Evaluation of Low Gravity Propellant Motion Experiments For Validation of Spacecraft Slosh Models

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Control, Mitigation, and Management of Liquid Propellant Dynamics

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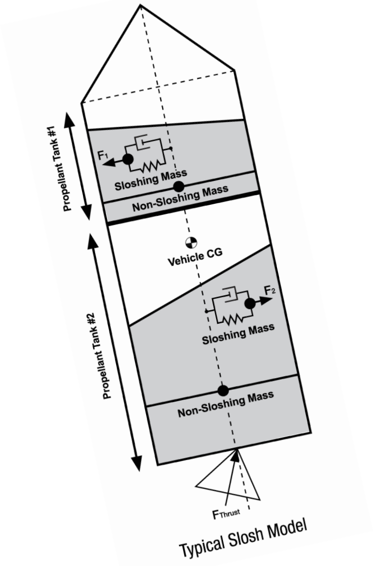
Background

- The NASA Engineering Safety Center (NESC) GNC Technical Discipline Team (TDT) is tasked to advance the state of the GNC discipline
  - The GNC TDT is comprised of GNC discipline practitioners from all NASA centers, academia, and commercial partners.
- GNC TDT identified low-g slosh modeling as an area of advancement
  - Slosh can have a detrimental effect on spacecraft dynamics (attitude control, delayed response).
  - Slosh must be considered when verifying spacecraft pointing, docking, and separation requirements.
  - Currently no fully validated models for modeling slosh suitable for use in a broad range of multi-DoF GNC flight simulations.
- NASA missions with potential for significant detrimental effects from low-g slosh
  - -HLS/Gateway Docking, HLS RPOD, Fuel depot propellant transfers, MPCV/ICPS separation
  - -These spacecraft have large amounts of propellant and ullage.
  - -NESC is assisting in assessing effect of slosh on spacecraft dynamics.



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Background

- NESC conducted a Low-g Slosh Workshop (February 22-23, 2023)
  - Goal: Determine low-g slosh state of the art with respect to models suitable for GNC simulations and availability of test suitable for validation and verification of those models.
  - Workshop participation from GNC, Flight Mechanics, and Fluid Mechanics disciplines.
  - NASA Centers: GSFC, GRC, KSC, LaRC, MSFC
  - Industry/Academia: Southwest Research Institute, Northrop Grumman, SpaceX, United Launch Alliance, Blue Origin
- Workshop findings and recommendations are documented in reference 2.

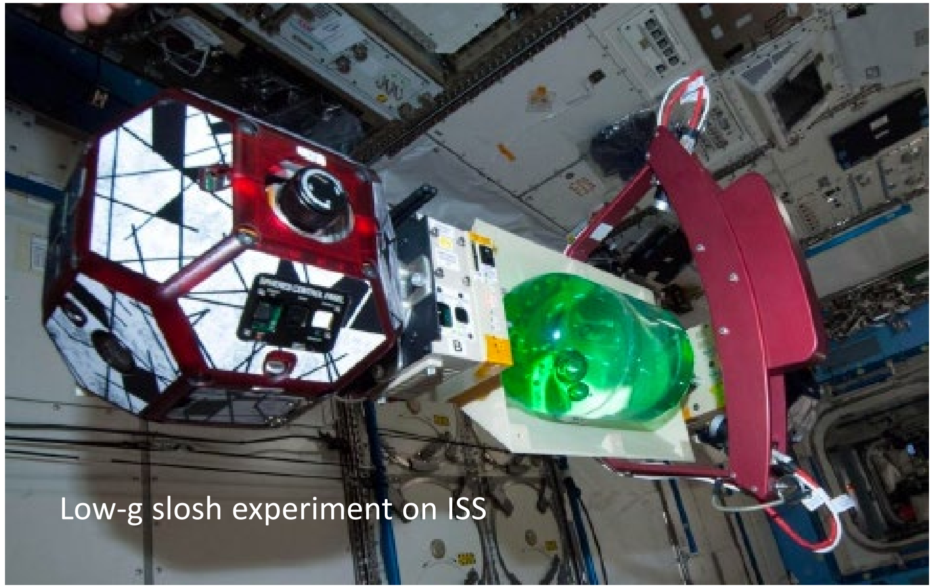

Low-g slosh experiment on ISS

Image from reference 1

Background

- Consensus of workshop participants regarding low-g slosh state-of-the-art:
  - There is a need for test data to validate low-g slosh models:
  - Many low-g slosh experiments have been conducted, but they have not been carried out in a way that directly addresses the low-gravity slosh / vehicle dynamics coupling problem.
  - To properly validate a slosh/vehicle dynamics model, the test data needs to include:
    1. Accurate measurement of the vehicle motion (navigation grade Inertial Measurement Unit (IMU), Global Positioning System (GPS)).
    2. Accurate measurement of the liquid motion (three-dimensional reconstruction of free surface; determination of the propellant contribution to the combined system inertia).
    3. Well-characterized initial conditions (velocity field of the entire fluid domain or settled tanks prior to testing).
    4. “Clean” low-gravity environment.

Low-g Slosh Model Development and Validation Study

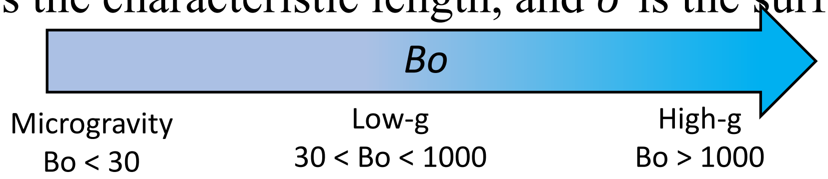
- In response to the workshop findings, the NESC performed a study to evaluate technical feasibility, cost, and schedule associated with acquiring low-g slosh data to ground models.

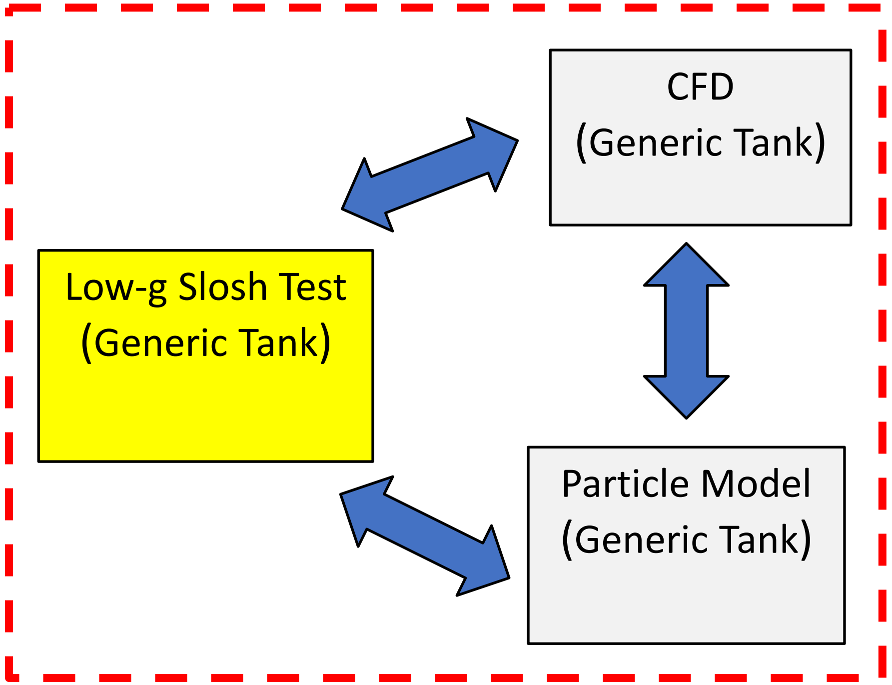
- Low-g Slosh Model Development and Validation Study Goals
  - Assess the current state of low-g slosh modeling
  - Evaluate the technical feasibility, cost, and schedule associated with acquiring low-g slosh data to validate models.

- Micro-g/low-g environment defined by Bond number

$$Bo = \frac{\Delta\rho g l^2}{\sigma}$$

where $\Delta\rho$ is the difference between the density of the propellant and the ullage, g is the acceleration (due to gravity and other forces), l is the characteristic length, and σ is the surface tension





Model Validation

State of Low-g Slosh Modeling

- Low-g slosh modeling methods
  - CFD analysis
    - High order approach to simulating fluid motion inside a tank
    - Run time is 3 to 6 orders of magnitude slower than real time
    - Not practical to run inside GNC flight dynamics simulations
    - High fidelity approach that provides an accurate estimation of the fluid motion resulting from excitations in a micro-g environment.

Image from reference 1

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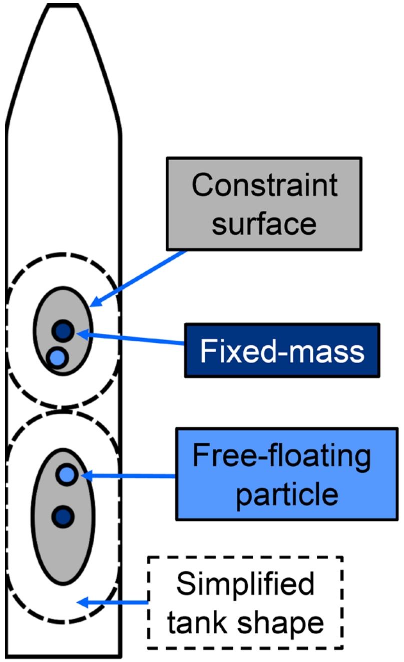

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  Equivalent mechanical models
    - Reduced order approach to simulating fluid motion inside a tank
    - The fluid is represented as a mechanical element such as a cohesive particle of mass
    - Multiple types: particle, harmonic oscillator, pulsating sphere
    - Equations of motion are more easily linearized and integrated into flight dynamics simulations.
    - Run time is less than real time making it feasible to run inside GNC flight dynamics simulations
    - Lower fidelity approach that often requires tuning the model with higher fidelity data (test, CFD).

State of Low-g Slosh Validation

- Low-g slosh model validation
  - CFD analysis
    - The chaotic nature of low-g slosh coupled with the numerical uncertainty associated with CFD models results in the need to validate those models.
    - “Best practice” validation is performed using test data from a representative flight system in a relevant environment.
  - Equivalent mechanical models
    - Harmonic isolators have been validated with drop tower data but are limited to the low-g regime.
    - Particle models have had limited success with correlation to drop tower data.
    - Unvalidated CFD has been used to tune/validate mechanical models.
- Micro/low-g slosh data sets exist but they have limitations:
  - Short duration and imprecise relevant gravitational environment
  - Lack of known initial conditions, high-quality fluid motion data, and imagery.
- Conclusion is that additional test data is needed for validation of both CFD and mechanical models.

Evaluation of Test Options For Acquiring Micro/Low-g Test Data

- Identified seven platforms for performing micro/low-g testing
  1. International Space Station Astrobee
  2. Sounding rocket, sub-orbital flights
  3. Aircraft parabolic flights
  4. High-altitude balloon drop
  5. Drop Tower
  6. Artemis II Orion flight test
  7. HLS Starship flights

- Each platform was evaluated for technical feasibility, cost, and schedule associated with acquiring low-g slosh data to ground models.

Evaluation Metrics

Test Environment	Level/magnitude of sensed acceleration (Bond number)
	Time spent in micro/low-g flight
	Quality of micro/low-g flight (constant/steady, variability, noisiness)
	Repeatability of environment
Test Fixture Capability	Ability to achieve and measure a desired initial condition.
	Ability to apply a full range of excitation: longitudinal, lateral, roll, pitch/yaw.
	Adequacy/degree of instrumentation to measure vehicle and slosh dynamics.
Mission and Programmatic Considerations	Complexity
	Schedule
	Cost

International Space Station (ISS) Astrobee

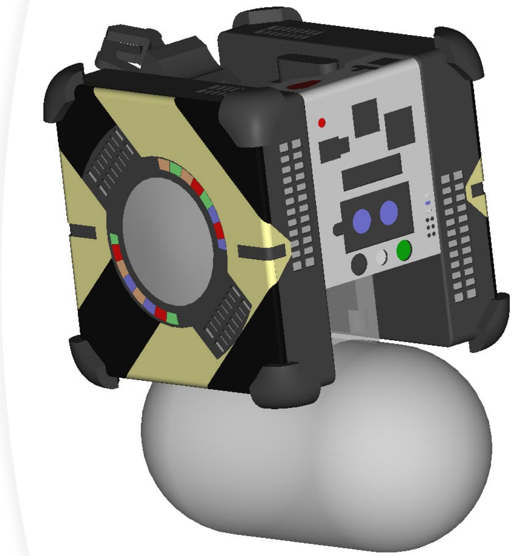
- Astrobee is a cubed shaped robot onboard ISS
  - Capable of free flight in ISS microgravity.
  - Designed to interface with guest science payloads.
  - Precision position and attitude control.
  - Can autonomously perform pre-programmed maneuvers.
  - Ideal candidate for performing small scale micro-g testing.
- Micro-g and low-g test evaluation:
  - Max 0.6 N thrust limits tank size, slosh excitation, and resulting dynamics.
  - Determined achievable Bond numbers for a spherical 15 cm diameter tank with 40% fill level for water, mineral oil, NOVEC 7100.

