analysis and test documentation, quality records, requirements validation, safety processes, waiver and deviation processing, flight readiness review rigor/processes, etc)
  - ALL project systems become functional (some through trial and error) usable infrastructure for the "real project" ahead
- Engages a core team, develops critical team member buy-in, and motivates team members far greater than "paper projects"
  - A dedicated flight test team can become deeply "invested" in the project goal
  - Personal rewards for team far greater than "book management" and "interface and requirements management"
  - Provides a path to leadership development within the team, and a testing ground for management decision-making processes

National Aeronautics and Space Administration

# ORION

## Crew Exploration Vehicle Progress and Success

Jay Estes

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# Pad Abort 1
# Overview and Results

ORION PA1

- Test of a newly developed, full scale Launch abort system for Orion
  - Protect crew by providing escape system from danger at pad, or off-nominal ascent
  - Test data used to correlate models and refine analysis targets
  - Demonstrated the performance of three new types of motors, and innovations to lessen their weight and eliminate need for ballast of a passive system

- Summary Primary Test Objectives
  - Performance of the Launch Abort System (LAS) and LAS/crew module interface
  - Capability of the LAS to propel the module to a safe distance from a launch vehicle
  - Stability and control characteristics of the LAV in the flight environment
  - Performance of the abort, jettison and attitude control motors
  - Demonstrates abort event sequencing from abort initiation through LAS jettison
  - Obtains LAS/crew module interface structural loads and external acoustics data

- Secondary Test Objectives Demonstrate
  - Parachute assembly system event sequencing
  - Performance of the main parachute systems

# Instrumentation Overview

ORION PA1

**Attitude Control Motor**
- Strain Gauges
- Pressure Transducers
- Accelerometers
- Thermal

**Jettison Motor**
- Strain Gauges
- Calorimeters
- Thermal

**Abort Motor**
- Accelerometers
- Calorimeters
- Thermal
- Strain Gauges
- Pressure Transducers

**Crew Module**
- Strain Gauges
- Pressure Transducers
- Accelerometers
- Thermal
- Voltage
- Cameras

**Nose Cone Assembly**
- RDAU
- FADS
- Accelerometers
- Thermal

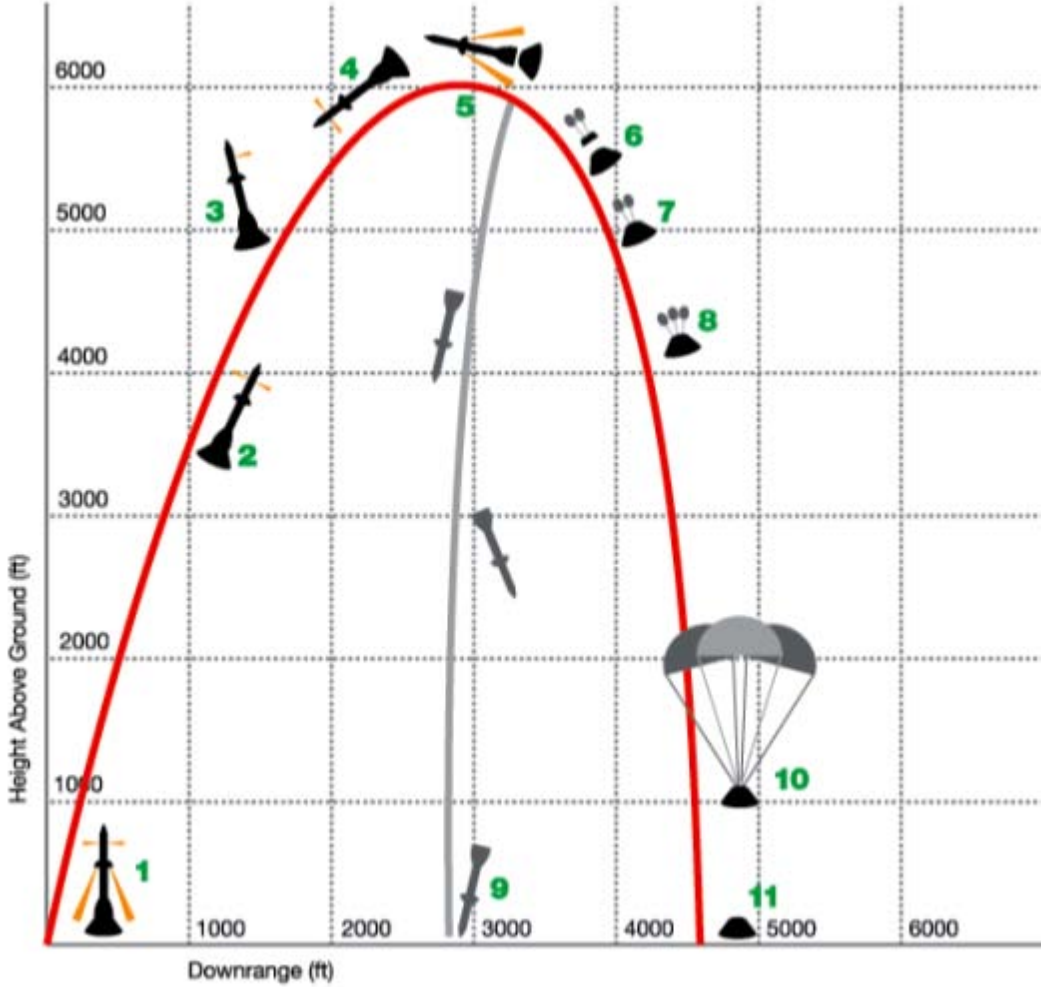
**Canard Interstage**
- RDAU (2)
- Strain Gauges
- Accelerometers
- Thermal
- Pressure Transducers

