

National Aeronautics and Space Administration

SPACE LAUNCH SYSTEM

Contributions of Engineering Risk Assessment to the Artemis Program

Advanced Modeling & Simulation (AMS) Seminar Series
https://www.nas.nasa.gov/pubs/ams.html

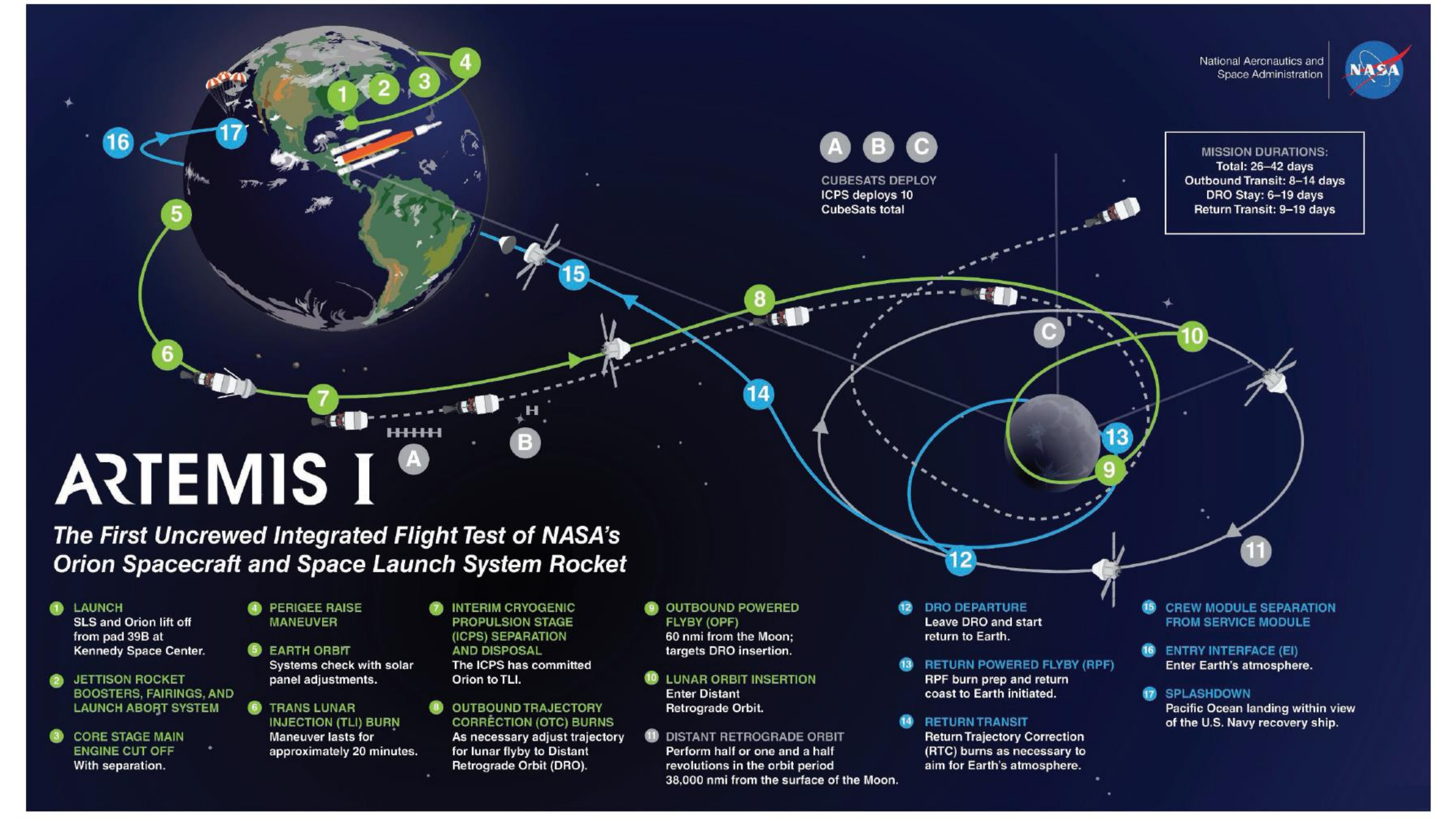
April 21, 2022

Scott Lawrence

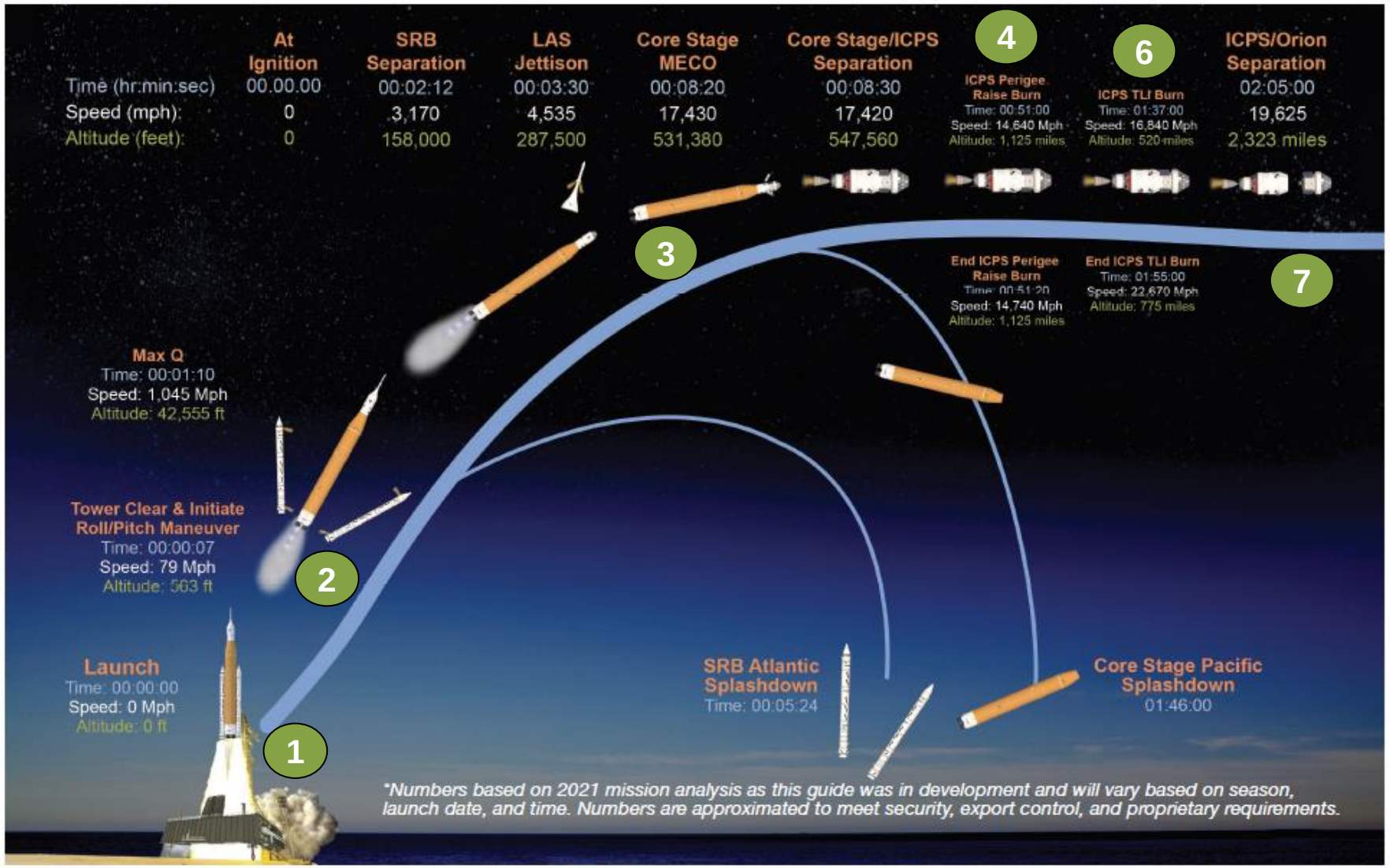
Current ERA Team
Donovan Mathias
Ken Gee
Ashley Coates
Lorien Wheeler
Darrel Robertson
Gregoire Chomette