	Water	Mineral Oil	NOVEC 7100
Bond Number	6.8	16.3	52.6

  - Initial fluid condition along any axis is achievable.
  - Translational and rotation excitations are possible. Two-hour test time.
  - High degree of instrumentation possible.
  - $1M Rough Order Magnitude (ROM) cost, 2 to 3 year timeframe.

NASA astronaut Anne McClain with an Astrobee robot
https://www.nasa.gov/astrobee/

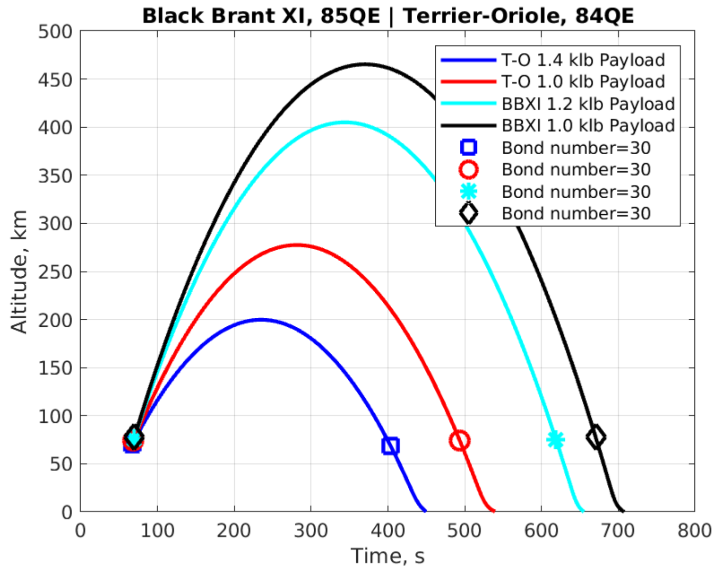
Astrobee robot 30.5 X 30.5 X 30.5 cm, 6 kg cube
https://www.nasa.gov/astrobee/

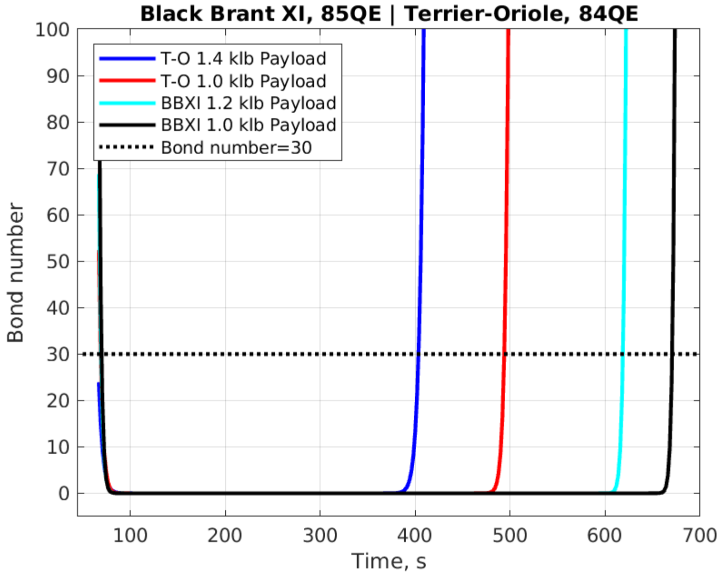


Sounding Rocket Flight

- Suborbital flights provide minutes of micro/low-g flight
  - Weightlessness Analysis Sounding Probe (WASP) experiment in ‘66.
  - 1528 lb payload | 22 inch diameter test tank | 6 minutes micro-g
- NASA Sounding Rocket Program offers sounding rockets suitable for micro-g testing. \$4-\$5M, 3 to 4 year timeframe.
  - Evaluated Terrier-Orion and Black Brant XI rockets.
  - Free flyer, I.C.s, translational and rotational excitation possible.
  - 5.6 ≤ Micro-g flight time ≤ 10 minutes

Sounding Rocket	Terrier-Oriole		Black Brant XI	
Slosh fluid: water				
Payload weight [lb]	1400	1000	1200	1000
Payload diameter [in]	22.0	22.0	22.0	22.0
Payload Ballistic coefficient [slug/ft^2]	23.55	16.82	20.18	16.82
Slosh test tank diameter [in]	18.0	18.0	18.0	18.0
Max Altitude [km]	200	277	405	465
Time above 100 km [s]	294	397	529	583
Time Bond number < 30 [s]	336	425	549	601
Altitude at Bond number < 30 [km]	70	74	76	78
Sensed accel at Bond number = 30 [m/s^2]	0.0415	0.0415	0.0415	0.0415



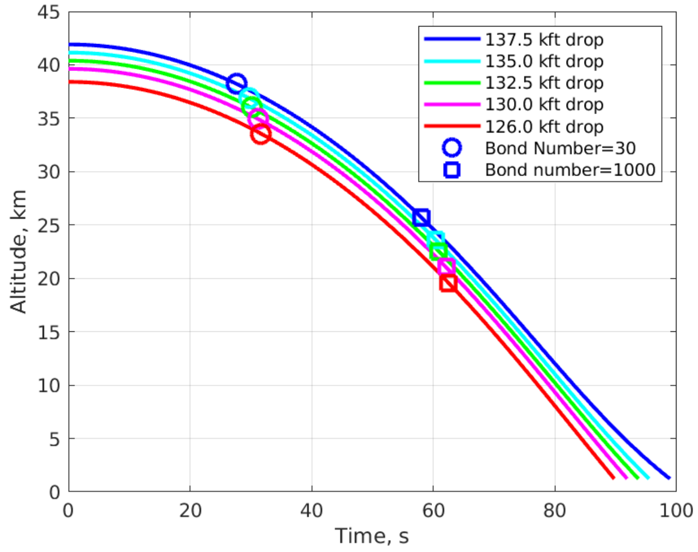


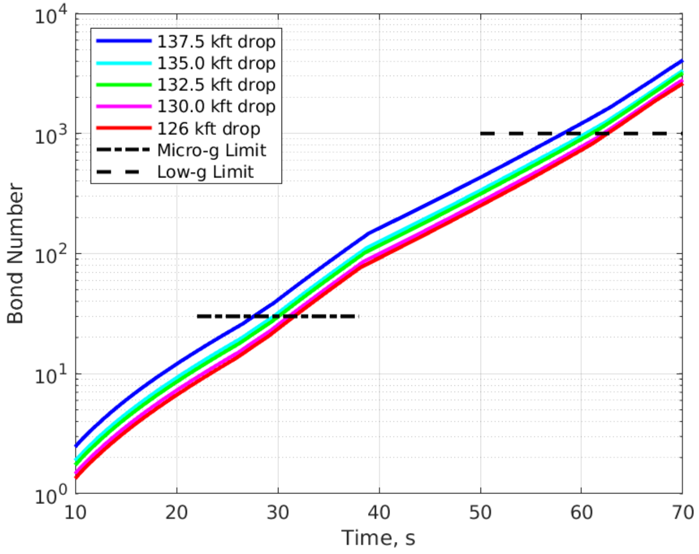
Balloon Drop

- A high-altitude balloon drop was evaluated as a possible micro/low-g test platform. $1.2-$5M, 3 to 4 year timeframe
  - Capable of floating above 99% of the atmosphere, reducing drag but not eliminating it. High ballistic coefficient fixture required.
  - Evaluated a 39.57 million cubic feet (MCF) balloon
  - 1-g initial condition (I.C.) at drop. Free flyer after. Translational and rotational excitations possible
  - Micro-g time ≈ 32 seconds, Low-g time ≈ 30 seconds
  - Gravity environment is not constant, changes rapidly.

39.57 MCF Balloon	Drop Altitude (kft)				
Slosh fluid: water	126.0	130.0	132.5	135.0	137.5
Suspended weight (lb)	6000	4600	3500	2900	2000
Payload weight (lb)	3600	2760	2100	1740	1200
Payload diameter (in)	24.0	24.0	24.0	24.0	24.0
Slosh test tank diameter (in)	20.0	20.0	20.0	20.0	20.0
Ballistic coefficient (slug/ft^2)	114.9	88.1	67.0	55.5	38.3
Time (s) at Bond number = 30	31.7	31.2	30.1	29.7	27.7
Time (s) at Bond number = 1000	62.5	62.1	60.9	60.4	58.1
Time (s) at Mach number = 0.85	27.6	27.8	27.9	28.0	28.1

Over water drop wo/parachute

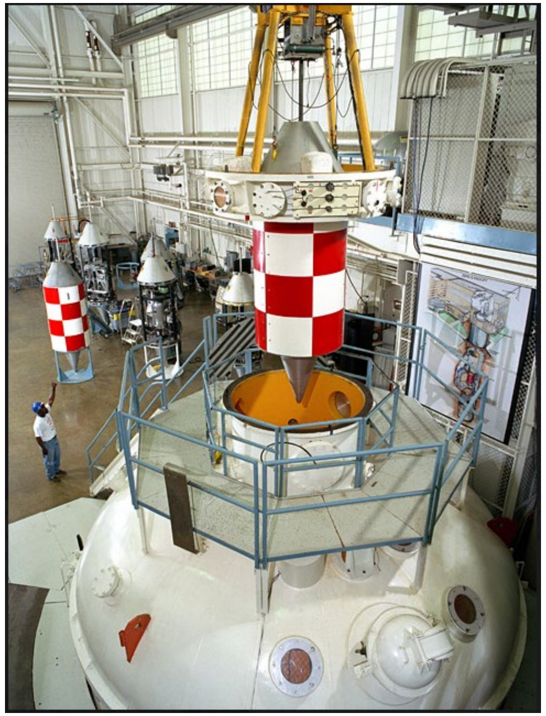




Drop Tower

- Drop towers have provided a means of performing low-cost, repeatable high quality micro-g environment testing over the past seven decades.
  - Vacuum tube and drag shield type towers are in operation today
  - NASA Glenn operates two drop towers
    - Zero Gravity Research Facility: 433 feet freefall below ground vacuum tube
    - 2.2 Second Drop Tower: 79 feet freefall above ground drag-shield type tower
  - ZARM Institute in Bremen Germany operates the Bremen Drop Tower.
    - 394 feet freefall vacuum tube, drop mode and catapult mode of operation.

	Environment		Payload Max Size			Peak Accel	
	Sensed Accel (g)	Duration (sec)	diameter (in)	length (in)	weight (lb)	Launch (g)	Impact (g)
Glenn Zero-g Facility Drop	< 1.00E-05	5.2	38	66	1000	0	65
ZARM Drop	1.00E-06	4.7	23.5	70	496	0	50
ZARM Catapult	1.00E-06	9.3	23.5	40	364	30	50

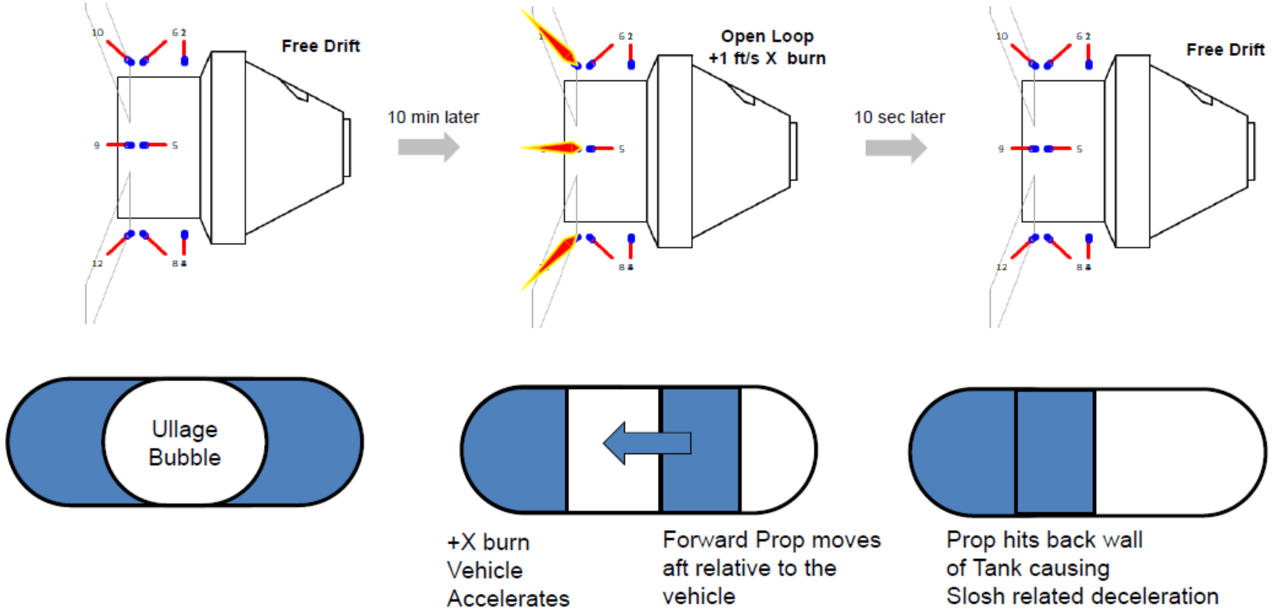


NASA Glenn Zero Gravity Research Facility
https://www1.grc.nasa.gov/facilities/zero-g/
Reference 4

- Drop tower benefits, limitations
  - Economical: estimated cost in the range of $150k to $200k (performing drop + project assistance).
  - Short lead time: schedule availability within weeks or months once experiment is ready for drop.
  - Short duration, single axis DoF, Lateral and pitch/yaw excitations are not possible.
  - Weight limitation in catapult mode. High deceleration at end of drop.