**Interstage**
- Strain Gauges
- Pressure Transducers

**Adapter Cone Assembly**
- RDAU (2)
- Strain Gauges
- Accelerometers
- Thermal
- Pressure Transducers
- Calorimeters
- Microphones

# Mission Profile

ORION PA1




| | Time | Event |
|---|---|---|
| 1. | 0.00 | AM/ACM ignition |
| 2. | 6.45 | AM burnout |
| 3. | 10.05 | Begin re-orientation |
| 4. | 15.77 | End re-orientation |
| 5. | 21.03 | LAS Jettison |
| 6. | 22.02 | FBC jettison |
| 7. | 24.56 | Drogue mortar fire |
| 8. | 30.56 | Pilot mortar fire |
| 9. | 49.32 | LAS touchdown |
| 10. | 52.54 | Reach 33 ft per sec descent rate |
| 11. | 96.83 | CM touchdown |

# Crew Module on Pad

ORION PA1

# Orion's First Flight Test

# Orion’s First Flight Test

ORION PA1

# Orion's First Flight Test

ORION PA1

| Forward Bay Cover Jettison | Drogue chute (23 ft dia.) each) | Pilot chute deploy of Mains | First stage inflation | Main Chutes (116ft dia. Each) |
|---|---|---|---|---|

# PA1 Results and Findings

ORION PA1

- PA1 was completely successful!
  - Performance on virtually all systems was nearly flawless
  - Findings indicate the system went a little higher, faster, farther and landed softer than expected
  - Complex reorientation maneuver completed as expected
  - LAS re-contact at jettison was non-existent – very clean separation
  - Forward bay cover jettison was shown to have no chance of entanglement with drogue chute deployment
  - LAS jettison plumes had no discernable affect on chutes
  - LAS successfully propelled the vehicle to sufficient altitude to deploy main chutes to full open (more than 70 sec on full-open mains)

# PA1 Results and Findings

ORION PA1

- CM landing achieved 23 ft/s vertical decent rate, all avionics remained on at landing despite not being designed to survive ground impact, no structural damage
- CM suffered only minor cosmetic (paint) external blemishes due to the flight. Reverse flow abort motor nozzles provide excellent separation of abort plumes from CM
- Dual string avionics was never needed, no software or hardware failures or glitches during the flight
  - Identification of the need for “smart release” from drogues on PA1 has lead to the planned incorporation of this logic on the manned vehicle
- Both sides of redundant pyrotechnic chains fired on all components, no malfunctions, all fired on-time as expected.
- Less than 1% of instrumentation (692 sensors) were suspect at launch, virtually no failures in flight

# Examples of Challenges for PA1

ORION PA1

- Commit to Flight Readiness
  - Attempts to redefine and simplify the process for flight tests met with great resistance
  - Endorsements only come with a heavy burden of proof via ground test, analysis, and part certification

- Discipline teams didn't have any solid guidance from management on "how to back off" from human spaceflight rigor
  - Most disciplines applied full-rigor due to no definition of "what to back-off to"

