# Persistent Challenges in Aerospace Dynamics and Control Verification and Validation

Jeb S. Orr, PhD
NASA Engineering and Safety Center GN&C Technical Discipline Team
Mclaurin Aerospace (AMA TEAMS 3)

SEPTEMBER 1, 2022

MCLAURIN
AEROSPACE

# Introduction

As a spacefaring society, we have had more than sixty years of experience designing, building, and operating orbital launch vehicles and spacecraft…

Space access is still a hard problem.

- Very complex systems-of-systems: $p_s = \prod p_{sk},\ p_{sk} < 1$
- High energy densities and performance requirements.
- High subsystem interdependence and sensitivity to design changes.

A few pitfalls:

- Low rate of new vehicle development means that knowledge expires from the community and must be re-learned.
- Cost of failure is extremely high – high public visibility & high cost.
- There is no integrated test environment or "envelope expansion" – the full-up flight is the only real test.

# Disclaimer & Acknowledgements

1. All data and case studies are taken from open-literature sources, and cited where appropriate.
2. My technical opinions do not represent the official position of NASA or my employer.


- Neil Dennehy (NESC), Tannen VanZwieten (NESC), John Wall (MSFC/DCI), John Ottander (GuideTech), Rob Hall (Draper), and many others contributed knowledge and experience that is discussed herein.

- Much of the consolidated 1960s literature on slosh is in part due to a collection assembled by the late Bernard Beard of ARES Corporation.

# Common Questions (To Ourselves)

Our community is attempting to realize cost and resource savings by migrating to a Model-Based Engineering (MBE) paradigm, but…

- Why does building high-performance space systems continue to challenge the GN&C and flight dynamics discipline?
- Why does development still require significant investment in test?
- Why can't the difficult features of rocket physics be defeated by advanced control?
- Why can't I buy a commercial software product to design a launch vehicle control system?
- What do I do with all of these poorly-written subsystem requirements?

# Common Questions (From The Chief Engineer)

We thought you were leveraging Model-Based Engineering to realize cost and resource savings…

- Why is the GN&C design so challenging?  Isn't it just a PID controller?
- Why should we have to re-test hardware that we flew on [*prior program*]? What about those flight-validated critical math models?
- Why can't GN&C solve this slosh problem? Can't you just filter it out?
- Why does it take your team 2 years to develop a 6-DoF and the mass properties still have errors?
- What do you mean the requirement isn't verifiable?

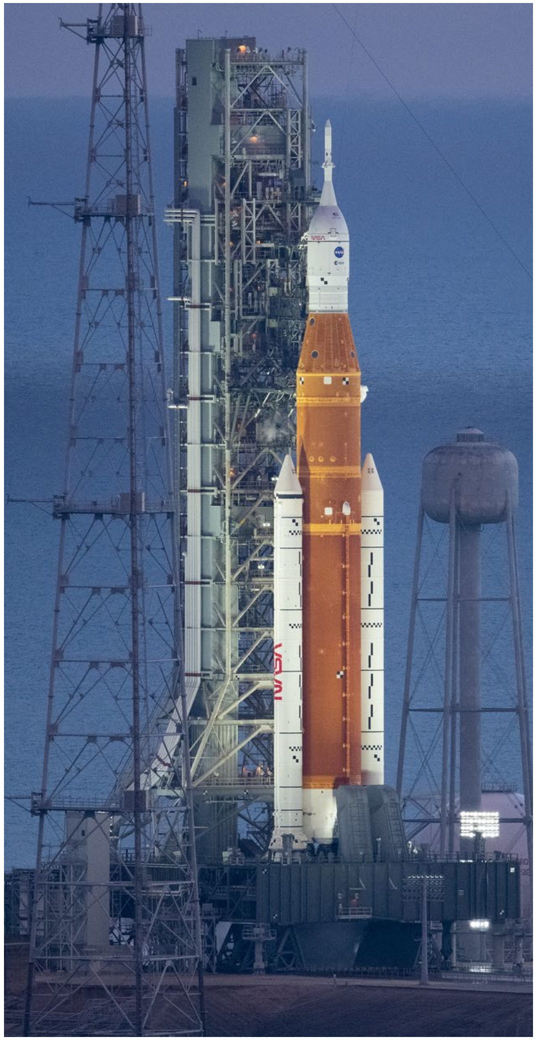
# Key Issues

**Systems that press the limits of physics and rely on all-up testing cannot use encapsulated subsystem designs.**

- SE process must proceed interdependently and simultaneously.
- Lack of margin implies that small changes have wide-reaching impacts.
- High-fidelity model-based engineering is well-suited to such designs.

**Model-based engineering must use rigorous models, not simplified representations or functional specifications.**

- Limitations of model fidelity must be understood and controlled.
- "Heritage" models and assumptions must prove their worth through testing in the relevant new environments.
- Requirements must be statistically verifiable.
- Advanced GN&C cannot solve epistemic problems.




SLS at LC-39B on the morning of 8/29/22
Image: NASA – Public Domain

# Outline

In this talk, we will attempt to answer each of these questions and highlight some persistent challenges in verification and validation.

- We will anchor our discussion with insights regarding slosh dynamics in launch vehicles (and spacecraft).
- First, we'll discuss the motivation with some historical examples.
- We'll review the history of slosh modeling and mitigation.
- Then, we'll talk more about how slosh is really a systems problem.