Artemis I Orion Flight Test

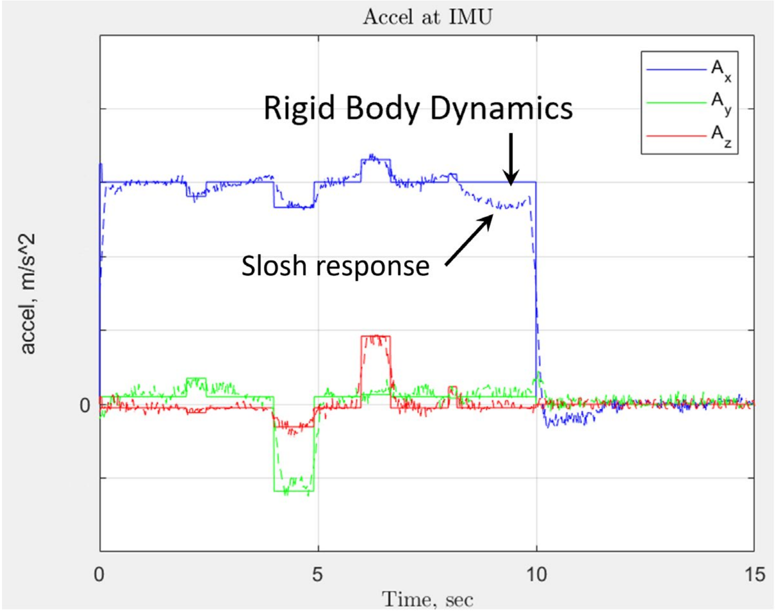
- A micro-g slosh test was performed during a coast phase of the Artemis I flight to quantify the effect of longitudinal slosh on Orion RPOD.
  - Evaluation of the flight data revealed limitations for model validation
    - A low signal-to-noise ratio (SNR) in the longitudinal IMU acceleration data made it difficult to clearly identify the effect of slosh.
    - The assumed initial distribution of the fluid in the tanks had some inaccuracy that led to a non-optimal timing of excitation thrusting.
    - Refer to paper reference 22 for an analysis of the Artemis I slosh test data



+X burn
Vehicle
Accelerates

Forward Prop moves
aft relative to the
vehicle

Prop hits back wall
of Tank causing
Slosh related deceleration

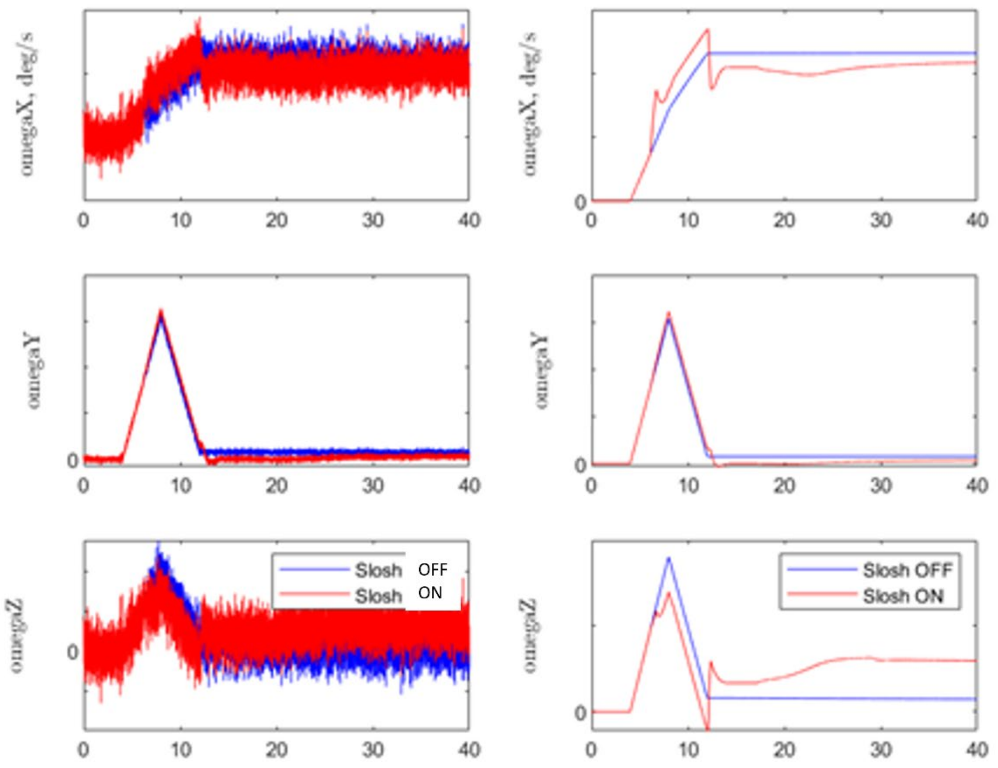


Artemis II Orion Flight Test

- The Artemis II flight could provide an opportunity to perform full scale micro-g slosh testing in a relevant environment.

- The NESC developed micro-g slosh test maneuver for Artemis II that would increase the slosh response SNR and provide a known fluid initial condition.
  - Axial thrusters are used to settle the propellant in the tanks.
  - A pitch and rate doublet is used to produce a slosh response in the lower noise IMU angular rate gyros.
- A flight simulation with a particle slosh model was used to quantify Orion's response to the maneuver.
  - Analysis results indicate Orion's response to the slosh dynamics will be more evident in flight data.

Response to Proposed Slosh Excitation Maneuver



HLS Starship Testing

- HLS offers an excellent platform for conducting full scale micro-g and low-g testing.
  - HLS has large wet-dry mass fraction
  - Developmental test flights provide an opportunity to conduct experiments during various flight phases and operations.
    - RPOD
    - Propellant aggregation phase when the propellant depot and Starship are filled.
    - Long term coast phases in LEO and NRHO
  - Flight data from onboard sensors could provide a wealth of information.

Artist's rendering of SpaceX Starship human lander design
https://www.nasa.gov/reference/human-landing-systems/

Parabolic Flight

- NASA’s Flight Opportunities Program provides support for conducting experiments onboard parabolic flight aircraft.
  - Zero Gravity Corporation (Zero-G Corp) is a flight provider to NASA.
  - Boeing 727-200F aircraft.
- The aircraft performs pitching maneuvers to fly a parabolic trajectory.
  - Approximately 30 parabolas performed during a flight.
  - 15 seconds micro-g flight time
  - Up to 30 seconds of low-g flight time
- Benefits and limitations
  - Economical: ROM cost in the range of $60k to $70k.
  - Short lead time: schedule availability within 6 months to 1 year.
  - Free flying experiment: lateral and pitch/yaw excitations are possible
  - Short duration test time, inconsistency in the micro/low-g environment
  - Size and weight limitation due to manual handling of the experiment.

Suborbital Flights

- Suborbital flights provide minutes of micro/low-g flight
- NASA Flight Opportunities Program sponsors suborbital flight experiments
  - Two suborbital flight providers: Blue Origin, Virgin Galactic
  - Both providers' flights offer up to 3 minutes of micro-g or low-g flight
- Recent slosh related testing
  - Blue Origin New Shepard Jan 23, 2025
    - Purdue University: "Zero-Gravity Green Propellant Management Technology"
    - Carthage College: "Microgravity Propellant Gauging Using Modal Analysis"
  - Virgin Galactic VSS Unity June 8, 2024
    - Purdue University: "Rotational Slosh Experiment"

Blue Origin's New Shepard reusable suborbital rocket
Photo: Blue Origin
Reference 5

www.nasa.gov/humans-in-space/commercial-space

Conclusions

- A summary of each test platform’s metrics is given below.
  - The test platforms evaluated offer both full-scale and sub-scale test options.
  - The viability of a particular method depends on the test goal.
  - Longer duration platforms are suitable for tests that quantify slosh dynamics.
  - Low cost, short duration platforms could be used to develop sensors or components in support of slosh dynamics testing.

	Test Fixture Capability						
	Fluid Initial conditions		Slosh Excitation				Level of Instrmentation
	Positioning Ability	Distribution	logitudinal	lateral	roll	pitch/yaw	
ISS Astrobee	multi-axis	measurable	yes	yes	yes	yes	limited
Sounding Rocket	multi-axis	measurable	yes	yes	yes	yes	full
Parabolic Flight	single axis	1g initial cond	yes	yes	yes	yes	full
Balloon Drop	single axis	1g initial cond	yes	yes	yes	yes	full
Drop Tower	single axis	1g initial cond	yes	no	yes	no	full
Artemis II	single axis	inferred	yes	no	yes	yes	limited
HLS	multi-axis	measurable	yes	yes	yes	yes	full

References

1. J. Storey, D. Kirk, B. Marsell, P. Schallhorn, “Progress Towards a Microgravity CFD Validation Study Using the ISS SPHERES-Slosh Experiment”, AIAA Propulsion and Energy 2020 Forum, In-Space Liquid Propulsion System Development, August 24-28, 2020 [virtual event]
2. Benson, W., et al, “LOW-G SLOSH WORKSHOP RESULTS FROM 2023: STATE OF THE ART, GAPS AND FORWARD WORK”, 46th Annual AAS Guidance, Navigation, and Control (GN&C) Conference, AAS-24-091, Breckenridge, Colorado, February 2024.
3. Columbia Scientific Ballon Facility website, scientific balloon page: https://www.csbf.nasa.gov/balloons.html
4. NASA Glenn Research Center Zero Gravity Research Facility website, Facilities-Micro-g page: https://www1.grc.nasa.gov/facilities/zero-g/
5. NASA website, Humans in Space-Commercial Space - Commercial Space News page: https://www.nasa.gov/humans-in-space/commercial-space/nasa-supported-payloads-to-get-lift-from-blue-origin/