- Org-to-Org consistency on handling of "flight hardware"
  - 2 categories: flight hardware (full-rigor), or "other hardware" (deserves no paper or special care)
  - Need a middle ground where projects can provide sufficient guidelines for HW processing (selectable, based on guidance from project)

# Examples of Challenges for PA1

ORION PA1

- Interfacing multiple centers and organizations can drive multiple layers of “responsible parties”
  - Ex: ground safety at WSMR (NASA + Army + Lockheed)

- Certification testing durations: Abort condition is extreme (170dB acoustic, high energy random vibe, but only lasts 3-4 seconds)
  - Standards for pyrotechnic/ordnance components: +6dB for at least 3mins
  - Sometimes, these levels are unachievable in ground testing, and include significant dwell time to ramp test rig up desired levels
  - Components fail due to excessive exposure (fatigue) in attempts to certify to recognized standards

# Ares I-X
# Overview and Results

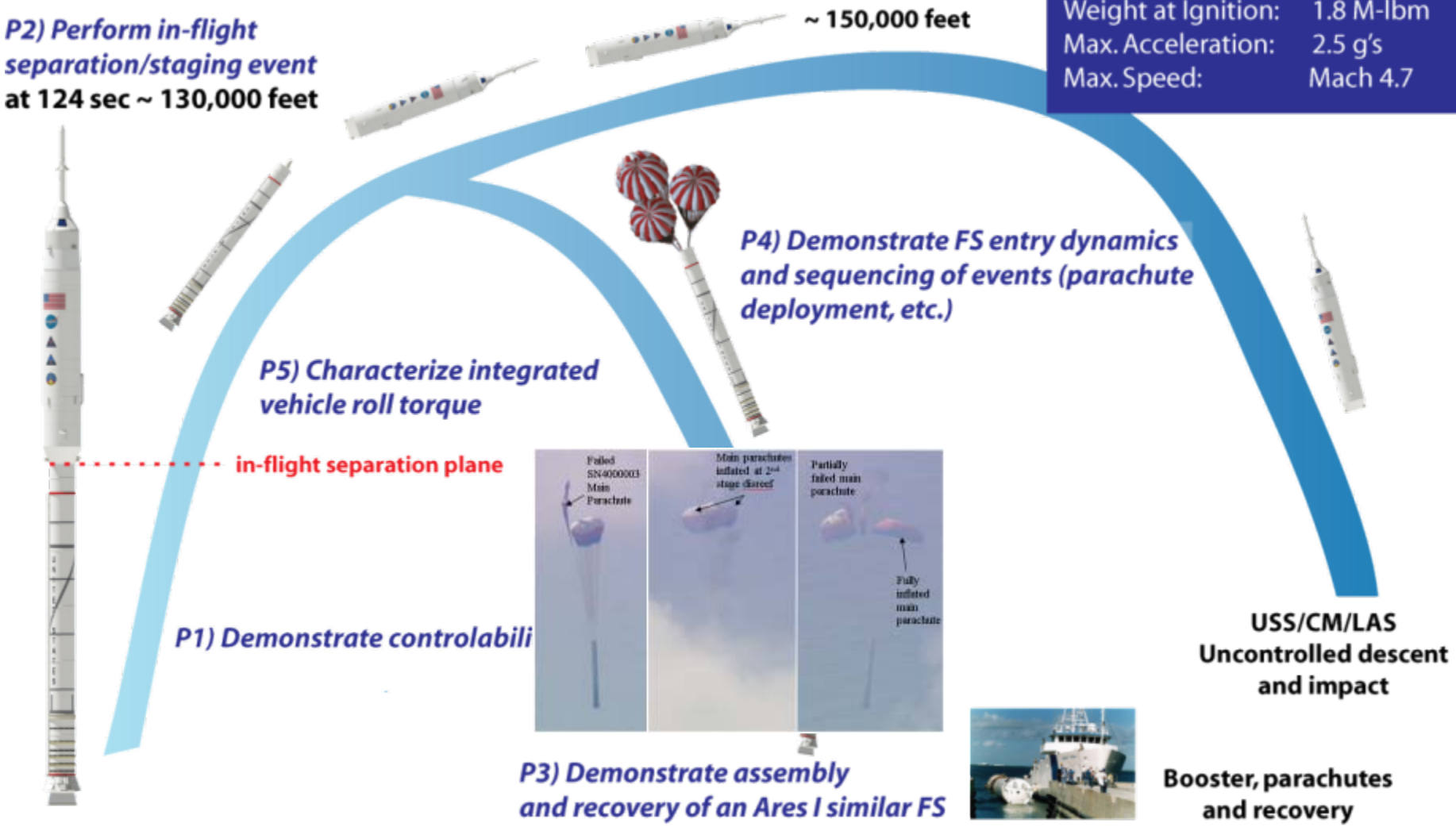
Bob Ess, Mission Manager

# Ares I-X: The Basics

- Mission overview
  - Uncrewed, suborbital development flight test
  - Collected engineering data from launch to first stage recovery
  - Support Ares I critical design review
  - Early data for development – “Engineers Flight test”
- Launch operations
  - Vehicle launched 11:30 a.m. Eastern Time, October 28, 2009, from Launch Complex 39B at Kennedy Space Center (KSC)
- Hardware overview
  - Primary flight hardware consisted of a four-segment solid rocket booster from the Space Shuttle program
  - Rocket controlled by Atlas V rocket avionics
  - Repackaged Peacekeeper Missile 4$^{th}$ Stage propulsion for Roll Control
  - Simulated flight hardware for Upper Stage and Crew Module

# Ares I-X Development Flight Test

| | |
|---|---|
| Vehicle Height: | 327 feet |
| Weight at Ignition: | 1.8 M-lbm |
| Max. Acceleration: | 2.5 g's |
| Max. Speed: | Mach 4.7 |



# Ares I-X Launch Was Successful!

Demonstrated control of a dynamically similar, integrated Ares I/Orion, using Ares I relevant ascent control algorithms

Performed an in-flight separation/staging event between a Ares I-similar First Stage and a representative Upper Stage

Demonstrated assembly and recovery of a new Ares I-like First Stage element at KSC

Demonstrated First Stage separation sequencing, and quantified First Stage atmospheric entry dynamics, parachute performance

Characterized magnitude of integrated vehicle roll torque throughout First Stage flight

# Ares I-X Assembly

# Ares I-X Roll Out

# Ares I-X
# First Stage Recovery

# Examples of I-X Challenges

1. Challenge to “contain” analyses to desired scope
2. Difficult to communicate what “Take more risk” really means