On-Site Former ERA
Susie Go
Ted Manning
Jerry Yan

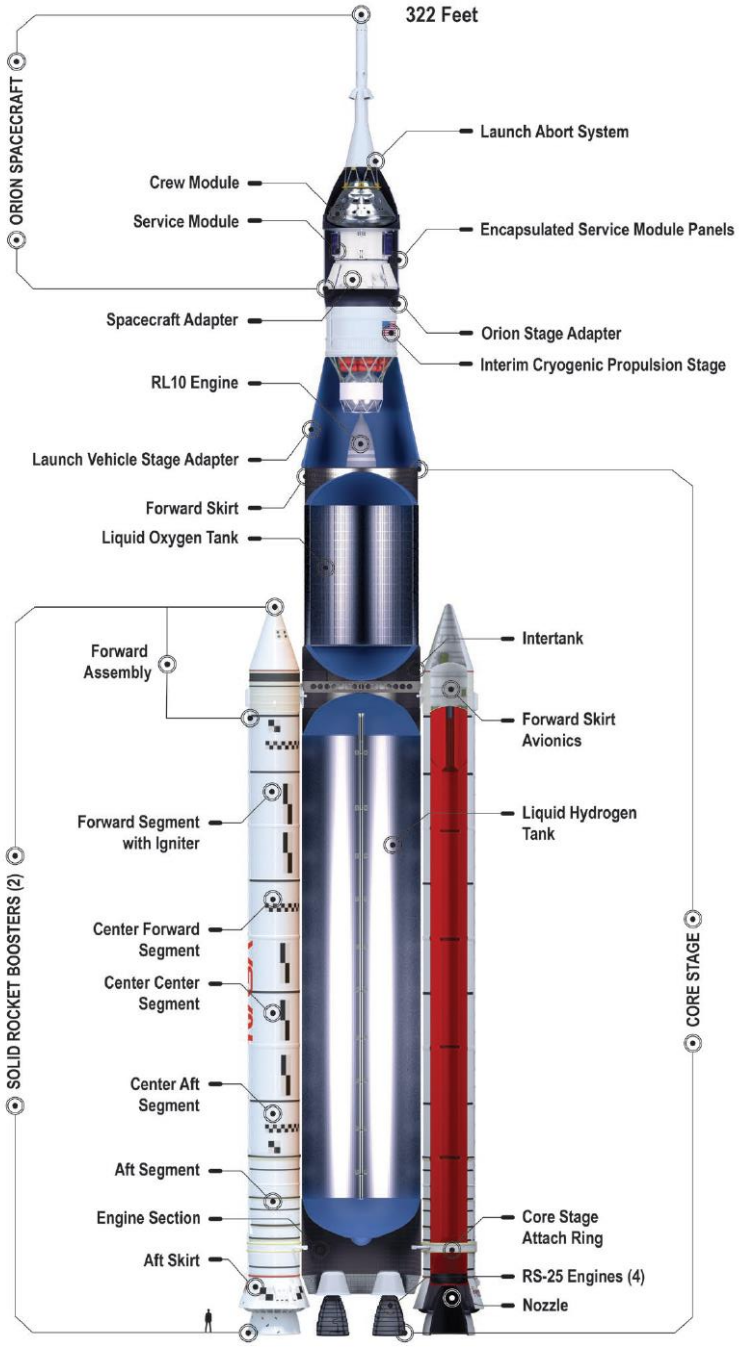
MSFC Team
Andrew Herron (IE DLE)
James Blackwood (IE/Abort Env SDLE)
Troy Skinner
Michael Hayes


National Aeronautics and Space Administration
NASA
A B C
CUBESATS DEPLOY
ICPS deploys 10 CubeSats total
MISSION DURATIONS:
Total: 26–42 days
Outbound Transit: 8–14 days
DRO Stay: 6–19 days
Return Transit: 9–19 days
ARTEMIS I
The First Uncrewed Integrated Flight Test of NASA's Orion Spacecraft and Space Launch System Rocket
1 LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center.
2 JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM
3 CORE STAGE MAIN ENGINE CUT OFF
With separation.
4 PERIGEE RAISE MANEUVER
5 EARTH ORBIT
Systems check with solar panel adjustments.
6 TRANS LUNAR INJECTION (TLI) BURN
Maneuver lasts for approximately 20 minutes.
7 INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL
The ICPS has committed Orion to TLI.
8 OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).
9 OUTBOUND POWERED FLYBY (OPF)
60 nmi from the Moon; targets DRO insertion.
10 LUNAR ORBIT INSERTION
Enter Distant Retrograde Orbit.
11 DISTANT RETROGRADE ORBIT
Perform half or one and a half revolutions in the orbit period 38,000 nmi from the surface of the Moon.
12 DRO DEPARTURE
Leave DRO and start return to Earth.
13 RETURN POWERED FLYBY (RPF)
RPF burn prep and return coast to Earth initiated.
14 RETURN TRANSIT
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere.
15 CREW MODULE SEPARATION FROM SERVICE MODULE
16 ENTRY INTERFACE (EI)
Enter Earth's atmosphere.
17 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ship.

Artemis I: SLS Flight Profile



Elements of SLS and Orion

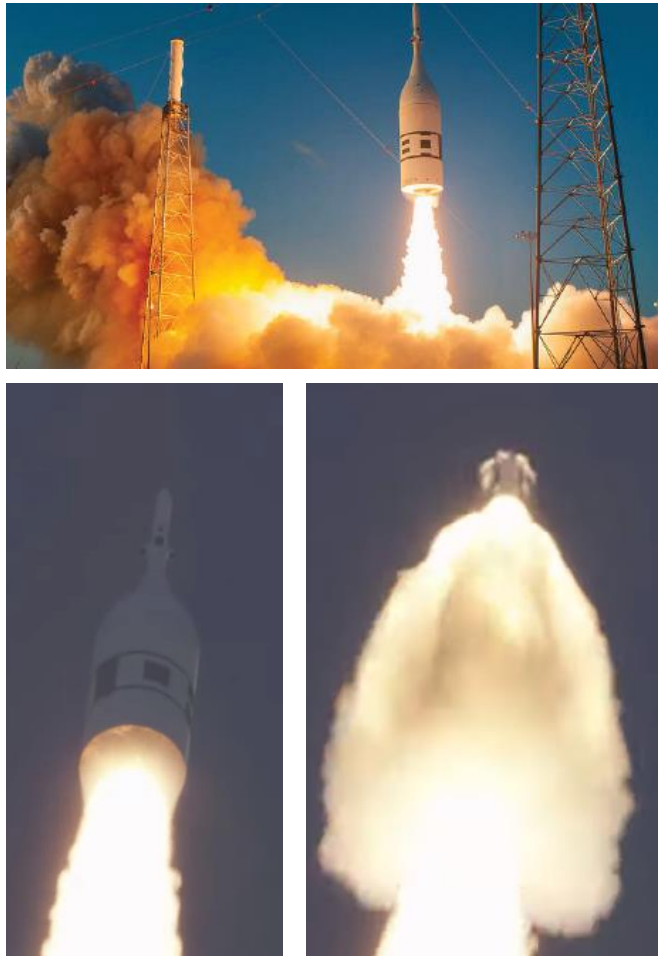


Abort System

- **Part of the design intended to isolate crew from launch vehicle failure risks**
- **Components**
  - Launch Abort Vehicle (LAV):
    Orion Crew Module + Launch Abort System (LAS)
    - Aero, structures, flight dynamics, …
    - Service Module (high-altitude)
  - Failure detection
    - On-board (SLS and Orion detection)
    - Crew
    - Ground
- **Modes:**
  - LAS abort: dynamic
  - SM abort: not dynamic
- **Ideally, this mission never gets flown**



[Service Module Abort]



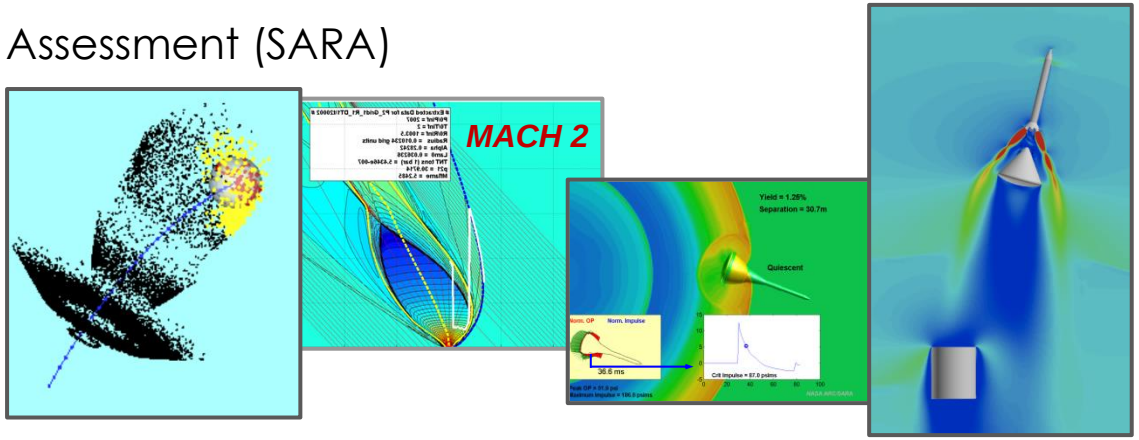
[LAS Abort]



Engineering Risk Assessment (ERA)

- **Goal: Fortify more traditional risk assessment methods with information from physics-based modeling and simulation**