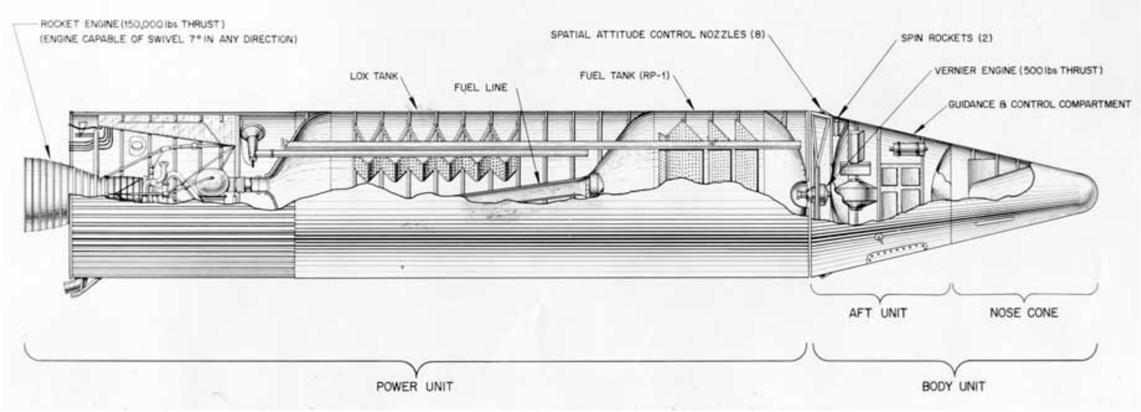
## Some Historical Perspective

# A Wild Propellant Slosh Appears!

**The first notable incident with propellant slosh occurred on the second flight of the Jupiter IRBM[1]**

- AM-1B, April 26, 1957
- Steps in guidance pitch program synchronized and excited the liquid oxygen slosh mode.
- Vehicle lost at maximum dynamic pressure.
- No analytical models had been used in development.
- Early solution was the use of a floating-can type slosh suppressor.

Jupiter AM-1A, March 1, 1957
*(https://history.redstone.army.mil/miss-jupiter.html)*




Later Jupiter configuration showing $LO_2$ accordion baffles
*(https://history.redstone.army.mil/miss-jupiter.html)*

"Some people were never convinced that the second Jupiter lost was due to sloshing. We had only primitive models before the loss in flight. It is difficult to make definitive conclusions without some good analytical models. This problem is still with us in some areas today, thus, exists the dependency on test data alone for those areas where modeling is inaccurate. The lessons keep repeating."

–Harold Scofield (MSFC), in NASA TP-3653

[1] Ryan, R.S., "A History of Aerospace Problems, Their Solutions, Their Lessons," NASA TP-3653, September 1996.

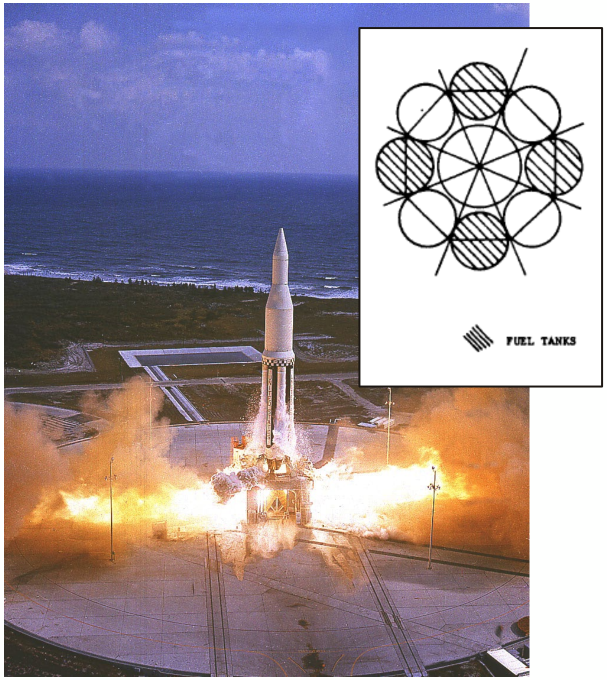
# Four Years Later, on Saturn I

**Slosh coupling with roll makes an appearance**

- Saturn SA-1, October 27, 1961
- More complex, clustered-tank configuration.
- Slosh was modeled and anticipated, but larger than expected, and developed into a nonlinear (rotary) oscillation.
- Engine cutoff occurred early due to vortexing of the propellants.

**The situation leading to this instability was due to late changes in structural attenuation requirements.**

- Roll bending filter updated due to revised uncertainties in the structural models.
- Systems impacts were not fully characterized due to limited resources and/or lack of system-level insight.




Saturn SA-1, October 27, 1961
*Image: NASA – public domain*

"The original… filter was thoroughly investigated… Later, uncertainties in the torsional model arose from the comparison of test results… a last-minute change… resulted in a stronger phase lag. Time did not permit a study of the influence of this change upon sloshing."

- Helmut Bauer (MSFC), NASA TM-X-50497, March 1962

[2] Bauer, H.F., "Propellant Sloshing Problems of Saturn Test Flight SA-1," NASA TM-X-50497, March 20, 1962.

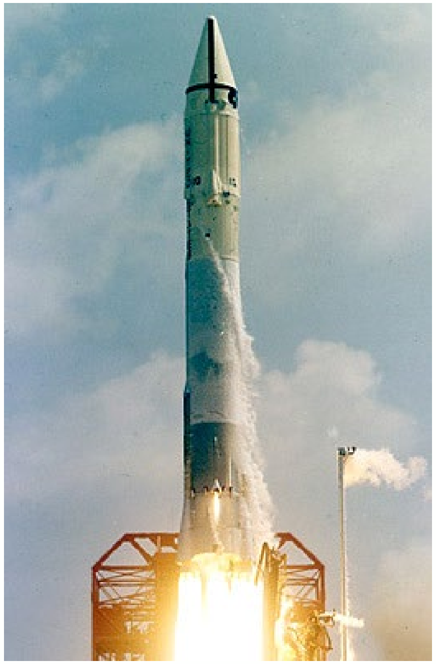
# Three Years Later, on Atlas-Centaur

## Unexpected venting causes loss of attitude control

- Atlas-Centaur AC-4, December 12, 1964
- Successful orbit injection of a Surveyor mass simulator followed by a restart attempt.
- $LH_2$ crashover after engine shutdown.
- $LH_2$ liquid venting forces overwhelmed RCS.
- Vehicle entered uncontrolled tumble and residual $LH_2$ was depleted.

## Although the proximate cause was a propellant management issue, this was an SE issue:

- Ullage jets were insufficient to settle propellants.
- Ullage plume interference (aerodynamics).
- Structural-dynamic-propellant interactions.
- Insufficient modeling of low Bond number liquid dynamics.



Atlas-LV3C Surveyor 1, March 3, 1965
*(Image: NASA – Public Domain)*

> "Failure to settle the liquid hydrogen at the time of venting resulted in venting of mixed-phase or liquid flow, which, on expanding from the vent exits, produced high impingement forces in excess of the attitude control system capability, and the vehicle tumbled out of control."
>
> \- NASA TM X-1189, December 1965.

[3] Szabo, et al., "Atlas-Centaur Flight AC-4 Coast-Phase Propellant and Vehicle Behavior," NASA TM X-1189, December 1965.