BACKUP Slides

The 39.57 MCF balloon was evaluated as a low-g test platform

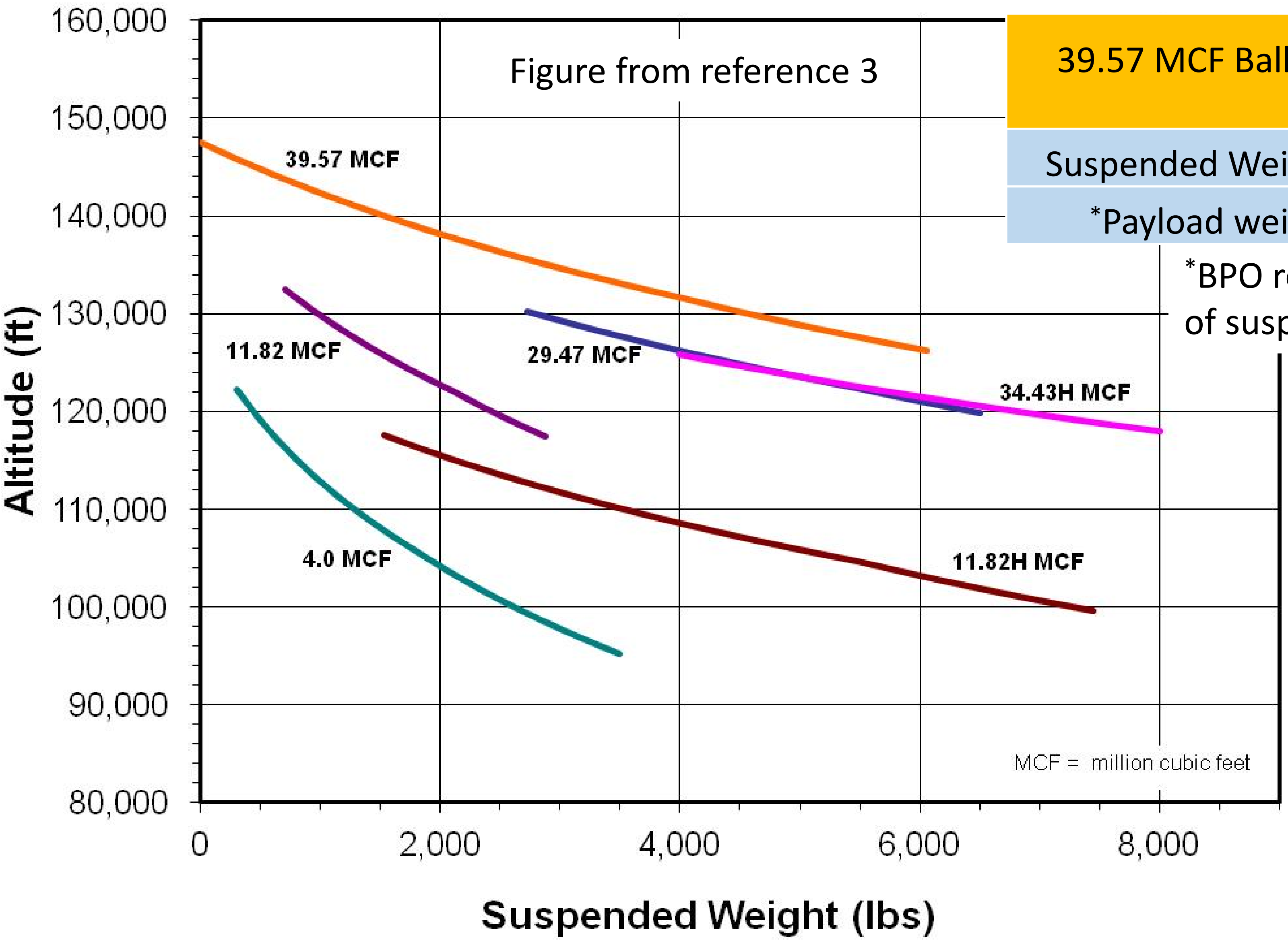


Figure from reference 3

39.57 MCF Balloon	Float Altitude (kft)				
	126.0	130.0	132.5	135.0	137.5
Suspended Weight (lb)	6000	4600	3500	2900	2000
*Payload weight (lb)	3600	2760	2100	1740	1200

*BPO recommends estimating payload weight as 60% of suspended weight for initial mission design.

Summary of Balloon Parameters

39.57 MCF Balloon	Drop Altitude (kft)				
Slosh fluid: water	126.0	130.0	132.5	135.0	137.5
Suspended weight (lb)	6000	4600	3500	2900	2000
Payload weight (lb)	3600	2760	2100	1740	1200
Payload diameter (in)	24.0	24.0	24.0	24.0	24.0
Slosh test tank diameter (in)	20.0	20.0	20.0	20.0	20.0
Ballistic coefficient (slug/ft^2)	114.9	88.1	67.0	55.5	38.3
Time (s) at Bond number = 30	31.7	31.2	30.1	29.7	27.7
Time (s) at Bond number = 1000	62.5	62.1	60.9	60.4	58.1
Sensed accel (m/s^2) at Bond number = 30	0.034	0.034	0.034	0.034	0.034
Sensed accel (m/s^2) at Bond number = 1000	1.11	1.11	1.11	1.11	1.11
Mach number at Bond number = 30	0.984	0.962	0.922	0.905	0.838
Mach number at Bond number = 1000	2.051	2.019	1.964	1.936	1.846
Dynamic Pressure (kPa) at Bond number = 30	0.518	0.409	0.324	0.277	0.199
Dynamic Pressure (kPa) at Bond number = 1000	18.26	14.00	10.50	8.65	5.71
Time (s) at Mach number = 0.85	27.6	27.8	27.9	28.0	28.1

- Sounding rockets can provide multiple minutes of micro-g flight environment for small diameter payloads.
- In 1966, the Project WASP (Weightlessness Analysis Sounding Probe) Experiment was performed at Wallops Flight Facility to study slosh dynamics during micro-gravity flight.
- The WASP vehicle provided six minutes of micro-g flight for a 22 inch diameter, 44 inch length tank.
- The experimental payload provided attitude control with both longitudinal and lateral slosh excitations.
- Currently available sounding rockets were evaluated to quantify their capability for providing micro-g flight environment.

WASP Sounding Rocket

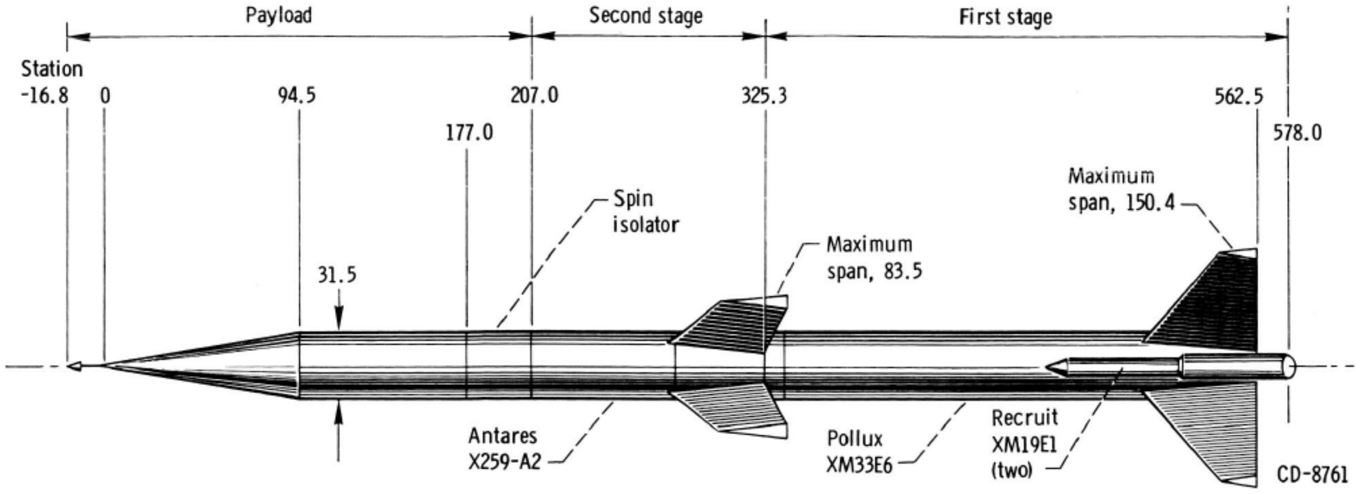


Figure 1 - WASP vehicle with nose cone attached. (Dimensions in inches.)

*from NASA TN D-3985, “Slosh Dynamics In Near Zero Gravity – Description of Vehicle and Spacecraft, Gold H. et al

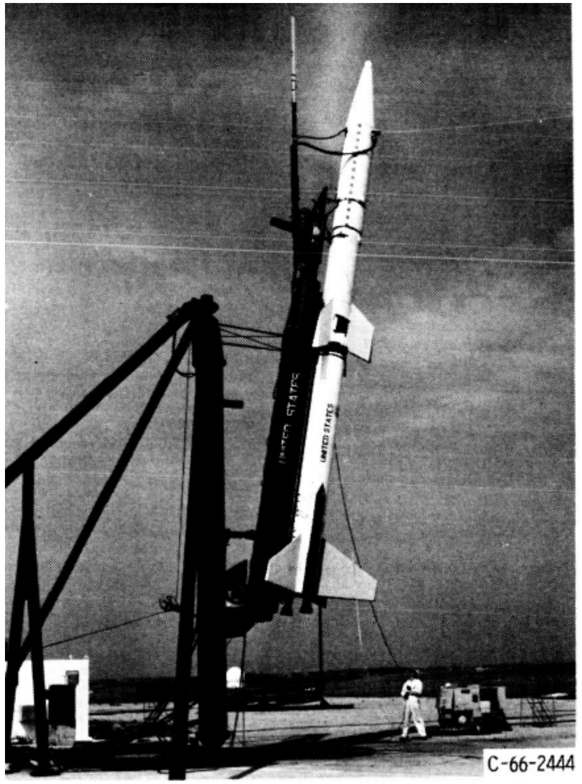
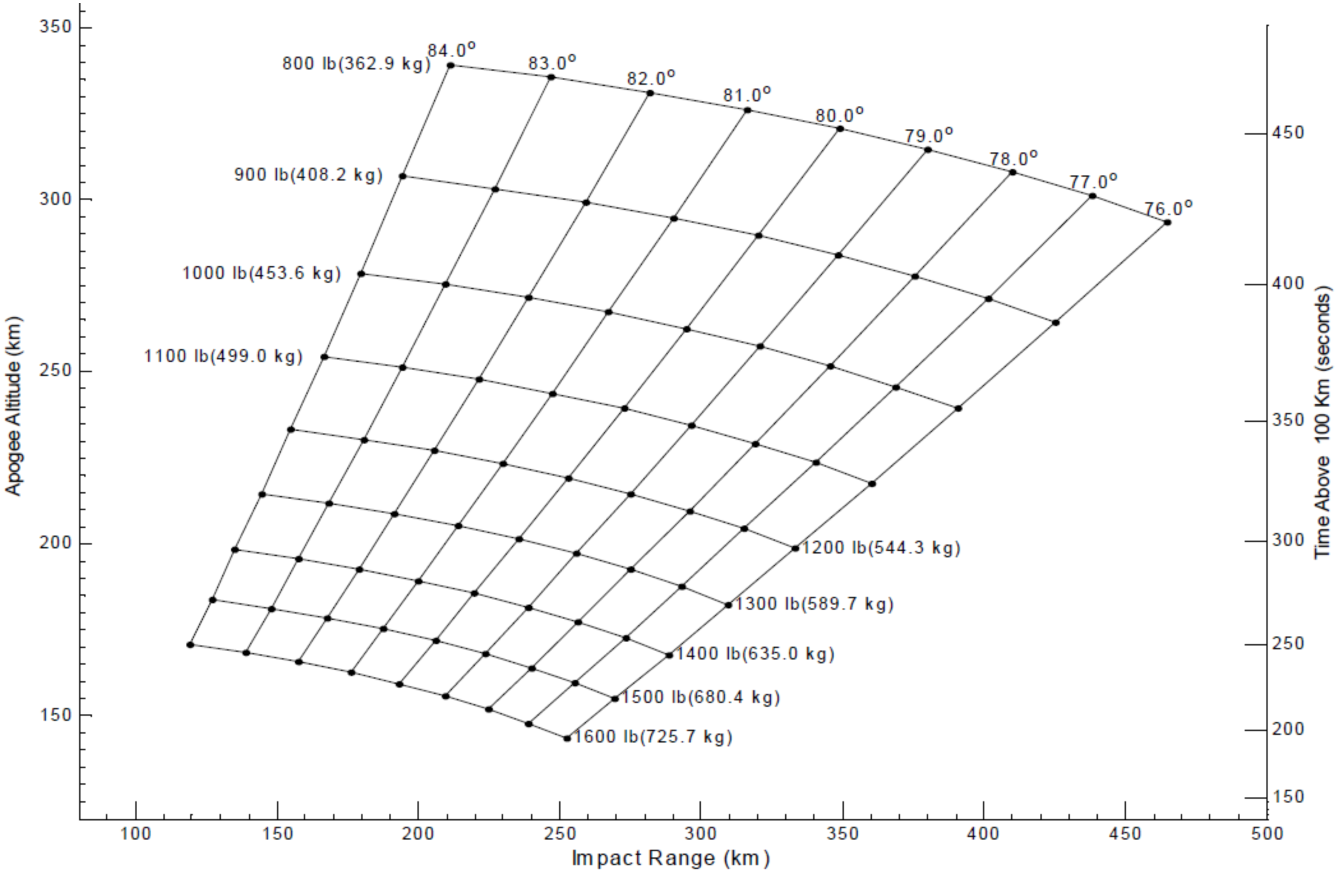


Figure 2. - WASP vehicle on launcher at NASA Wallops Station, Wallops Island, Virginia