- **Program Support**
  - Pre-Constellation/Constellation: Simulation-Assisted Risk Assessment (SARA)
    - More of a modeling archeology effort
      - Coding mainly Apollo-era models in VBA (Excel) and Matlab
    - Exceptions:
      - Debris strike probabilities
      - Vehicle velocity effects on blast propagation
      - Orion overpressure vulnerability estimates
      - 6-DOF Overflow of LAV separation



  - Commercial
    - SpaceX
    - Sierra Nevada
    - Boeing
    - Stratolaunch



  - SLS/Artemis: Engineering Risk Assessment (ERA)

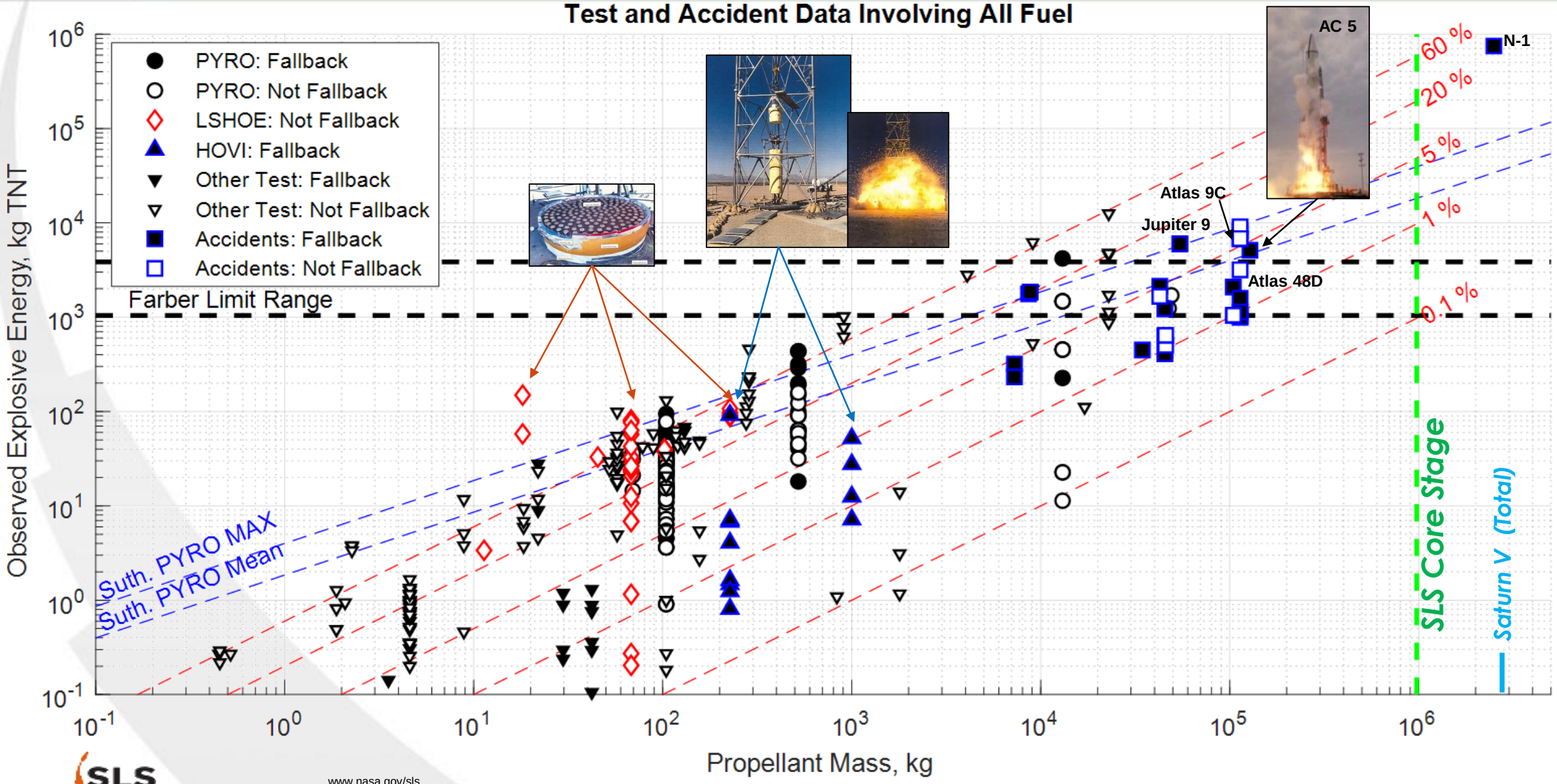
Probabilistic Risk Assessment

- **What can go wrong?** ***SLS PRA***
  - Frequency (probabilistic), by cause
  - Flight conditions (mission phases)
  - Initial failure manifestation

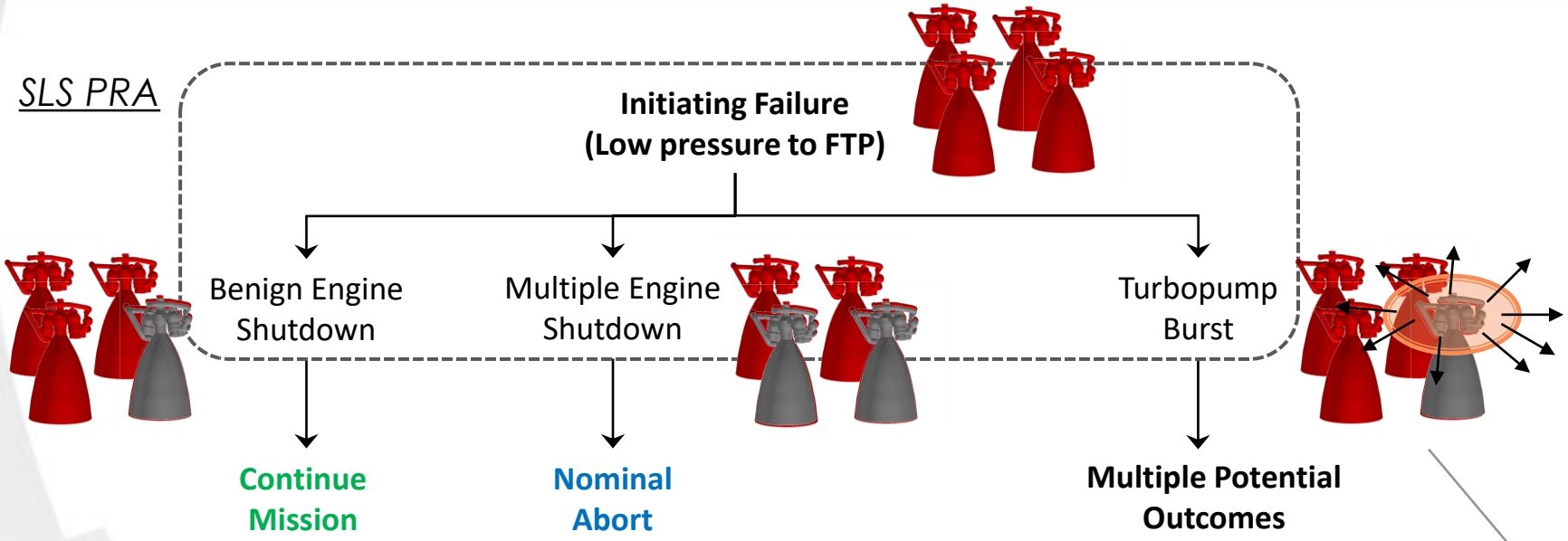
- **What are the consequences?** ***Multiple, including ERA***
  - Continue mission
    - Redundancy
  - Reduced mission
  - Loss of mission [LOM]
  - Loss of crew [LOC] (Art I: Loss of vehicle [LOV])

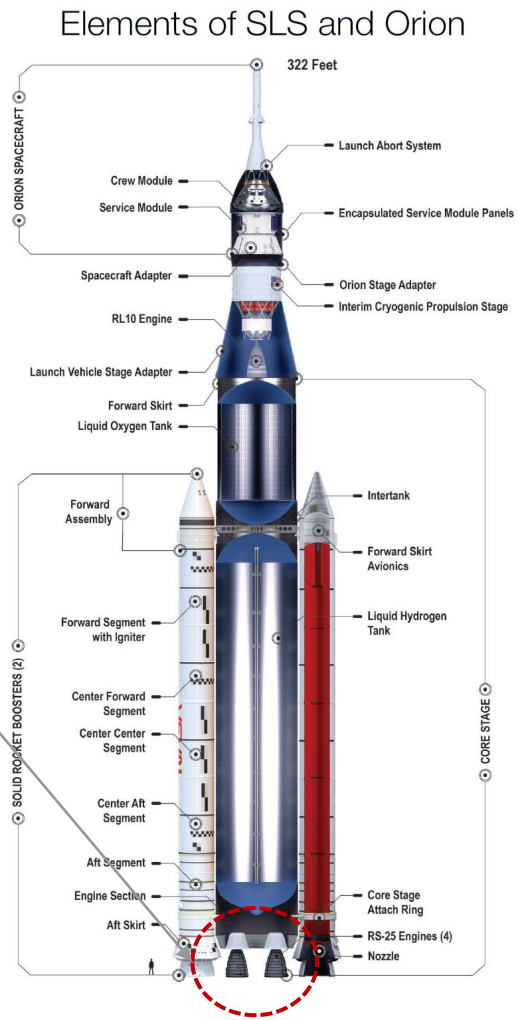
- **Uncertainty dominates: Fidelity balancing**
  - Epistemic: knowledge shortage
  - Aleatory: natural variability, sensitivity