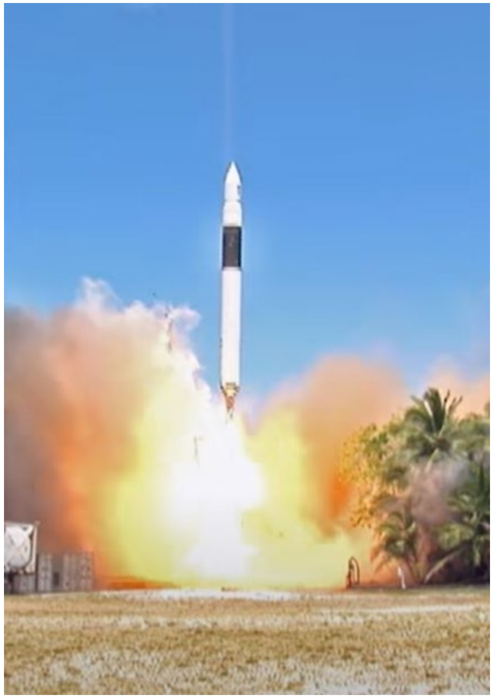
# Forty-Three Years Later, on SpaceX Falcon 1

**Unexpected sloshing causes loss of roll control.**

- T+90s due to guidance transient, which induced a slosh perturbation in the $LO_2$ tank.
- Slosh coupled in pitch and yaw and continued until converting into a rotary mode.
- Rotary mode overwhelmed roll control actuator.
- *"High confidence that LOX slosh was the primary contributor."*

**This was a classic coupled slosh-flight control instability, but was a systems issue:**

- Preflight models did not account for envelope of initial slosh disturbances from the guidance system.
- Baffles were not included in the design.
- Risk was judged to be negligible compared with mass impacts.



SpaceX Falcon 1 – Demo Flight 2
*(Image: SpaceX/YouTube – Public Domain)*

"Falcon 1 did not use slosh baffles in the second stage tanks, as simulations done prior to flight indicated the slosh instability was a low risk. Given that in space there are no gust or buffet effects, the simulations did not take into account a perturbation, as occurred due to the hard slew maneuver after stage separation. Extensive 2nd stage slosh baffles will be included in all future flights, as is currently the case with the 1st stage." – SpaceX [4]

[4] Demo Flight 2 Flight Review Update, Space Exploration Technologies Corporation, June 15, 2007. (DARPA – Public Domain)

# Systems Perspective

Recurring Themes:

1. Non-existent or insufficient modeling.
2. Under-conservative assumptions or risk posture.
3. Lack of appreciation of subsystem interdependencies.
4. “Systems pressure” to avoid mass-intensive design solutions.

How can fully-integrated MBE help us avoid repeating history?

1. Identify that there is, or could be, a problem.
2. Design a solution, with margin, in a low-risk, cost-effective way.*
3. Verify, with confidence, that the solution is effective.

*Hint: it’s almost always baffles.

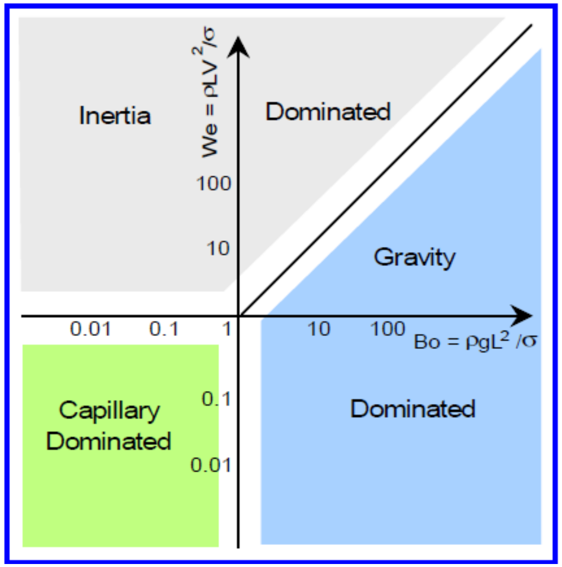
## Introduction to Flow Regimes and Mechanical Models

# Sloshing Liquid Flow Regimes

Dynamic fluid phenomena can be broadly classified by Bond and Weber number:

$$Bo = \frac{\rho \bar{g} a^2}{\sigma} \qquad We = \frac{\rho v^2 a}{\sigma}$$

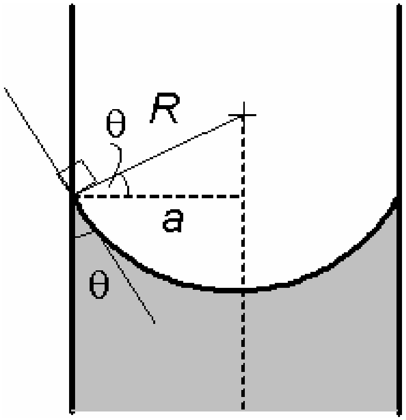
- Bond number is used to describe the transition into gravity-dominated flows (high-G slosh).
- Weber number is used to describe the transition into capillary-dominated flows (i.e., PMDs).




Dodge [5]

The parameters are:

- Mean or quasi-steady axial acceleration $\bar{g}$
- Characteristic length or cylinder radius *a* and velocity *v*
- Fluid density $\rho$, surface tension $\sigma$.
- A critical parameter for the capillary regime is the contact angle, which depends on surface tension, materials, and temperature.