Terrier-Oriole Sounding Rocket

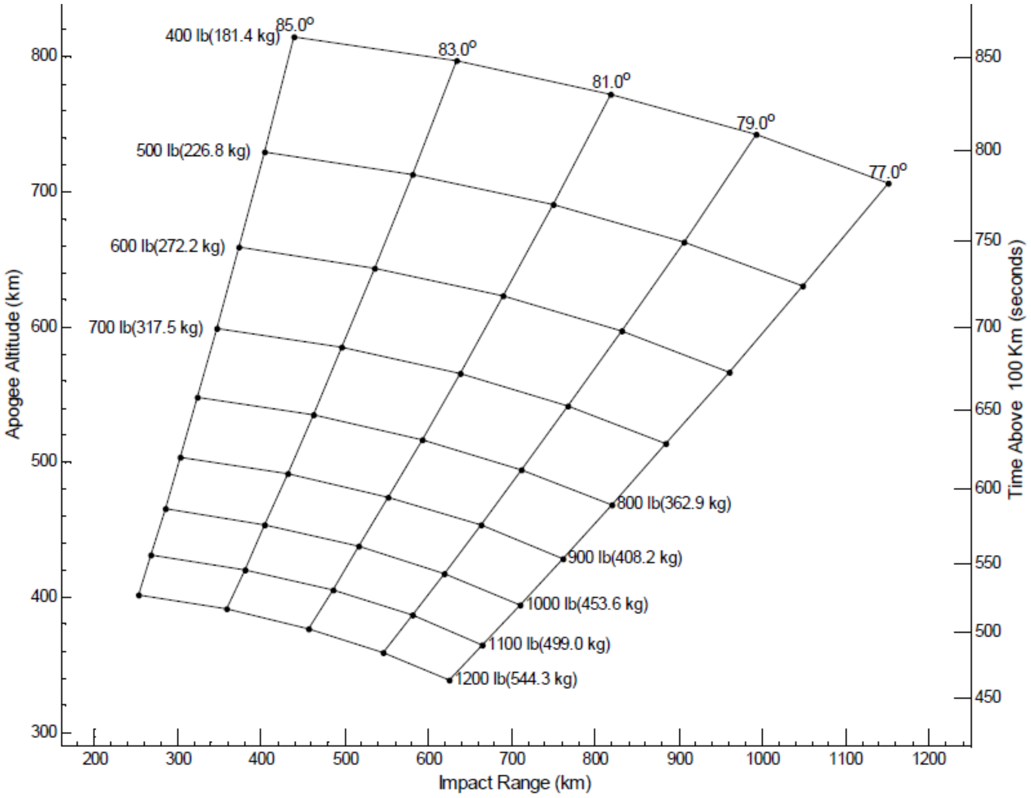
- Two-stage sounding rocket
  - Terrier MK70 first stage booster, Oriole second stage
  - Up to 1600 lb payload. 22 inch nominal diameter. 24 inch can be accommodated.
  - Spin stabilized: 2 Hz during boost, 4 Hz at payload separation.



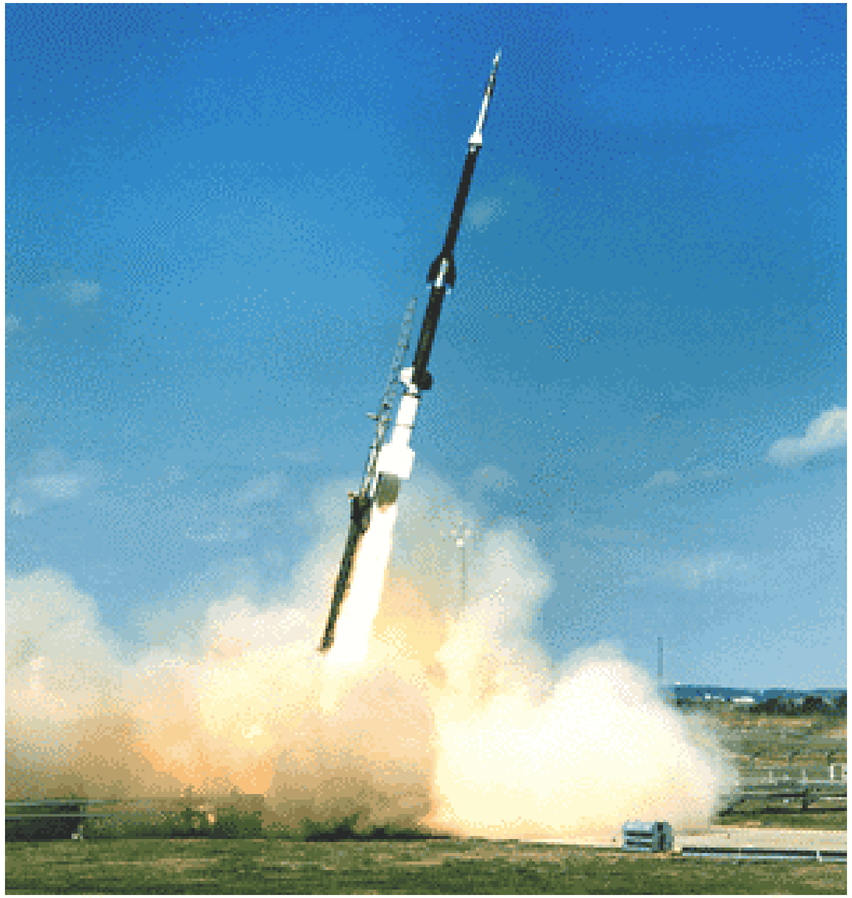
*From SRPO Terrier-Oriole vehicle guide

Black Brant XI Sounding Rocket

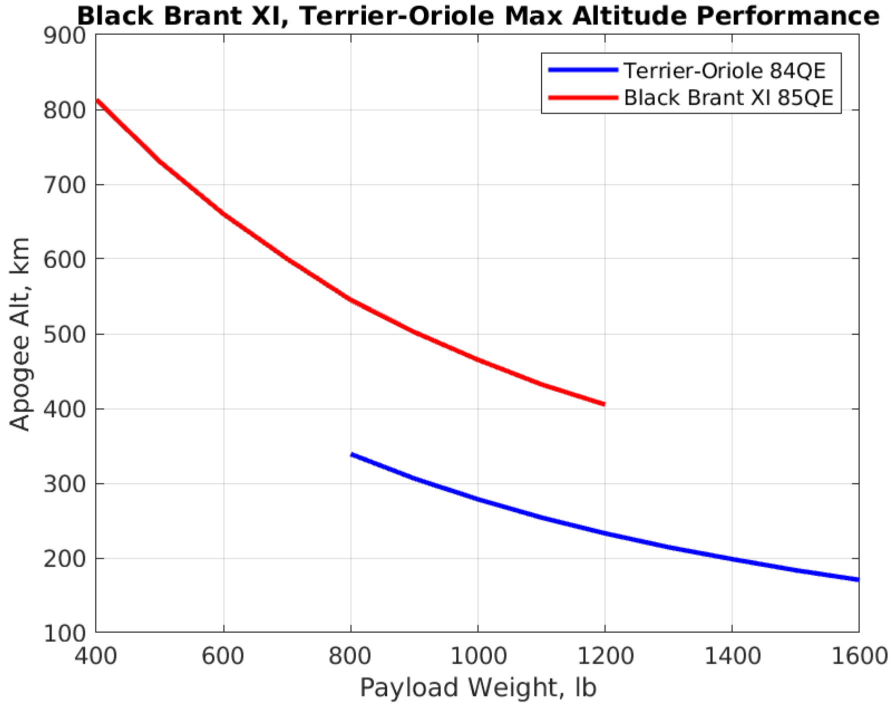
- Three-stage sounding rocket
  - First stage: Talos | Second stage: Taurus | Third stage: Black Brant VC
  - Up to 1200 lb payload. 17.3 inch nominal diameter. 24 inch can be accommodated.
  - Spin stabilized: 1 Hz first stage, 2 Hz second stage, third stage rate unspecified.



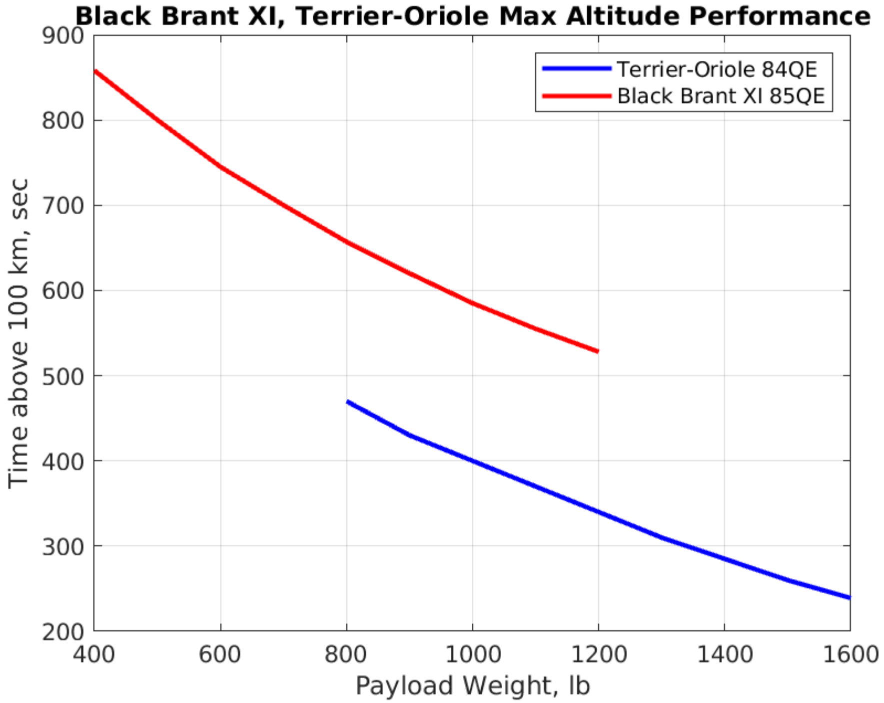
*From SRPO Black Brant XI vehicle guide



Summary of Terrier-Oriole, Black Brant XI Maximum Altitude Performance



Black Brant XI, Terrier-Oriole Max Altitude Performance



Black Brant XI, Terrier-Oriole Max Altitude Performance

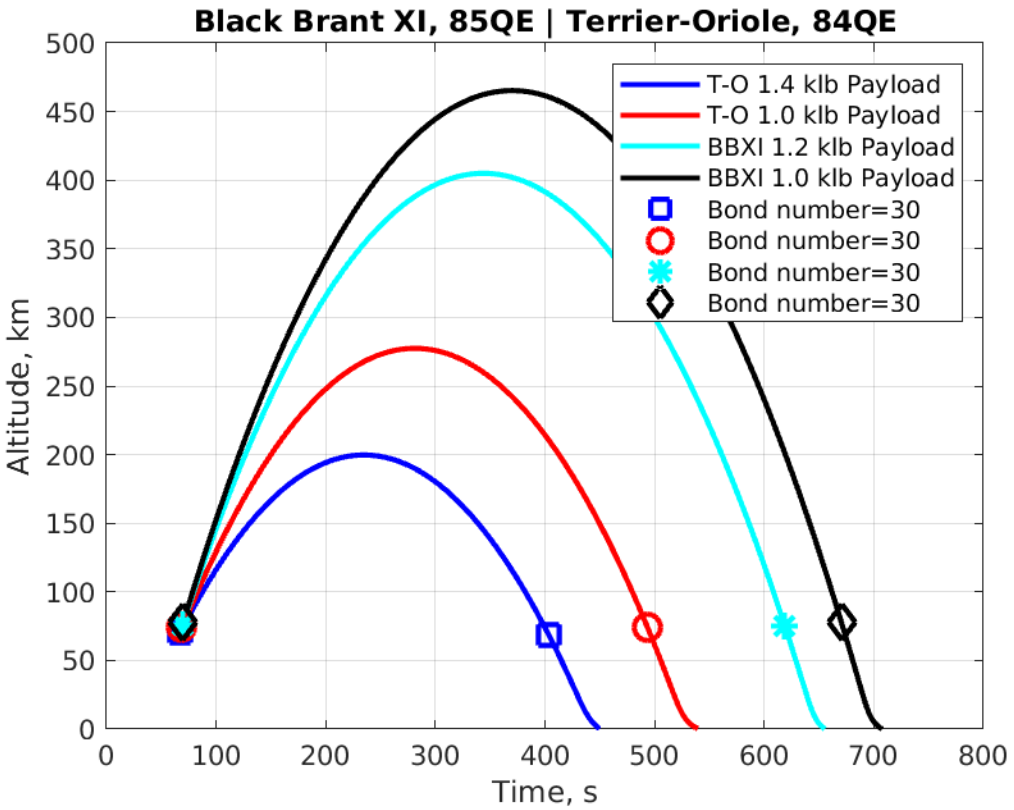
- The Sounding Rocket Program Office (SRPO) publishes performance data for their rockets.
  - SRPO data includes flight time above 100 km where atmospheric effects are negligible.
  - Flight time above 100 km provides a reasonable estimate of micro-gravity flight time.
- Flight simulations were performed to quantify the amount of time the Terrier-Oriole and BBXI rockets provide a flight environment with Bond number ≤ 30.
  - Simulations verified above what altitude micro-g conditions would exist.
  - For high ballistic coefficient payloads, micro-g acceleration could extend below 100 km.