   - So some disciplines used usual human spaceflight rigor
3. CoFR process grew in scope as got closer to flight
   - Additional reviews and “angst” as to what is enough
4. Centers had own standards and own review/approval processes for logistics, pyros, FS

Picture taken by Calvin Turzillo

# Common Themes Between PA-1 and Ares I-X

- Both tests were early in the design cycle:
  - I-X was well before Ares I launch vehicle CDR
  - PA-1 occurred approximately 4 months before Orion PDR
- Both test configurations combined items that directly apply to final config and are “one off”s
  - I-X used LV OML and flight control algorithms etc
  - PA-1 used early adapter cone LAS/CM attachment, boilerplate crew module simulator, and “protoflight” LAS HW
- Both tests had many dedicated sensors
  - Both had debates with technical community on what is required vs desired – there are never enough data systems onboard
- Both were very successful and provided huge amounts of data to engineering team and integrated team (logistics, CM, requirements…)
  - Data is still being applied in model correlation

# Common Themes Between PA-1 and Ares I-X

- Both were attempted to be done in a more efficient, less Human Spaceflight rigor and were met with some impediments:
  - Risk acceptance (which happens at the project manager level) was not easily translated down to engineering level
  - CoFR process encourages questions of "Have we done everything we possibly could do?"
    - Answer should be "No" for early flight tests
    - Institutional managers asked to sign CoFR when they don't necessarily agree with risk acceptance level of Project Manager (torn between programmatic requirements and signing their name that system will work)
  - Default approach was to start with current standards/specs and reduce on a case by case basis
    - Not practical to start with Human spaceflight rigor and whittle down
    - Need to start with clean sheet and build up as justified
    - Again, related to risk acceptance. Project management doesn't see every analysis or test
- Perception of importance and need for success increased dramatically as launch date approached
  - NASA is very image-sensitive and any failure (even a good one) is frowned upon by many in and outside of NASA

# Point and Counterpoint for Early Flight Testing

- Development flight tests do not need to be the final config. Emphasis is on the key areas that are being tested and the end-to-end execution. The rest can be 'simulators' etc
  - COUNTER: "One-off" h/w and s/w distracts the team from the final configuration. Extra Money is spent on a unique flight test configuration much of which does not apply to final config.