Dodge [5]

[5] Dodge, *The New Dynamic Behavior of Liquids in Moving Containers,* Southwest Research Institute, 2000

# Transition from Gravity Flow Regime to Zero-G

## High-G slosh (Bo>1000)

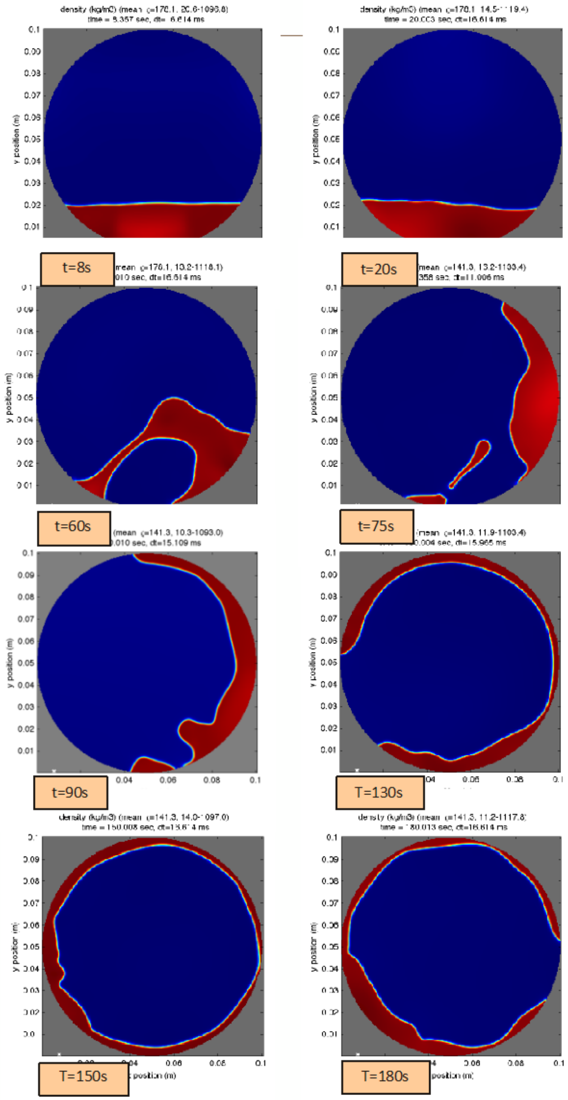
- Flat free surface (contact angle $\theta = \frac{\pi}{2}$)
- Extensive test-correlated analytical models for common geometries.
    - Spring-mass model, pendulum models, etc.
- Very good agreement for linear and some nonlinear motions (e.g., rotary).

## Low-G slosh (~30<Bo<1000)

- Curved interface (minimum potential energy)
- Corrections to mechanical models for linear motions.
- Relatively long time scales (100s of seconds).

## Microgravity slosh (Bo<~30)

- All bets are off – use CFD solutions, then settle the propellant.
- Concerned with maintaining interface stability.
- Basic questions: “Where is the propellant?”




1g to 0g dynamics of $LO_2$ in a 10 cm domain
Orr and Powers, “Lattice Boltzmann Method for Simulation of Propellant Dynamics in Microgravity,” ESSSA-FY15-1718, 2015.

# Low-G Regime (Bo < 100)

Example in a 10 cm diameter container (coffee cup)

- Liquid oxygen at 94K ($\sigma = 0.0122\,\mathrm{N/m}$)
- Acceleration magnitude ~0.001 $g$

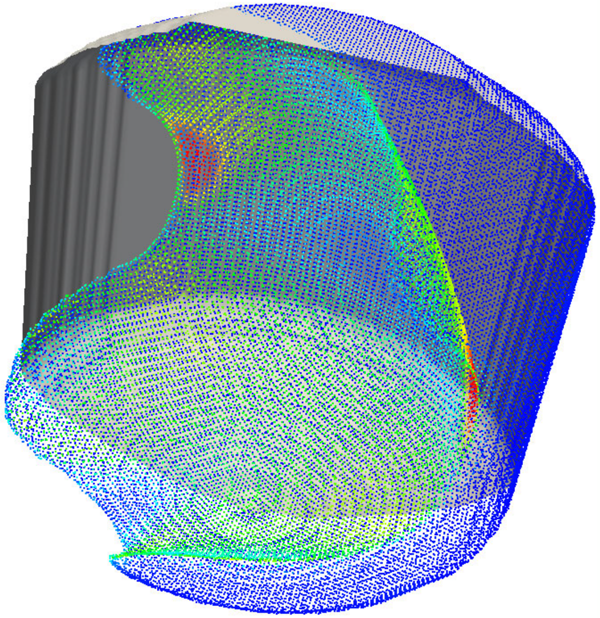
$$Bo = \frac{\rho \bar{g} a^2}{\sigma} \approx 2.3$$

- *Characteristic time*[5] $T = \sqrt{\frac{\rho a^3}{\sigma}} \approx 3.4\,\mathrm{s}$

Example in a 1 m diameter spacecraft tank

- Acceleration magnitude ~0.0002 $g$ (i.e., venting)

$$Bo = \frac{\rho \bar{g} a^2}{\sigma} \approx 45 \qquad T = \sqrt{\frac{\rho a^3}{\sigma}} \approx 100\,\mathrm{s}$$



1m diameter tank with $LO_2$ after lateral acceleration
Orr and Powers, "Lattice Boltzmann Method for Simulation of Propellant Dynamics in Microgravity," ESSSA-FY15-1718, 2015.

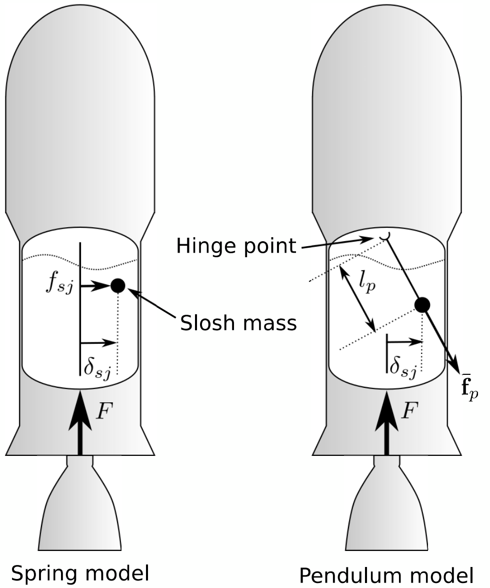
For linear motions, even very low G conditions still have Bond numbers large enough to use mechanical models.

[5] Dodge, *The New Dynamic Behavior of Liquids in Moving Containers,* Southwest Research Institute, 2000

# Mechanical Spring-Mass Analog for Propellant Slosh

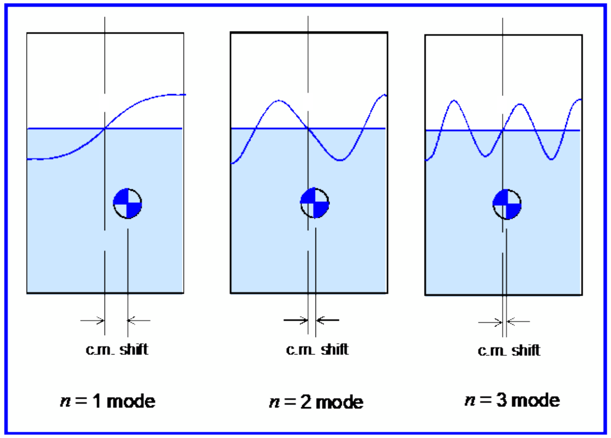
A spring-mass mechanical analog is an established method for modeling liquid dynamics (Bo>30).