Chemical Energy Release: Test and Accident Data



An Example: Core Engine Failure





Contributing Groups

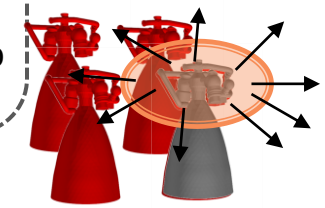
- SLS Probabilistic Risk Assessment (PRA)
- SLS Mission & Fault Management (M&FM)
- SLS Induced Environments (IE)
  - Abort Environments
    - MSFC
    - ARC/ERA

An Example Continued: Abortability Defined

SLS PRA

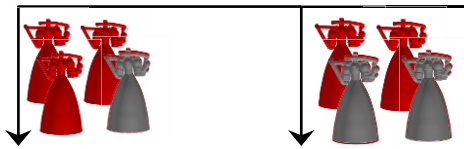
Initiating Failure
(Low pressure to FTP)

- Benign Engine Shutdown
- Multiple Engine Shutdown
- Turbopump Burst

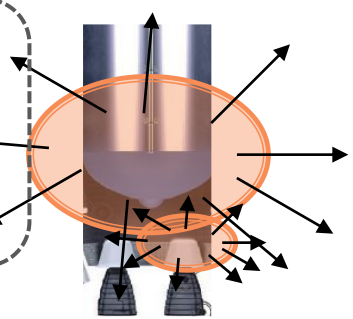


Local "explosion"

ERA Failure Propagation



- No Propagation
- Other Engine Shutdown
- Stage Explosion



Large scale explosion

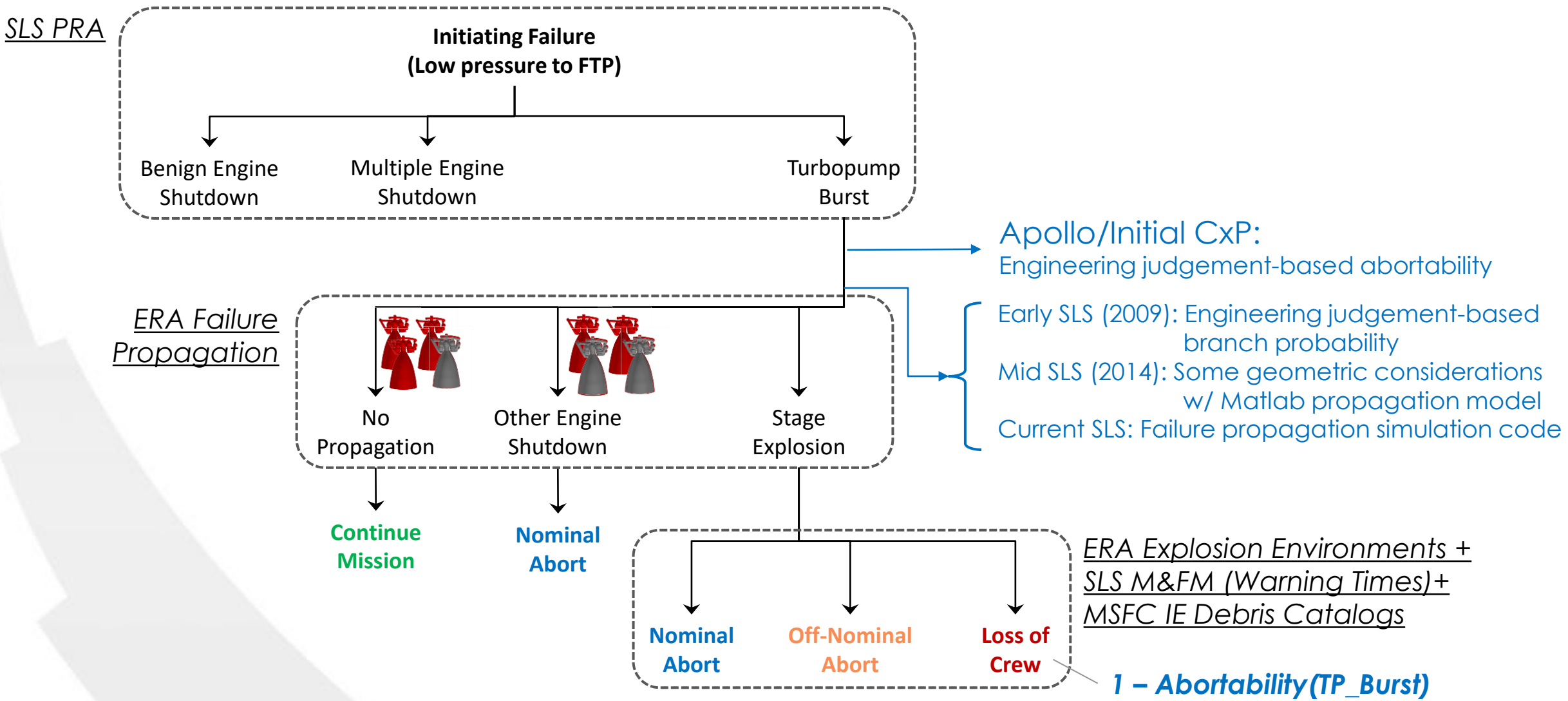
- **Continue Mission**
- **Nominal Abort**
- **Nominal Abort**
- **Off-Nominal Abort**
- **Loss of Crew**

ERA Explosion Environments + SLS M&FM (Warning Times)+ MSFC IE Debris Catalogs

1 – Abortability(TP_Burst)

Potential LOC, but do not count against abortability

An Example: Failure Propagation History

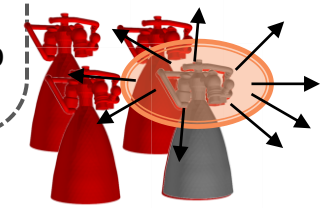


An Example Continued: Conclusions

SLS PRA

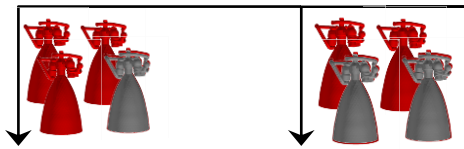
Initiating Failure
(Low pressure to FTP)

- Benign Engine Shutdown
- Multiple Engine Shutdown
- Turbopump Burst



Local "explosion"

ERA Failure Propagation



- No Propagation
- Other Engine Shutdown
- Stage Explosion — X

High (good) abortability from one or more:
- Low propagation to stage explosion
- Weak stage explosions
- Early detection

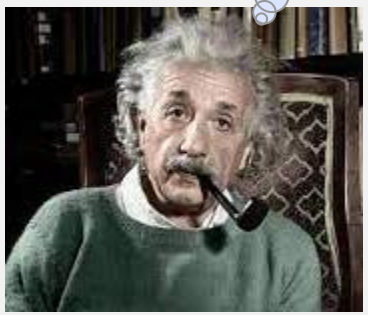
- **Continue Mission**
- **Nominal Abort**
- Stage Explosion — X
  - **Nominal Abort**
  - **Off-Nominal Abort**
  - **Loss of Crew**

ERA Explosion Environments + SLS M&FM (Warning Times)+ MSFC IE Debris Catalogs

1 – Abortability(TP_Burst)

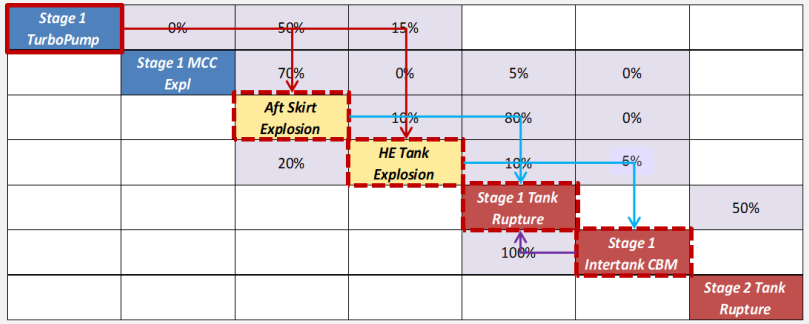
Potential LOC, but do not count against abortability