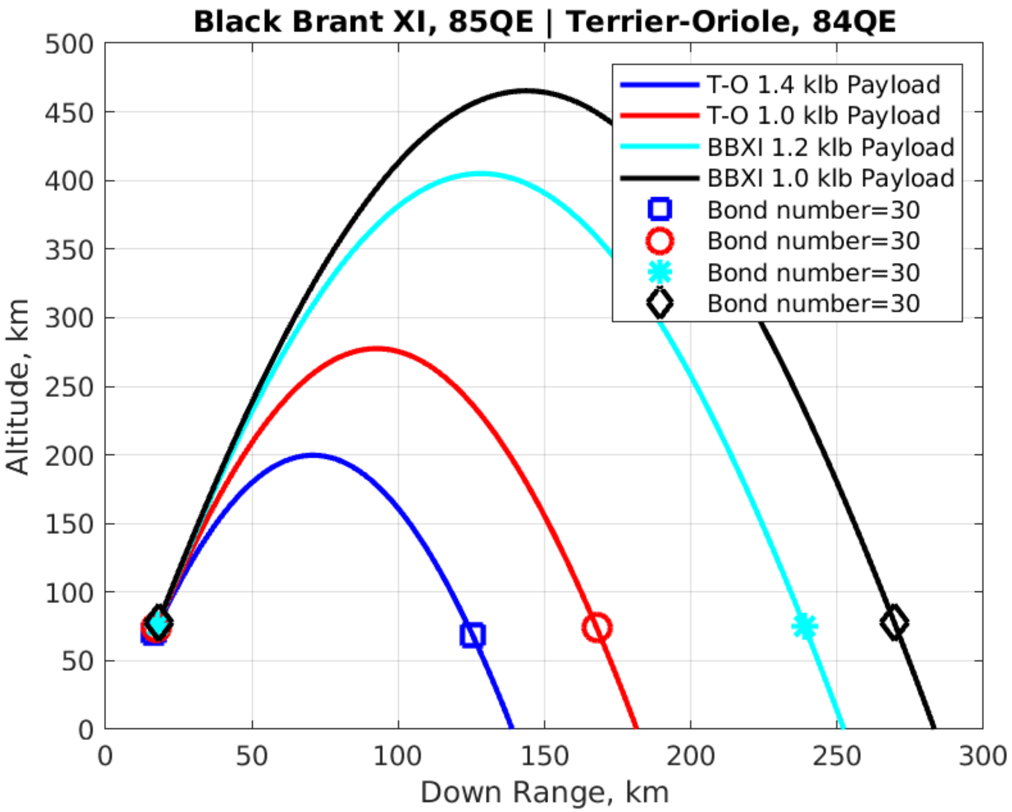
Summary of Sounding Rocket Micro-gravity Test Capability

Sounding Rocket	Terrier-Oriole		Black Brant XI	
Slosh fluid: water				
Payload weight [lb]	1400	1000	1200	1000
Payload diameter [in]	22.0	22.0	22.0	22.0
Payload Ballistic coefficient [slug/ft^2]	23.55	16.82	20.18	16.82
Slosh test tank diameter [in]	18.0	18.0	18.0	18.0
Max Altitude [km]	200	277	405	465
Time above 100 km [s]	294	397	529	583
Time Bond number < 30 [s]	336	425	549	601
Altitude above which Bond number < 30 [km]	70	74	76	78
Sensed accel at Bond number = 30 [m/s^2]	0.0415	0.0415	0.0415	0.0415

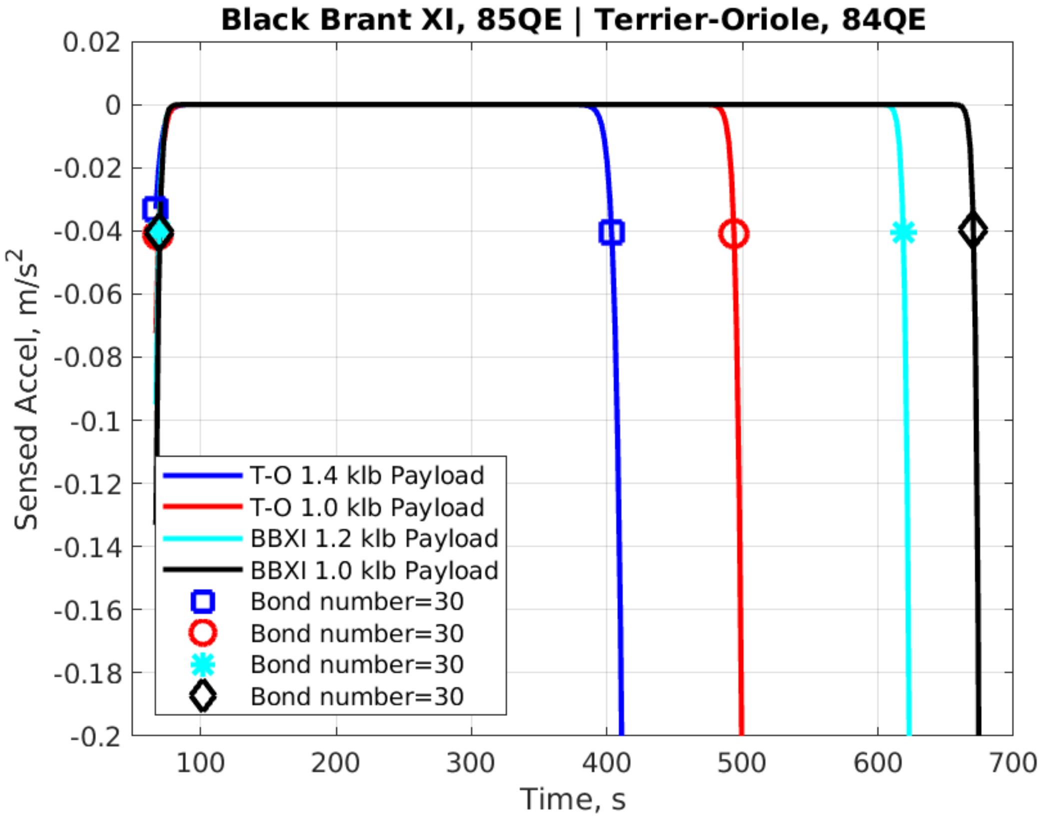
- The Terrier-Oriole rocket provides a micro-g flight time similar to the Weightlessness Analysis Sounding Probe (WASP) rocket.
- The altitude above which Bond number ≤ 30 is in good agreement with the WASP flight.
  - The WASP sounding rocket’s goal was to provide free-flight above 250 kft (76.2 km).

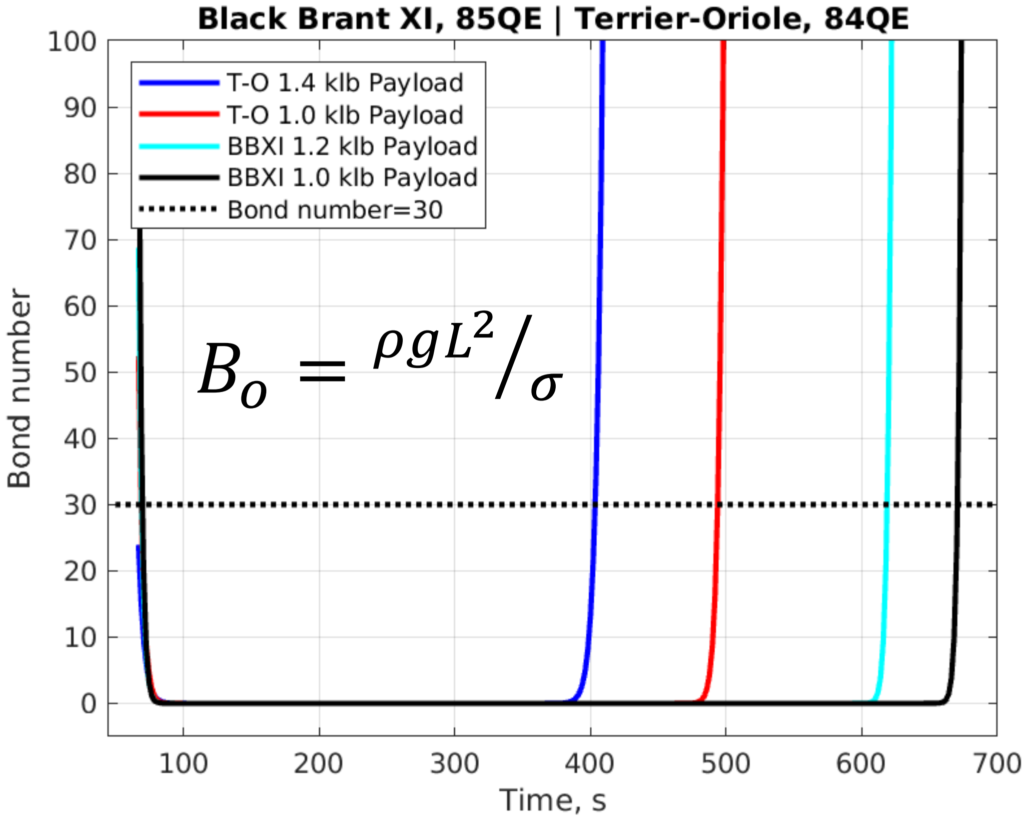
Flight Time and Range





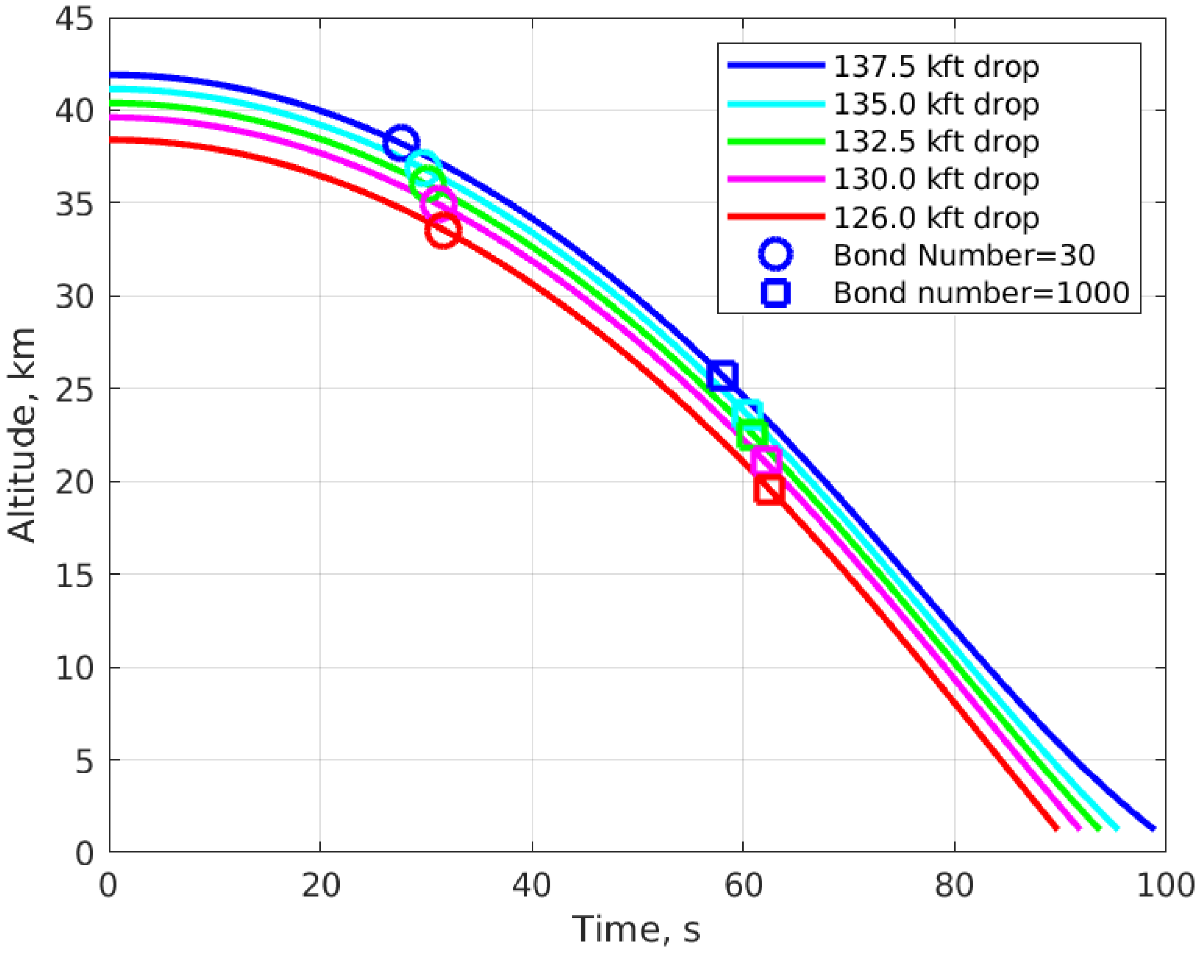
Sensed Acceleration and Corresponding Bond Number