- Primarily for axisymmetric, cylindrical tanks.
- Models exist for rectangular, spherical, conical, radially & annular segmented tanks.
- Usually concerned with only the first few modes.




Assumptions (cylindrical tank):

- Irrotational, incompressible fluid in a *rigid*, *flat-bottom* tank.
- No inherent damping (inviscid fluid, must be added later).
- Solved via the velocity potential function φ (Laplace eq.)
  - Subject to boundary conditions at wall and free surface.
  - A periodic solution is assumed to solve the PDE.




Dodge [5]

Excellent correlation with test for *linear* motion!

# Mechanical Spring-Mass (Continued)

For axisymmetric cylindrical tanks in the barrel section:

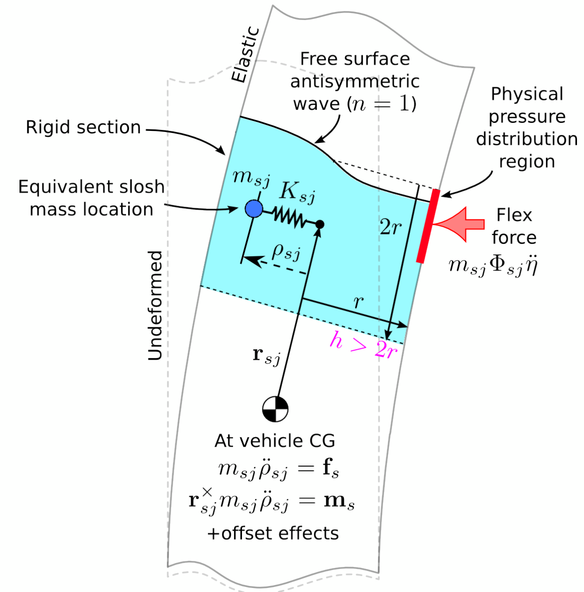
$$\omega_n = \sqrt{\frac{\bar{g}}{a}\tanh\left(\epsilon_n \frac{h}{a}\right)} \qquad \epsilon_n \triangleq \{\epsilon \ni J_1'(\epsilon) = 0\}$$

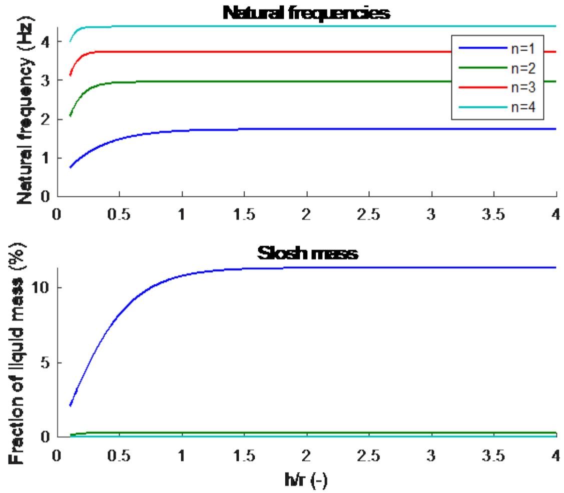
- Equivalent mechanical parameters can be extracted.

$$m_n = 2m_L \frac{\tanh(\epsilon_n \frac{h}{a})}{\epsilon_n \frac{h}{a}(\epsilon_n^2 - 1)} \qquad \begin{aligned} k_n &= m_n \omega_n^2 \\ d_n &= 2m_n \zeta_n \omega_n \end{aligned}$$

- An equivalent set of parameters exists for a linear pendulum.
- In any *section* of the tank where $h > 2a$, the fluid cannot "see" the flat bottom.
- Numerical solutions are available for other geometries.[7]
- Corrections are included for low Bo (curved interfaces).

Many other more sophisticated and <u>nonlinear</u> models exist.




[6] Fontenot, L. L., NASA CR-941, Dynamic Stability of Space Vehicles, Volume VII – The Dynamics of Liquids in Fixed and Moving Containers, March 1968.
[7] Lomen, D.O., "Liquid Propellant Sloshing in Mobile Tanks of Arbitrary Shape," NASA CR-222, 1965.

# Systems Perspective

We have established and well-understood models and decades of experience.