Evolution of ERA Failure Propagation Analysis



Engineering Judgment

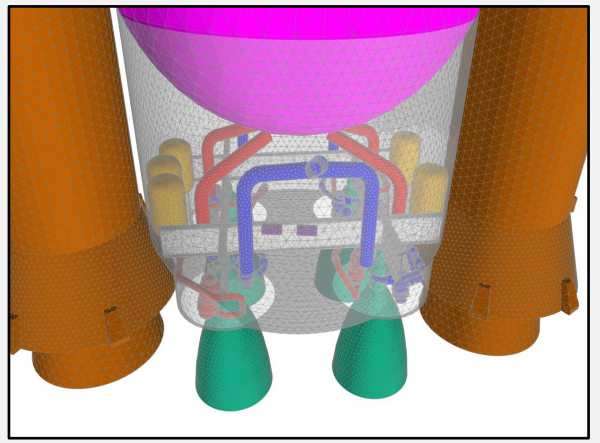
Static Model



Transition probabilities populated by
- Engineering judgment
- Off-line analysis/simulation

Less judgment
More engineering

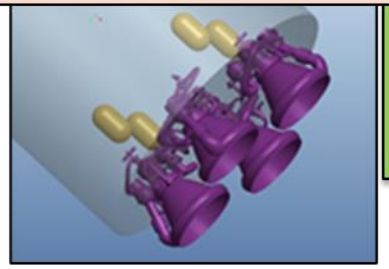
Physics-Based Simulation



Holy Grail: inputs would consist only of:
- Component geometric information
- Component engineering information
- Some important functional relationships (component A depends on inputs from component B)

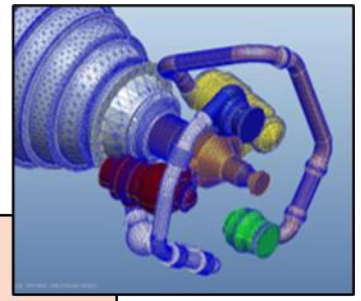
Failure Propagation Simulation Code

- Component surface grids
- Component rotation & translation



Vehicle configuration

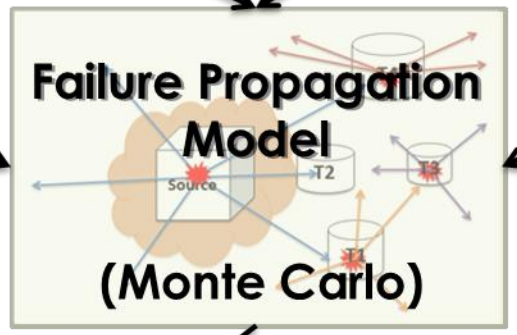
Component specifications



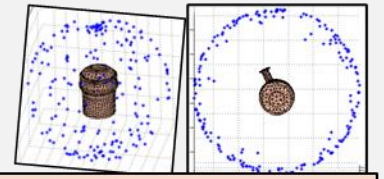
- Pressures, temperatures
- Total masses, volumes
- Wall materials and thicknesses
- Rotation rates & radii

Environment propagation models

- Blast propagation
- Debris trajectories
- Altitude effects



Failure assumptions

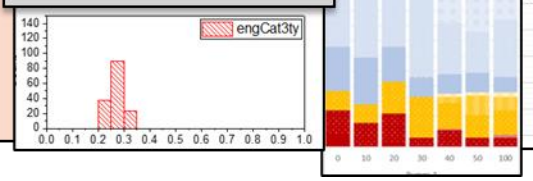


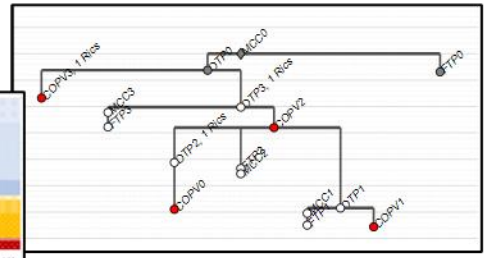
- Overpressure limits
- Blast energy scaling factors
- Debris counts, velocities, directions

Judgment goes here

- Component failure sequences & event trees
- Experiment-averaged probabilistic results
  - Component failure probabilities
  - Most common scenarios
  - Debris strike patterns
  - Etc

Outputs





Mathias, Motiwala, Go, Lawrence, Levine, et al

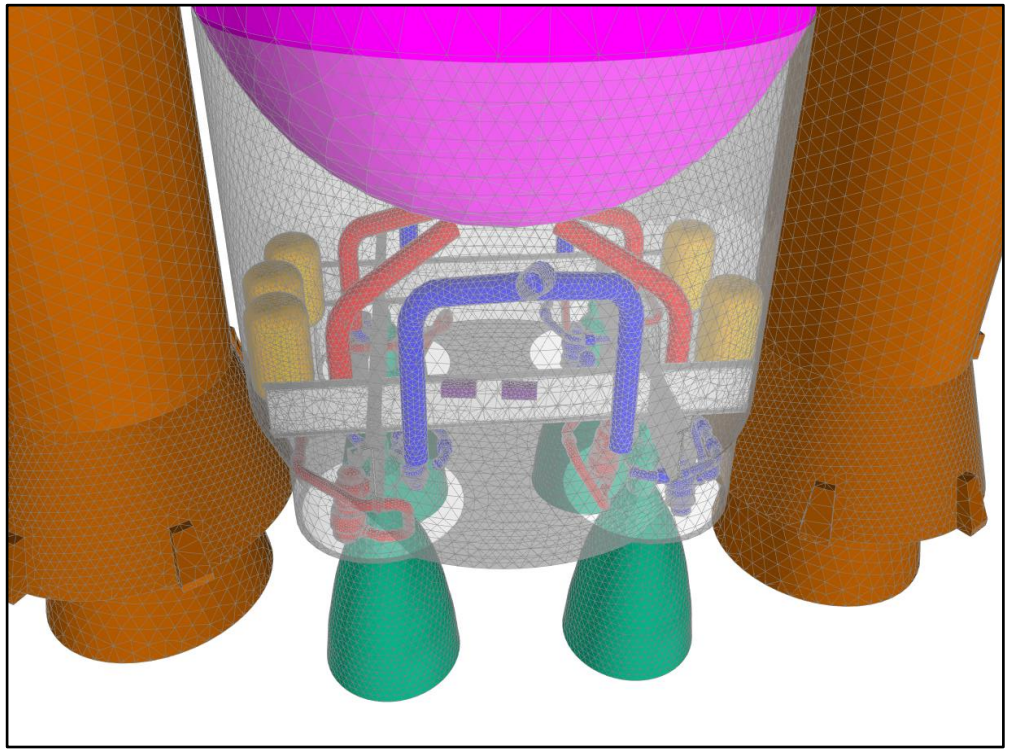
Physical Models for Propagation Modes

- **Blast**
  - Spherical TNT blast-based (Kingery-Bulmash)
  - Near-field clipping to prevent excessive peak OP
  - Impulse threshold included
- **Debris**
  - Ray tracing algorithm to determine component triangle of intersection
  - Simple drag effects
  - Ricochet effects
  - Failure threshold based on ballistic limit equation (BLE)
- **Loss of Function**
  - Functional dependencies
- **Container Modes**
  - Burst, Deflagration, Detonation
- **Vented Volume**
  - Pressure, Temperature, & mixture ratio vs. time

Core Engine Section Modeling Process

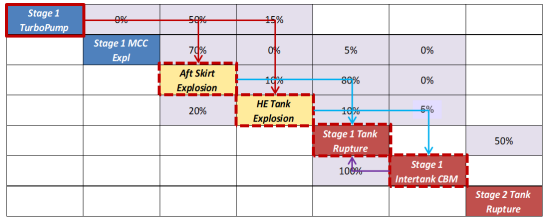
Model (60 components)

- 4 engines
  - 8 "hard" components each + "envelope"
- 10 feedline sections
- 5 COPVs
- Thrust structure
- 2 CCSE
- Fuel tank
- 2 boosters
- Enclosure
- 2 non-geometric "conditions"