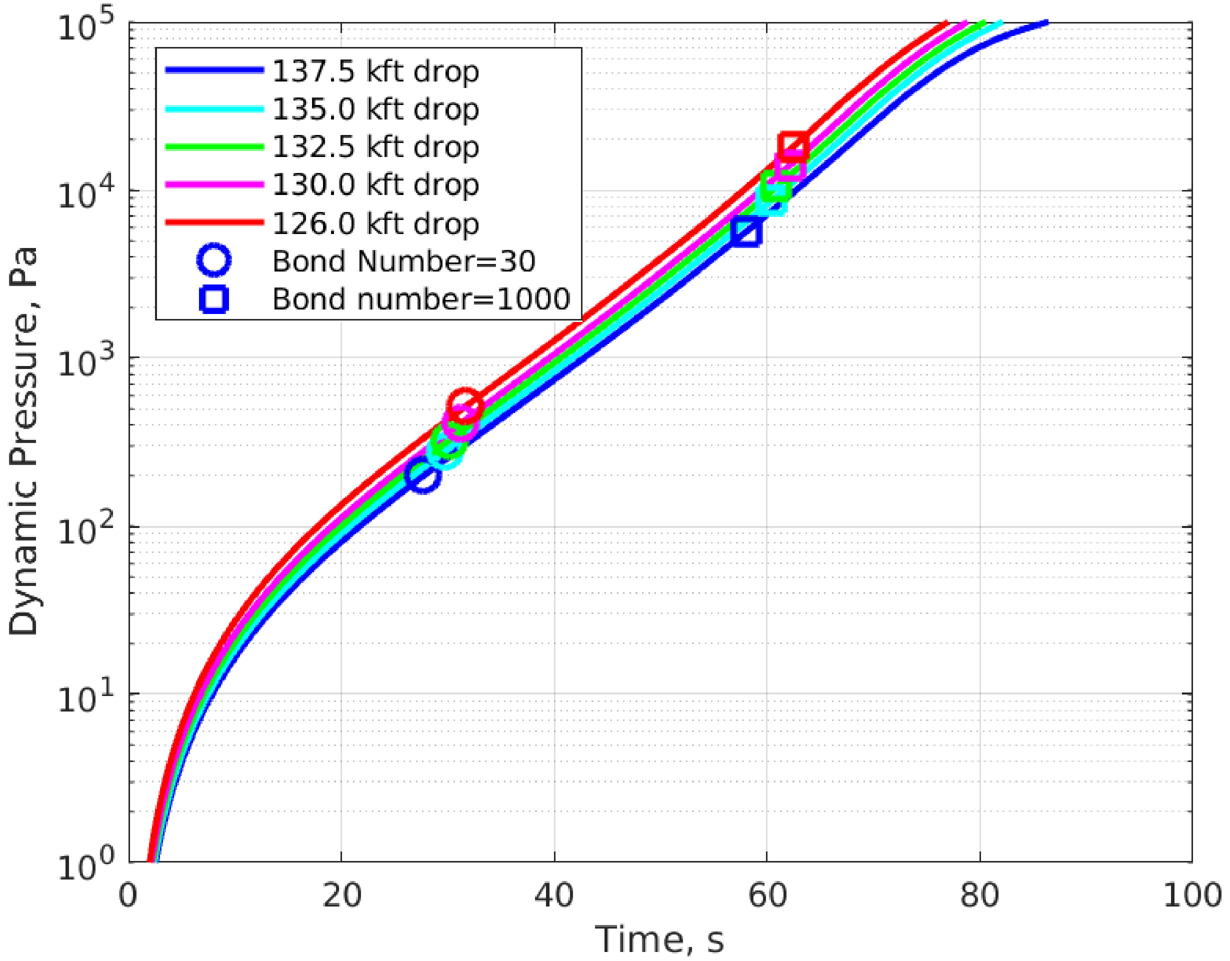




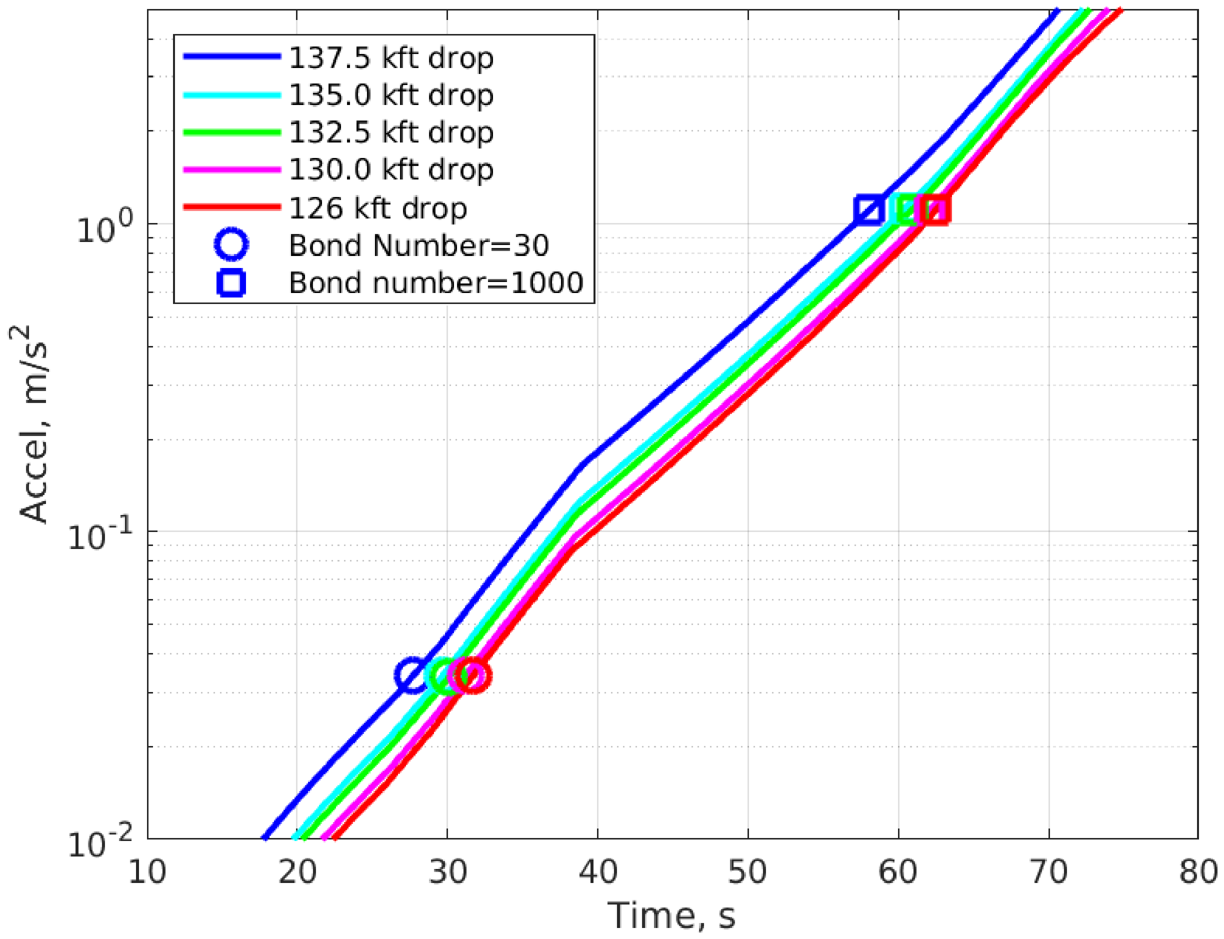
$$B_o = {}^{\rho g L^2}/_{\sigma}$$

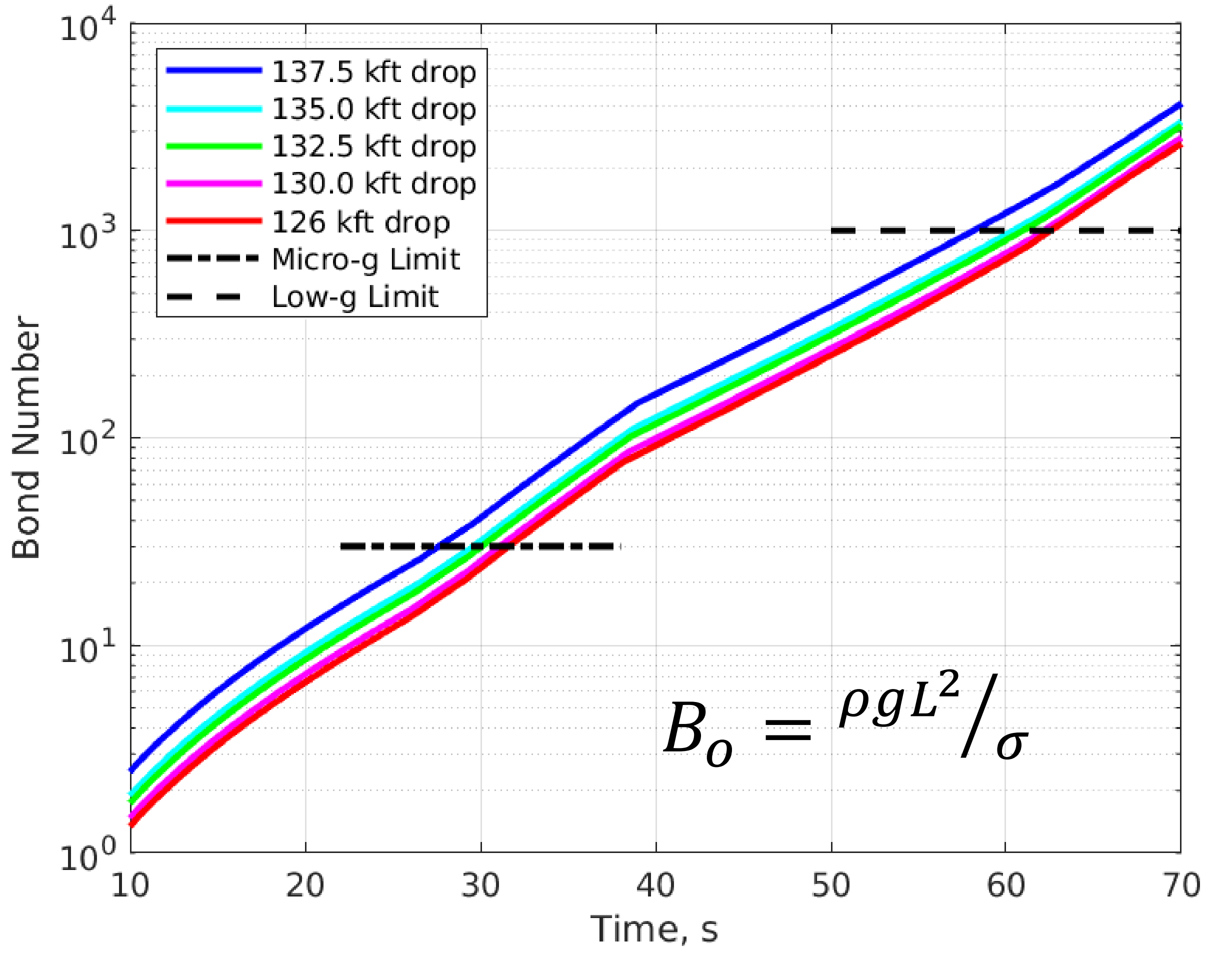
Balloon Sim Results





Balloon Sim Results

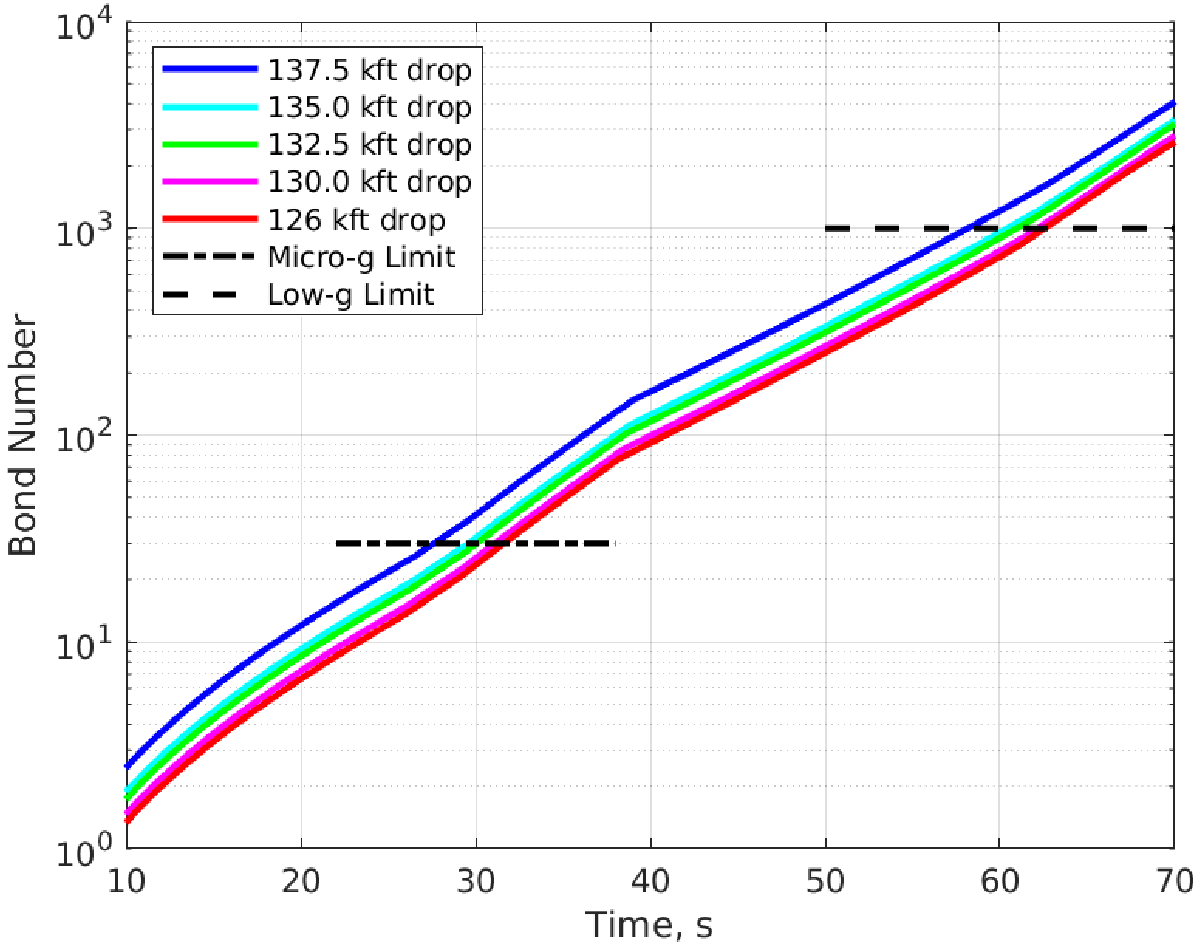


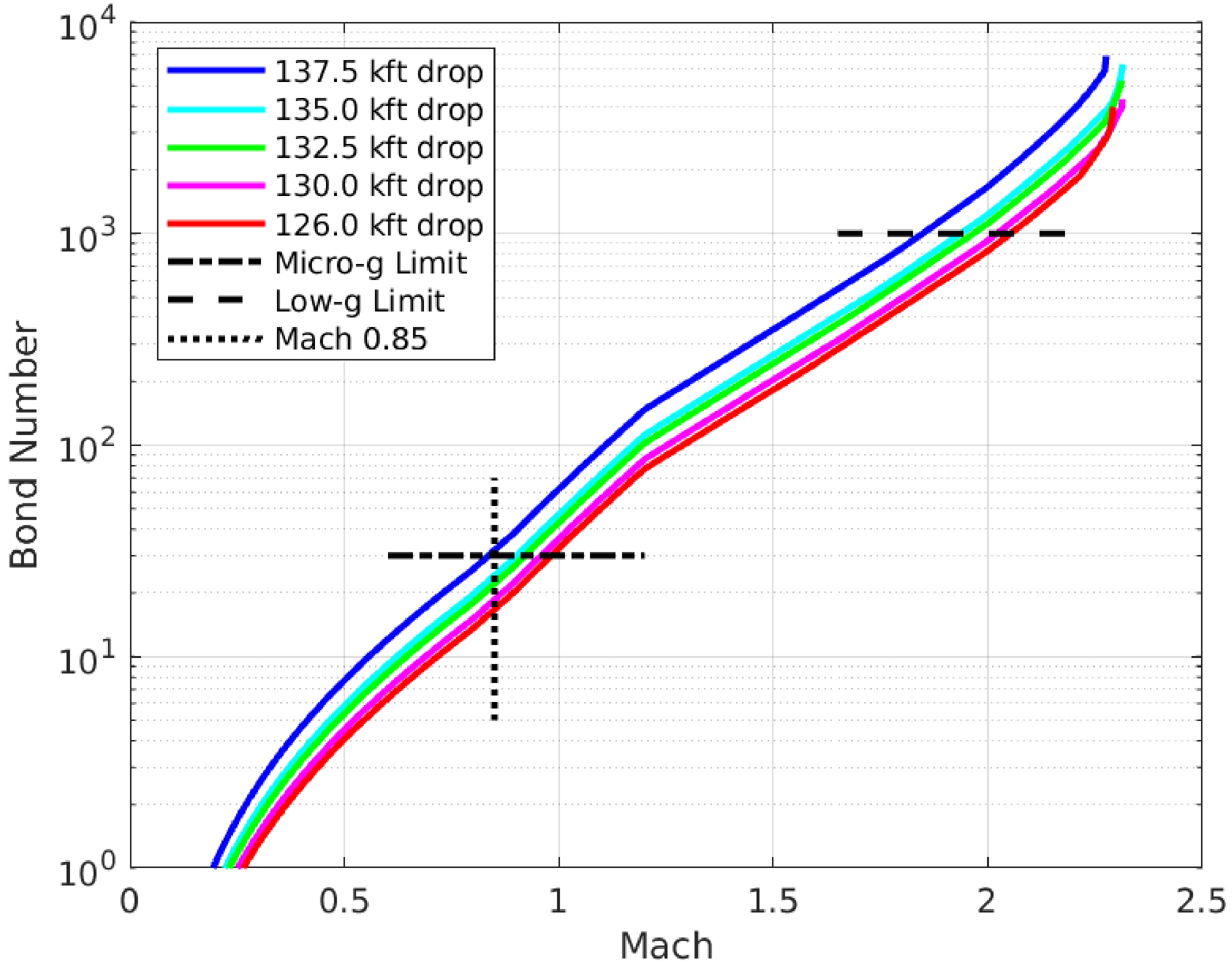


$$B_o = {}^{\rho g L^2}\!/_{\sigma}$$

$$\rho = fluid\ density$$
$$g = acceleration$$
$$a = characteristic\ length\ (tank\ radius)$$
$$\sigma = fluid\ surface\ tension$$

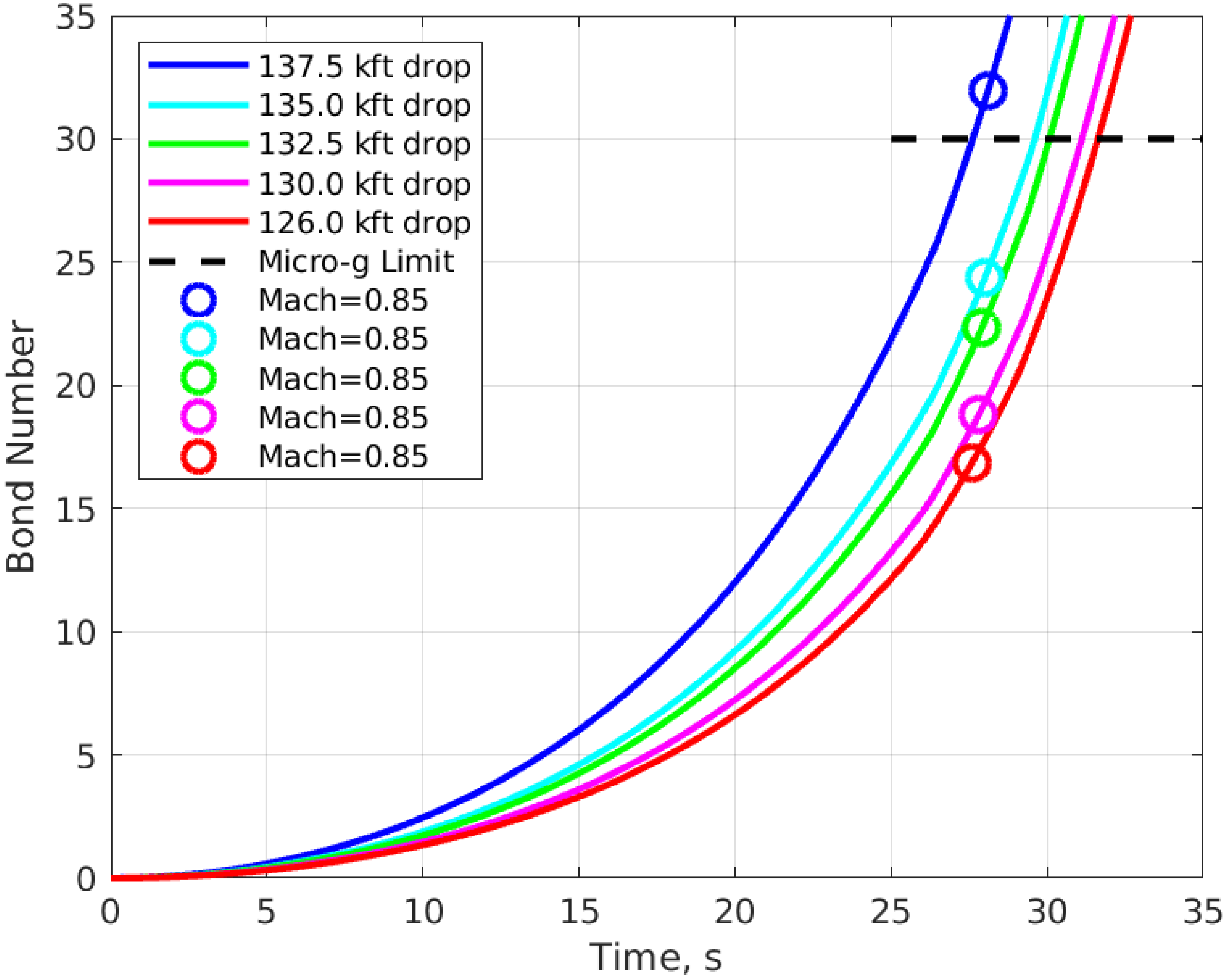
Balloon Sim Results





A parachute is required for a mission flown over populated areas.
Parachute deployment before reaching trans-sonic speed reduces risk.

Balloon Sim Results



Desired Location in the Timeline

- Low-G slosh effects will be minimal for empty or completely full tanks
- Upstream tanks are expected to be nearly empty after the TLI burn, which will render low-g slosh response undetectable
- Request that PTI be implemented when the upstream tanks will be partially full, preferably near 50%
- Possible opportunities after PRB or prior to 3rd Trajectory Correction Maneuver prior to lunar flyby
- A single test is sufficient, but multiple tests are desired

ARTEMIS II

First Crewed Test Flight to the Moon Since Apollo

① **LAUNCH**