- Flight tests can just focus on key critical data items that cannot be obtained in any other manner, don't need final configuration, final design etc
  - COUNTER: Need to get as much data as possible from the flight. Need as many sensors as possible and claim as many test objectives as possible.

# How Far Do You Go?

- When does an unmanned flight test on an isolated range need redundant systems?
  - Is the cost of buying, integrating, testing, and operating two sets of components less than a reflight?
- Is use of full-rigor on systems requirements, and verifications per NASA procedural requirements required for unmanned flight test?
  - No. Ideally any 'relief' on such requirements should be documented up front. But flight tests tend to be very "fast track" and start up quickly and typically don't spend months documenting relief
  - A solution: Anoint a dedicated manager with authority to decide and accept risk using Technical Authority to illuminate risks.
- Ares I-X and PA1 were fully successful as very first full scale flight test, a testament to procedural rigor across systems, discipline and their integration
  - But at what cost? If you can reduce rigor and fly with more risk at half cost – opportunity for cost savings or *additional tests emerge*, with no loss in objectives

# Risk vs Success

- Approval processes and risk acceptance tend to mirror planned processes for Human spaceflight
- Tug of war between timely (i.e. get it soon) flights and risk tolerance
  - Default levels honed from decades of human spaceflight
- What is true Objective of test?
  - Instrumentation
    - “As much as possible” vs “just enough”
  - Flight Demonstration
  - OR: establishment and exercise of project production processes, approvals, and mechanized infrastructure

# Items to Be Addressed for Future Flight Testing

- If we are performing developmental flight tests and failures occur (they will) – why should mishap boards be convened?
  - How is the occurrence of a failure of a new craft, in a heretofore un-experienced environment considered something we "must correct and avoid"? *(Write Mishap Plans carefully to allow failures of "unit under test")*
  - Failure in flight tests should be expected, embraced. Failures always lead to learning
- Inter-discipline protection of margin
  - Discipline teams are trained to protect sufficient margin to "guarantee" performance
  - Stacking of margins from discipline to discipline drives design conditions which become very hard to satisfy with the fully integrated system
  - *Flight test vehicle development should clearly define goals, provide "back-off" from crewed-systems standards including both test levels and durations for acceptance and certification for flight test. (e.g. 3-sigma is not a requirement)*
  - Project Manager (and Chief Engineer) should "own" the integrated margin
    - *CE needs to be cognizant of summed margins across system and manage on an integrated system approach, not system by system*

# Items to Be Addressed for Future Flight Testing

- Lean toward executing on schedule as opposed to executing without failure
  - “Better” is the enemy of “good enough” (and “perfect” is the enemy of “better”!)
  - Highly trained and motivated teams have a difficult time accepting non-optimal solutions *(Project Manager and TA’s need to be on the same page and provide frequent and clear guidance)*
- Testing rigor tends to be driven by standards which are “tailorable” but without guidance, disciplines default to full-rigor, highly conservative approaches
  - Management owes the team ***clear guidance*** on what can be allowed for flight test –vs- what must be done for crewed vehicles

# Other Suggestions for Future Human Flight Test Programs

- Start Early with a configuration sufficient to test a few critical objectives
  - Every test does not need to be Prototype
  - The one-off 'overhead' will still be very useful to training the team for more complex configurations
- Limit Scope of early flight tests
  - Risk-based ("Top Down") approach to deriving objectives as opposed to "bottoms up" approach a la wish list
  - Use project/program risk database to identify key areas OR improve risk databases
- Don't overestimate the relevant experience of your team and downplay or delete need for early flight tests
  - Not just technical team, but CM, logistics, COFR processes
  - Flight h/w will be handled differently than a 'pathfinder' so the whole team will learn from a development flight test
  - Go find a few people with development flight test experience
- Consider "spiral vehicle development" starting with simple, lo-fidelity test articles, and increasing rigor, capability, objectives, and test conditions through a few incrementally directed flight tests
  - Include mock-ups and pathfinders as the crudest forms
  - Develop a useful series of vehicles with incremental maturity

# Conclusions

- Flight Testing in Human Spaceflight is critical for new spaceflight programs/projects
- Tendency is to “price” test out of feasibility due to Human Spaceflight Rigor being used as default content for all aspects
- Risk Tolerance and acceptance drives cost and schedule
  - Challenging to delegate “Take more risk”
  - Need to translate into relief on standards, review etc
- NASA team needs benefits from real flight tests
  - All disciplines can benefit

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