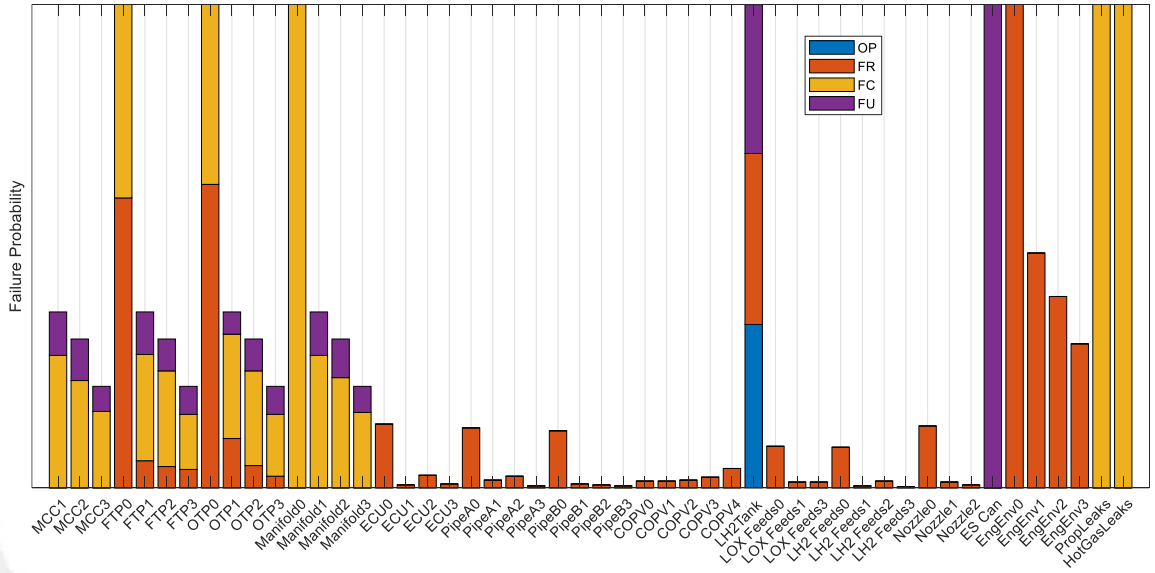
Process

- Altitude sweeps → Phase-averaged transition values
- Average over all initiators within a class (e.g., MCC_1-4)
- Output: Core fuel tank punctures
- Sensitivities → Variants
  - PV OP capability (scaled internal pressure)
  - Fragment count
  - Fragment velocities
  - Puncture size catastrophic threshold
  - ES explosion flame speed
  - Loss of function propagation
- Values entered into (simplified) Propagation Table for Matlab propagation

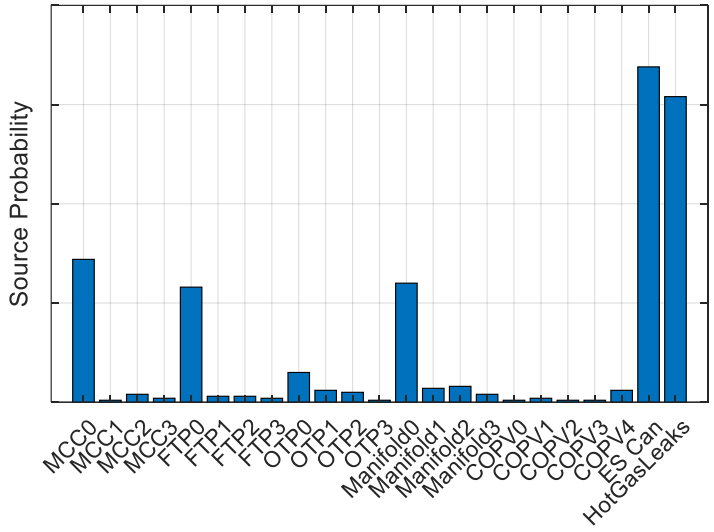


Failure Propagation Simulation: Monte Carlo Outputs

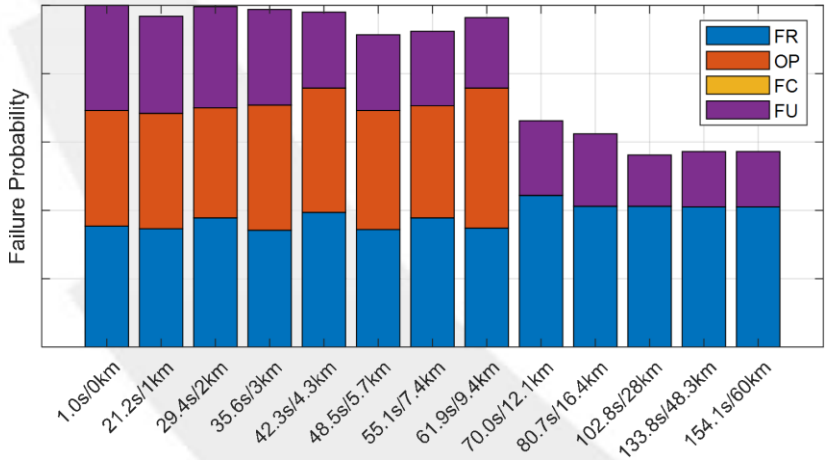
Component Failure Probabilities, Sea Level



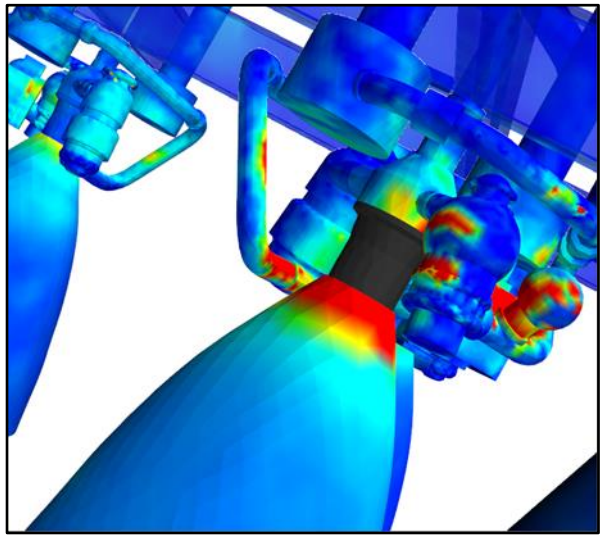
Contributor Breakdown



Altitude Sensitivity

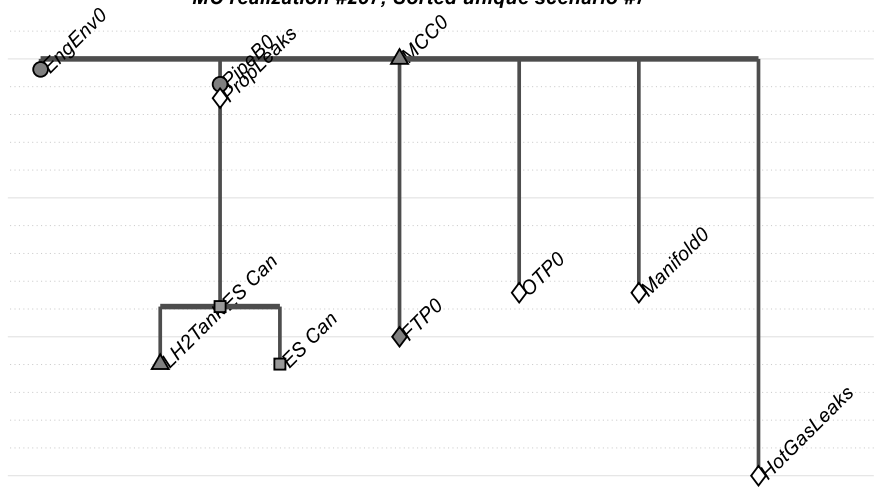


Debris Strike Patterns



Single-Sample Event Tree

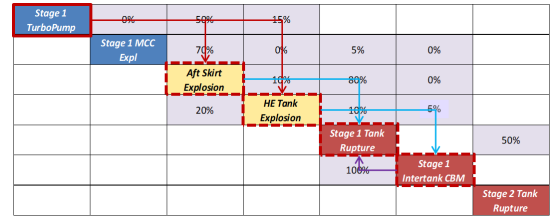
MC realization #257; Sorted unique scenario #7



Vehicle-Level Propagation Model

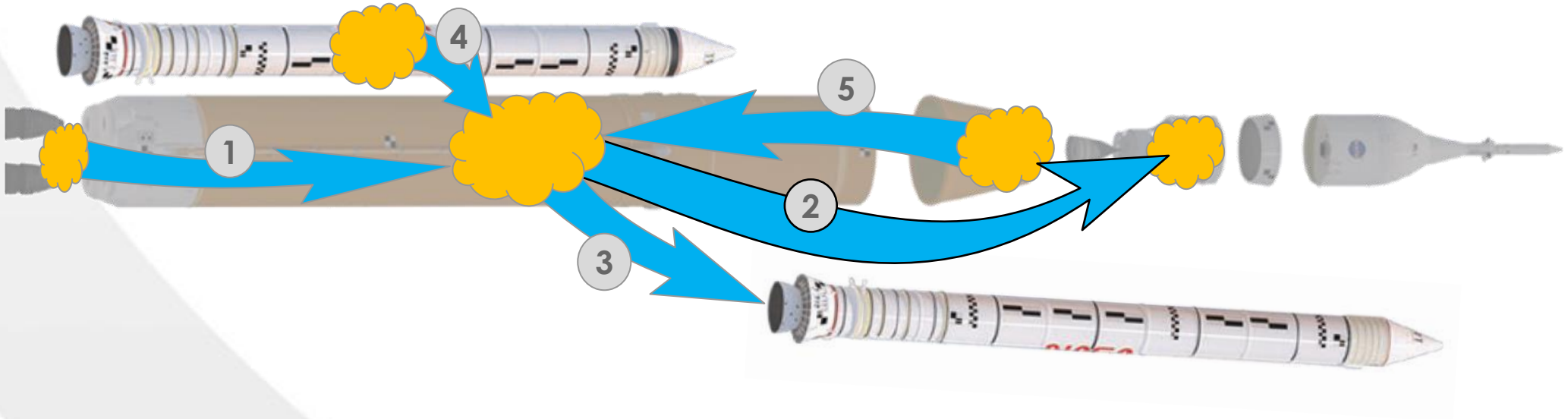
- **Matlab code**

- **Primarily used for stage-to-stage propagation**
  1. Engine section explosion → Core stage explosion
  2. Core stage explosion → Upper stage explosion
  3. Core stage explosion → free-flying booster
  4. Booster burst → Core stage explosion
  5. Upper stage or adaptor explosion → Core explosion