Astronauts lift off from pad 39B at Kennedy Space Center.

② **JETTISON SOLID ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**

③ **CORE STAGE MAIN ENGINE CUT OFF**
With separation.

④ **PERIGEE RAISE MANEUVER**

⑤ **APOGEE RAISE BURN TO HIGH EARTH ORBIT**
Begin 23.5 hour checkout of spacecraft.

⑥ **ORION SEPARATION FROM INTERIM CRYOGENIC PROPULSION STAGE (ICPS) FOLLOWED BY PROX OPS DEMO**
Plus manual handling qualities assessment for up to 2 hours.

⑦ **ORION UPPER STAGE SEPARATION (USS) BURN**
Begins high Earth orbit checkout. Life support, exercise, and habitation equipment evaluations.

⑧ **PERIGEE RAISE BURN**

⑨ **TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE**
Lunar free return trajectory initiated with European service module.

⑩ **OUTBOUND TRANSIT TO MOON**
Outbound Trajectory Correction (OTC) burns as necessary for Lunar free return trajectory; travel time approximately 4 days.

⑪ **LUNAR FLYBY**
6,479 miles / 10,427 km (mean) lunar farside altitude.

⑫ **TRANS-EARTH RETURN**
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time approximately 4 days.

⑬ **CREW MODULE SEPARATION FROM SERVICE MODULE**

⑭ **ENTRY INTERFACE (EI)**
Enter Earth's atmosphere.

⑮ **SPLASHDOWN**
Ship recovers astronauts and capsule.