1. How do we use them?
2. Equally important: how do we not misuse them?

## The Systems Coupling Dilemma

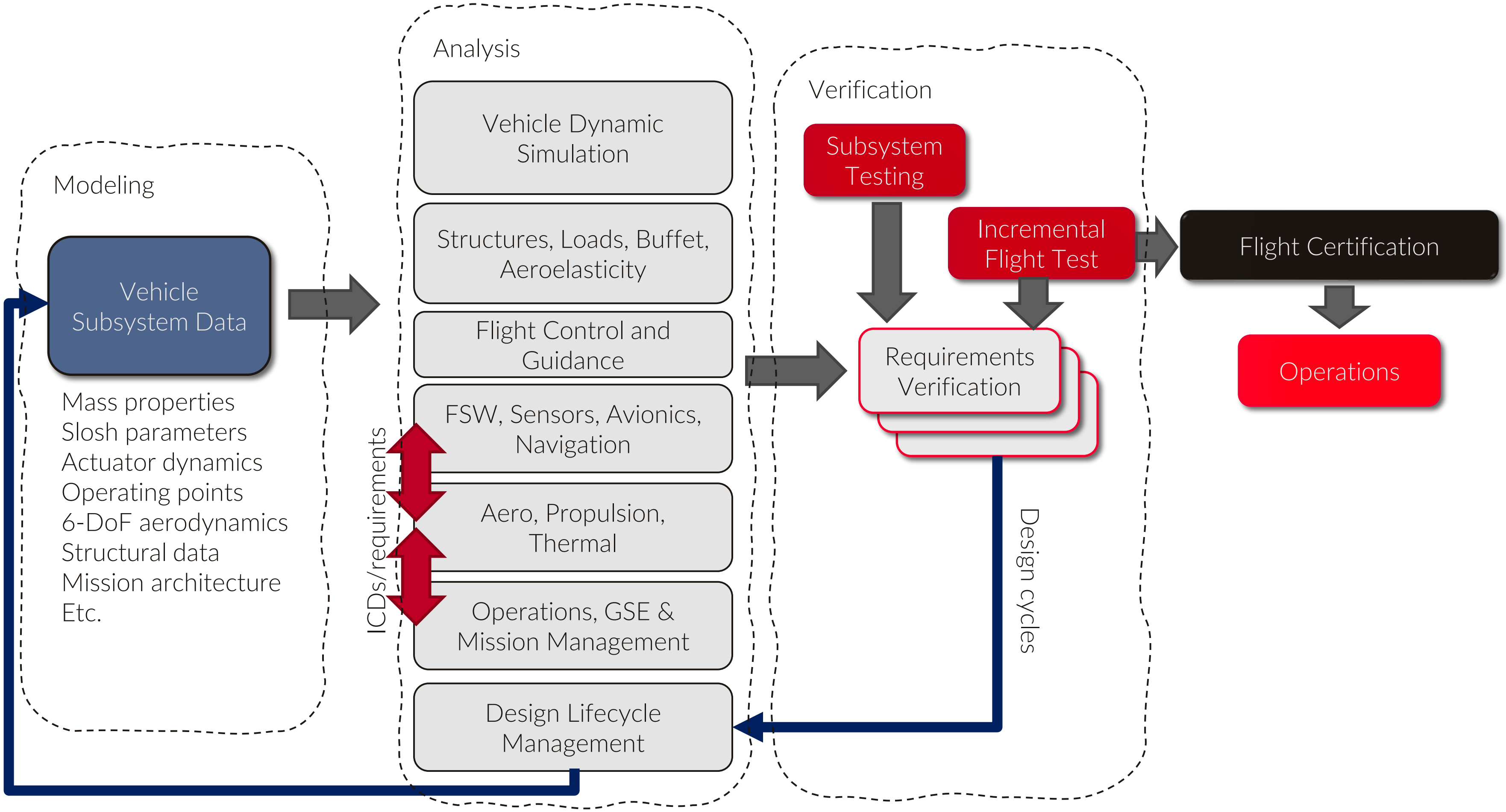
1. Some amount of damping is required for slosh suppression.
2. Ring baffles have a cost, mass, thermal, and propellant volume penalty.
3. Structure must be designed early in the program lifecycle.
4. Slosh mode parameters are dependent on tank radius, acceleration, fill level, etc.
5. Control system is dependent on actuators, bending, latency, etc.
6. Acceleration is dependent on mass, propulsion, aerodynamics, trajectory, month of launch…

## Persistent Challenges

# V&V Insights

**Traditional SE processes carefully manage requirements via margin allocation.**

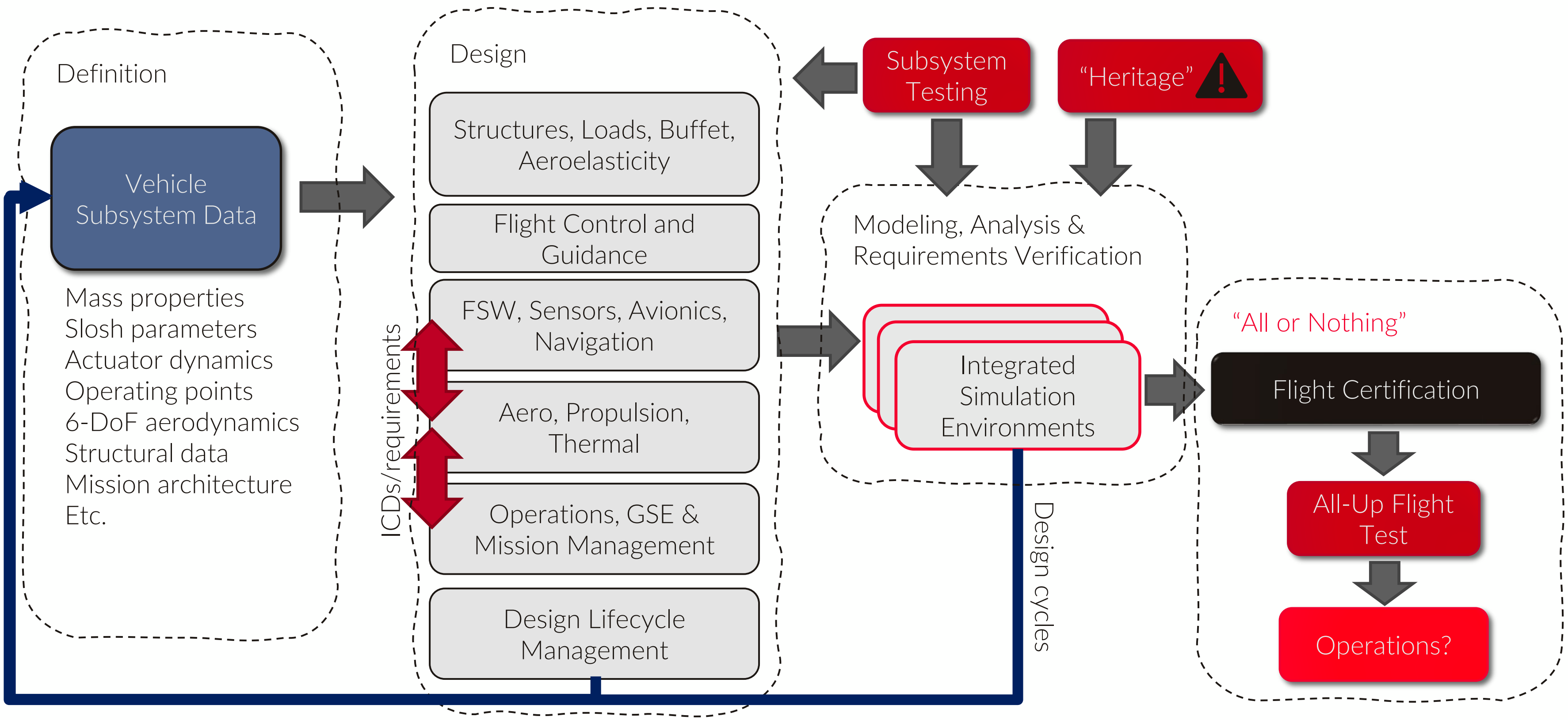
- Subsystem interfaces can be defined "on paper" or via functional specs.
- Margins preclude unintended consequences through the entire lifecycle.