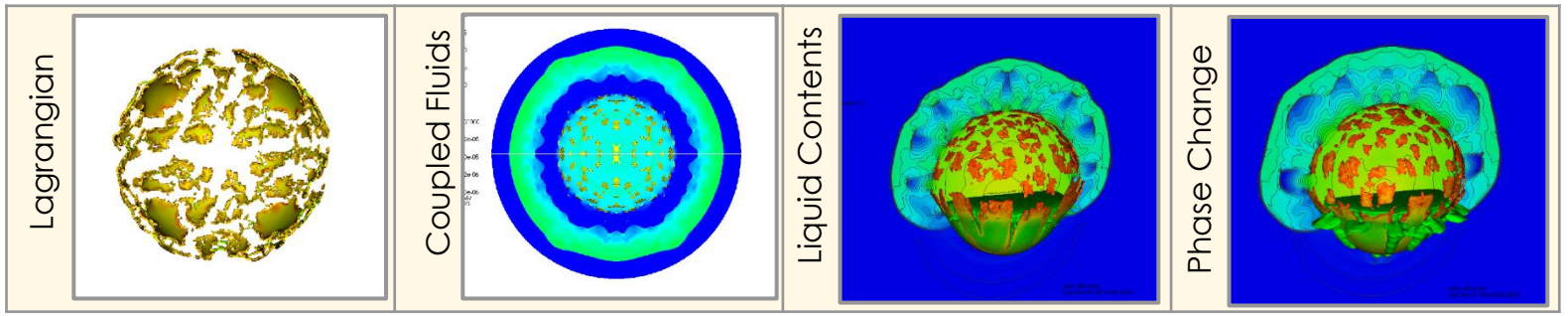
Quantification

values from FPS
accident history analysis
engineering judgment
engineering judgment/Shuttle analysis
engineering judgment

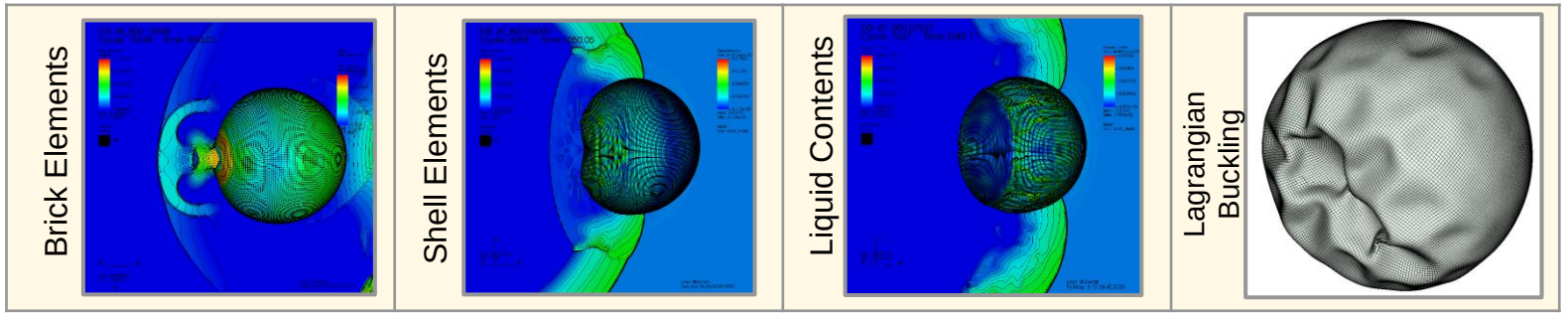


Uncertainties: Supporting Simulations

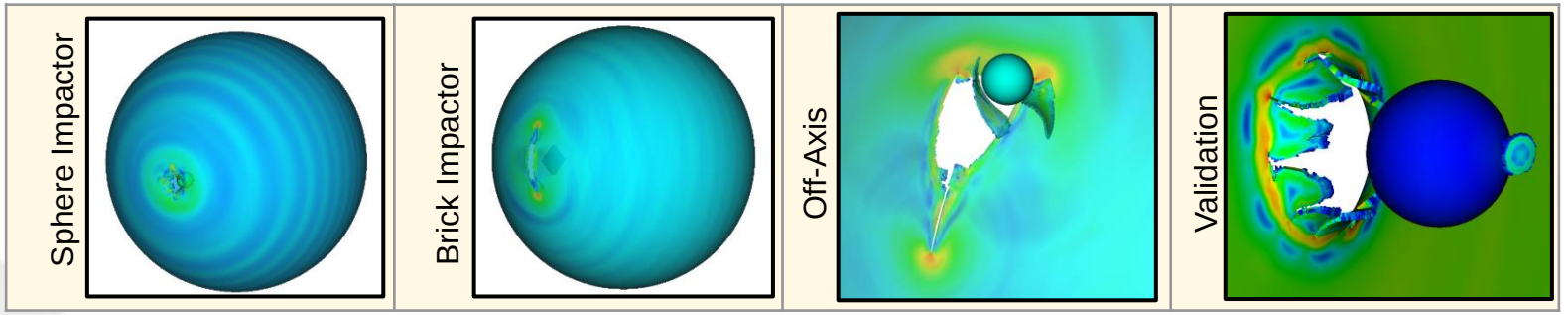
- **Vessel fragmentation & imparted velocities**