# V&V Insights in the "Big Rocket" Environment

**The structure of an MBE environment *can* allow SE to uncover hidden dependencies.**

- This becomes necessary when the requirements do not allow for margin.
- How much fidelity is enough fidelity?
- How do we manage & allocate uncertainties?



# Challenge: GN&C Capability (Physics)

*Why is the GN&C design so challenging? Isn't it just a PID controller?*
*Why can't GN&C solve this slosh problem? Can't you just filter it out?*

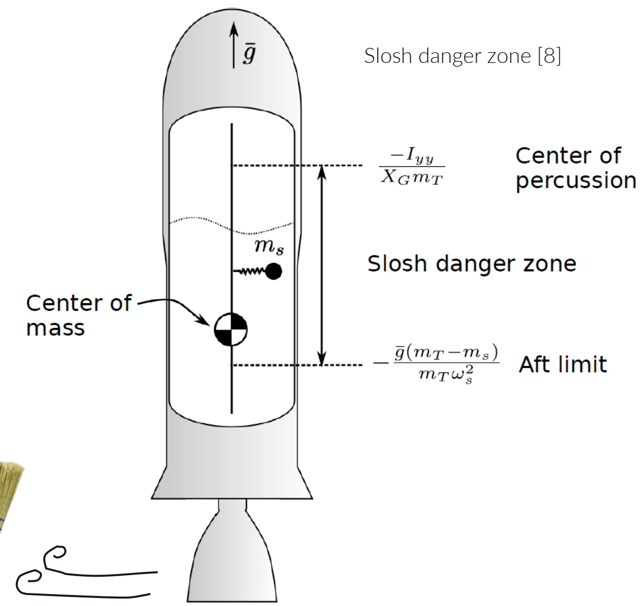
## Physical limitations in the dynamics

- Fundamentally unstable, low damping.
- Non-minimum phase, time-varying nonlinear dynamics.
- Model fidelity and test experience is limited to linear regimes.
- Secondary impacts (propellant management, cryo-thermal).
- Tank and baffle loads.

## Many programs encounter slosh challenges and "analyze to death" at great cost.

- All roads lead to baffles.
- MBE can help identify when more analysis will not make the physics better.

Slosh danger zone [8]




Control input: Broom handle forces

> "Flying a rocket is like balancing a broomstick, except the broomstick is super flexible, has pitchers of volatiles sloshing around, is constantly getting lighter, the handle is hinged, and it's very windy."
>
> – John Wall, SLS Flight Control

[8] H.F. Bauer, Fluid Oscillations in Containers of a Space Vehicle and Their Influence on Stability, Tech. Rep. TR-R-187, NASA, Feb. 1964.

# Challenge: Knowledge Transfer & Validity

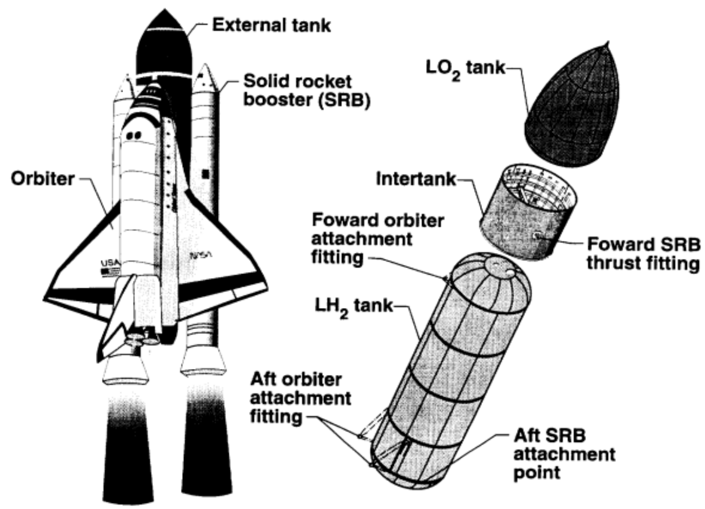
*Why should we have to re-test hardware that we flew on [prior program]? What about those flight-validated critical math models?*

Alarms go off in the mind of any GN&C engineer.

- "Heritage" actually means "insufficient testing planned to validate an existing design in a new environment."

Early SLS designs assumed that 3 baffles would be sufficient in the SLS $LO_2$ tank.

- Each baffle weighed more than 200 kg.[9]
- Baffles were reduced over the life of the program to save mass.[10,11]
- However, the original system had 8 baffles and they were reduced in number over 91 flights!
- The baffle design was highly optimized to the STS configuration and was not applicable to SLS.




Nemeth [9]

[9] Nemeth, et al., "Nonlinear Analysis of the Space Shuttle Super-Lightweight External Fuel Tank," AIAA 96-1552, April 1996.
[10] Use of Higher-Fidelity Slosh Models to Reduce Conservatism in Launch Vehicle Flight Control Designs," 2015 Aerospace Control and Guidance Systems Committee Meeting, NASA DAA M16-4921.
[11] Coldwater, H.R. et al., "Space Shuttle External Tank Performance Improvements – The Challenge," Space Shuttle Technical Conference, NASA CP-2342, N85-16889, 1985.

# Challenge: M&S Development

*Why does it take your team 2 years to develop a 6-DoF and the mass properties still have errors?*

Aerospace engineers must now also be software engineers!

The launch vehicle and spacecraft M&S community still requires discipline-specific custom dynamics models.

- Multibody flexible system, time-varying mass, etc.
- Some domain knowledge is not documented or available in the open literature.
- Desire to run in real time or generate lots of MC results quickly.

Modeling software is custom-built to make the problem:

1. Tractable
2. Transparent
3. Useful for design
4. Domain-specific (e.g., SWIL vs. flight dynamics)

However, we are still plagued by the same problems in verification:

- …consistency in definition of coordinate frames and unit systems.

# Challenge: Writing Verifiable Requirements

*What do you mean the requirement isn't verifiable?*

Real example of a poorly written requirement:

- "The air data system shall provide an estimate of $\alpha$ with a $3\sigma$ error within $\pm 1$ degree."

The requirement is ambiguous and allows an analyst to speculate.

- The requirement is not formally verifiable.
- Inevitably the contractor will use the verification method that is <u>least costly</u>.

A better (more verifiable) requirement might read:

- "The air data system shall provide an estimate of $\alpha$ with 99.865% maximum error (taken over all time from flight condition A to flight condition B) less than 1 degree absolute with 90% confidence. A procedure for verifying the requirement using simulation data is documented in Appendix X."

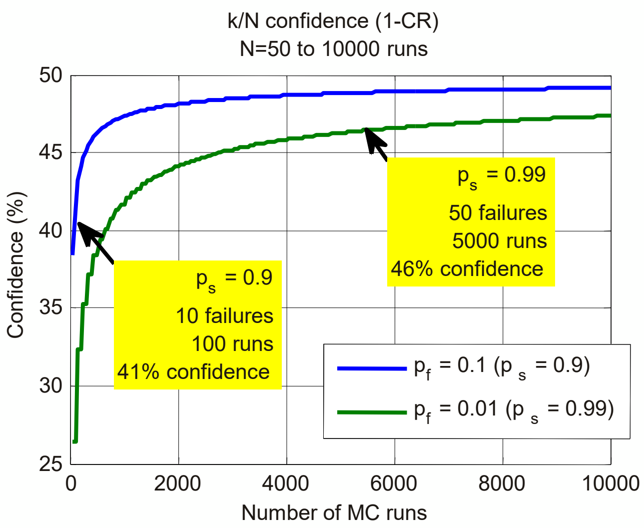
*Derivation* of requirements can leverage engineering judgment, but *verification* should not.

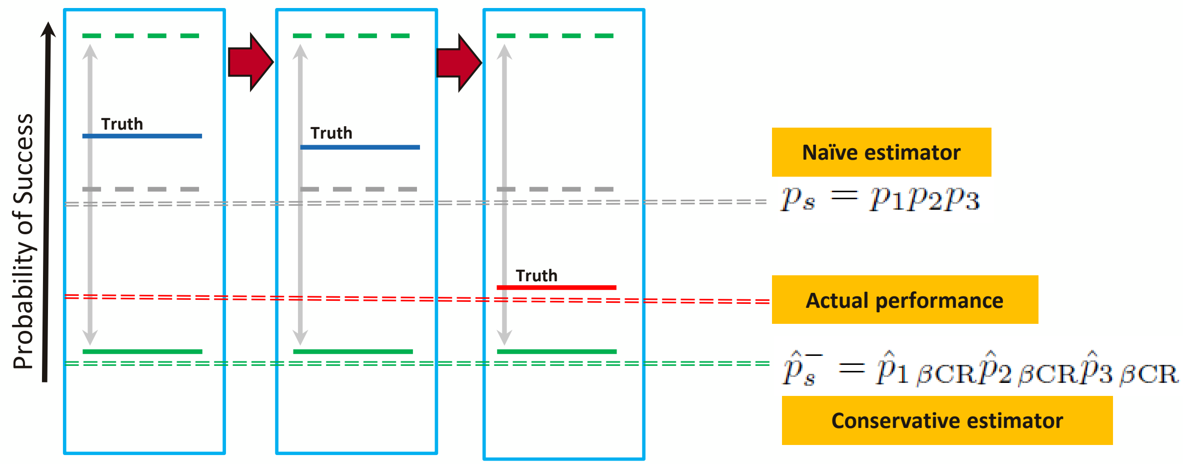
# Challenge: Allocation of Uncertainty

Consistent and uniform program-level guidance is necessary to control risk.

- Subsystem requirements can be derived from end-to-end performance, or vice versa.
- Interpretation and utilization of reliability estimates and/or subsystem performance data must be centrally informed.
- Monte Carlo-based verification of subsystem and system-level performance should rely on rigorous sampling plans.

> Both requirements and uncertainties should be optimally allocated to subsystems to minimize cost. **This is not a solved problem.**



# NASA Constellation Case Study

## NASA's Constellation Program developed the Ares I Launch Vehicle.

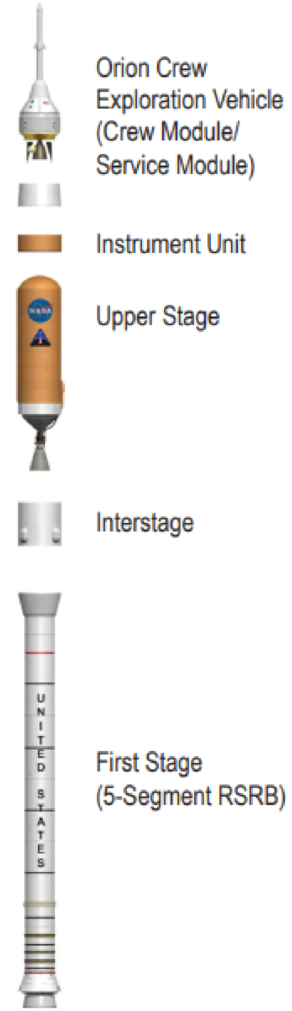
- A test flight with a simulated upper stage was flown in 2009 (Ares I-X).

## Payload tank slosh was identified as a risk.

- Payload tanks had been designed without baffles.
  - There was no requirement because it had not been analyzed, and it was assumed the tanks would be full.
  - Fluid properties, material compatibility, and manufacturing challenges were a major factor.
- Slosh coupled with FCS, bending, and rigid-body dynamics on a very long (94 m) structure.

## At first, few believed that such small tanks could cause an issue, even with smooth walls.

- It was eventually recommended that baffles be retrofit and installed.
- It may have been possible to fly with nonlinear fluid motion, but not at an acceptable risk.




Ares I Launch Vehicle
*Image: NASA – public domain*

Ares I-X FTV, October 28, 2009
*Image: NASA – public domain*

# Concluding Remarks

As we continue toward a model-based paradigm, we can realize benefits:

- Reduced cost & complexity in requirements development & verification.
- Ability to uncover and assess hidden interactions.
- Support a framework for optimal allocation of margins & uncertainties.

MBE (and GN&C) can not address epistemic problems.

- Expert insight and past experience must still be used to uncover issues.
- We will always need to "test like you fly, fly like you test."

The GN&C and academic community must also invest in software engineering.

- We are finding it easier to train computer scientists to be aerospace engineers.