- **Component failure thresholds**
  - Blast impact

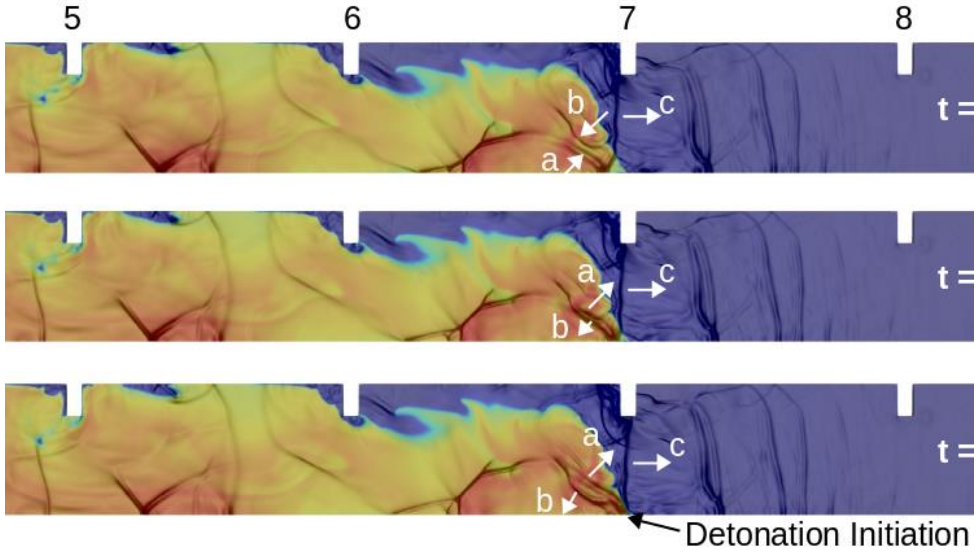


  - Debris impact

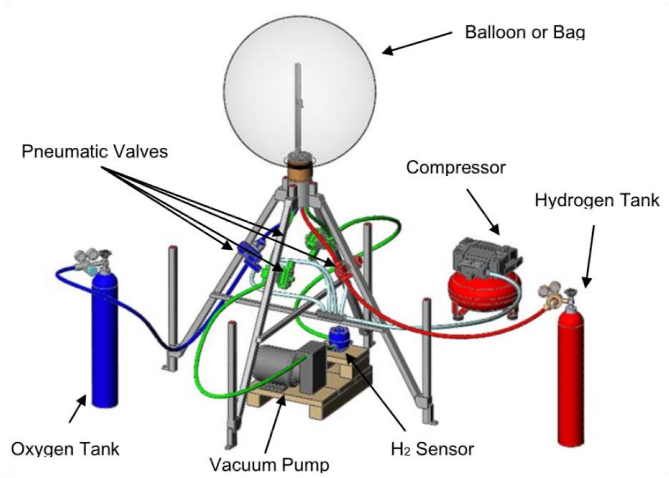


Deflagration or Detonation?: Flame Acceleration

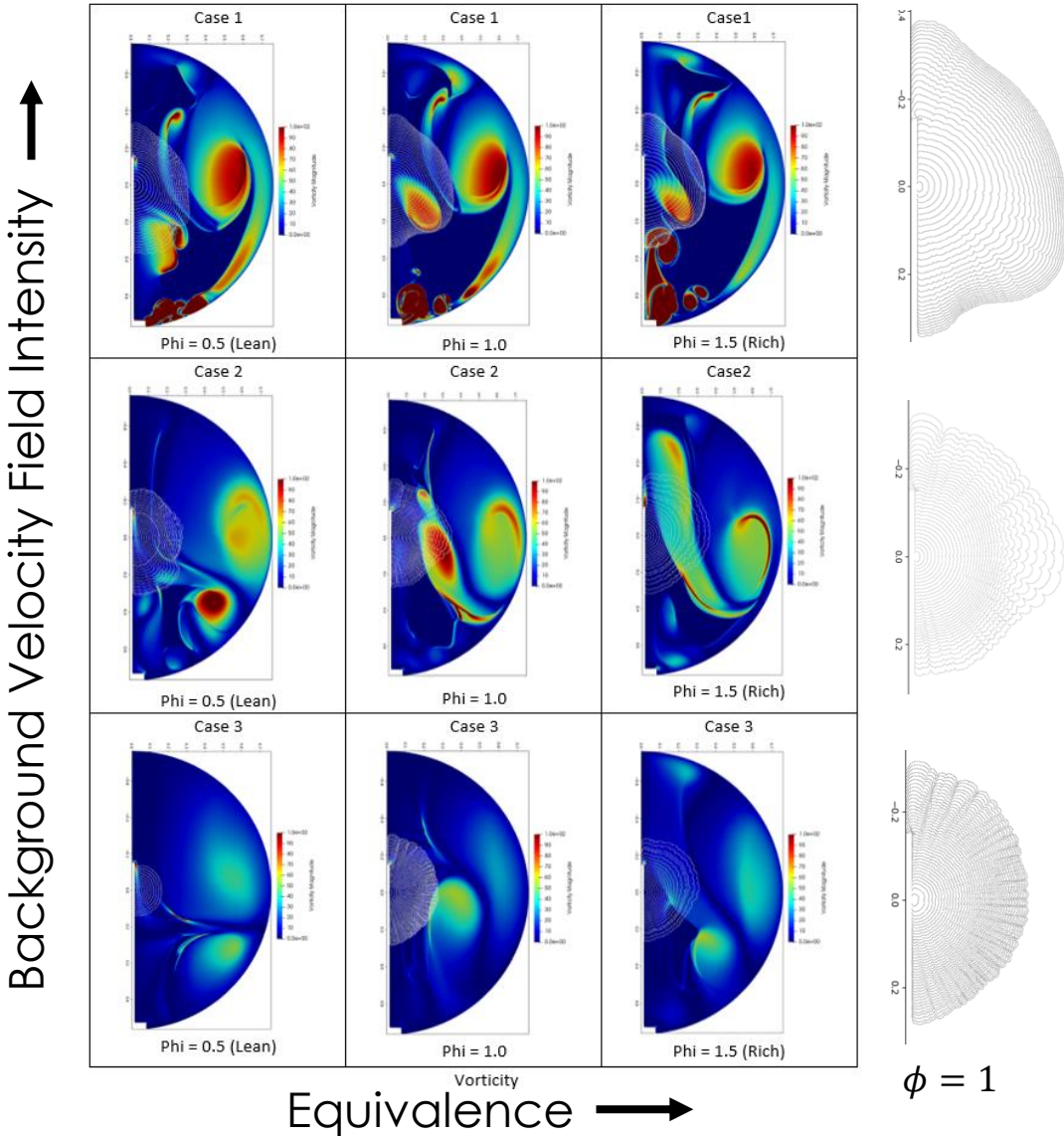
LOCI/Chem Simulations (ERA, Ashley Coates)



Tube with obstacles: emergence of detonation



Hydrogen Uncontained Test Apparatus (HUCTA) (MSFC/IE)



Flame propagation w/ nonuniform ICs

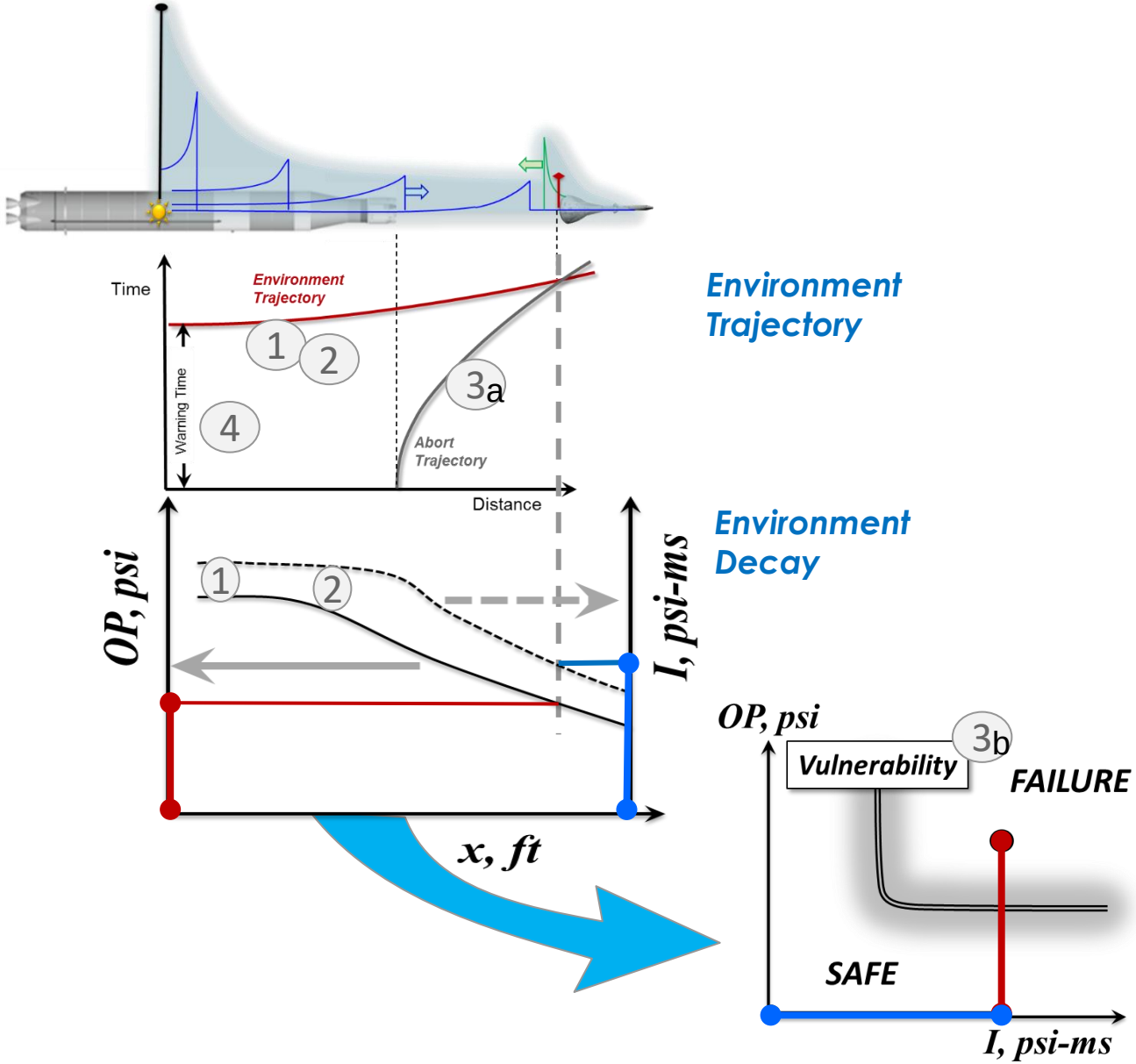
Explosion Environment Characterization: Blast Overpressure

Considerations:

1. Intensity of initiating event
2. Environment propagation
3. Escape system capabilities
   a) Trajectory
   b) Vulnerabilities
4. Detection capabilities

Each factor dependent on flight conditions

- ***Unique to flight vehicle explosion characterization***
  - *Potentially low ambient pressures*
  - *Potentially high vehicle velocities (winds)*
- *Limited data on these effects*



Blast Overpressure: Modeling & Simulation Tools

Blast models

• Kingery-Bulmash:	Curve fit to TNT data	TNT data	f(Radius, Energy, p_infty)
• Baker-Strehlow-Tang:	Tabulated/digitized	Vapor cloud Exp	f(Radius, Energy, p_infty, Flame speed)
• Brode	Tabulated/digitized	PV burst CFD	f(R, E, h, p0, T0)

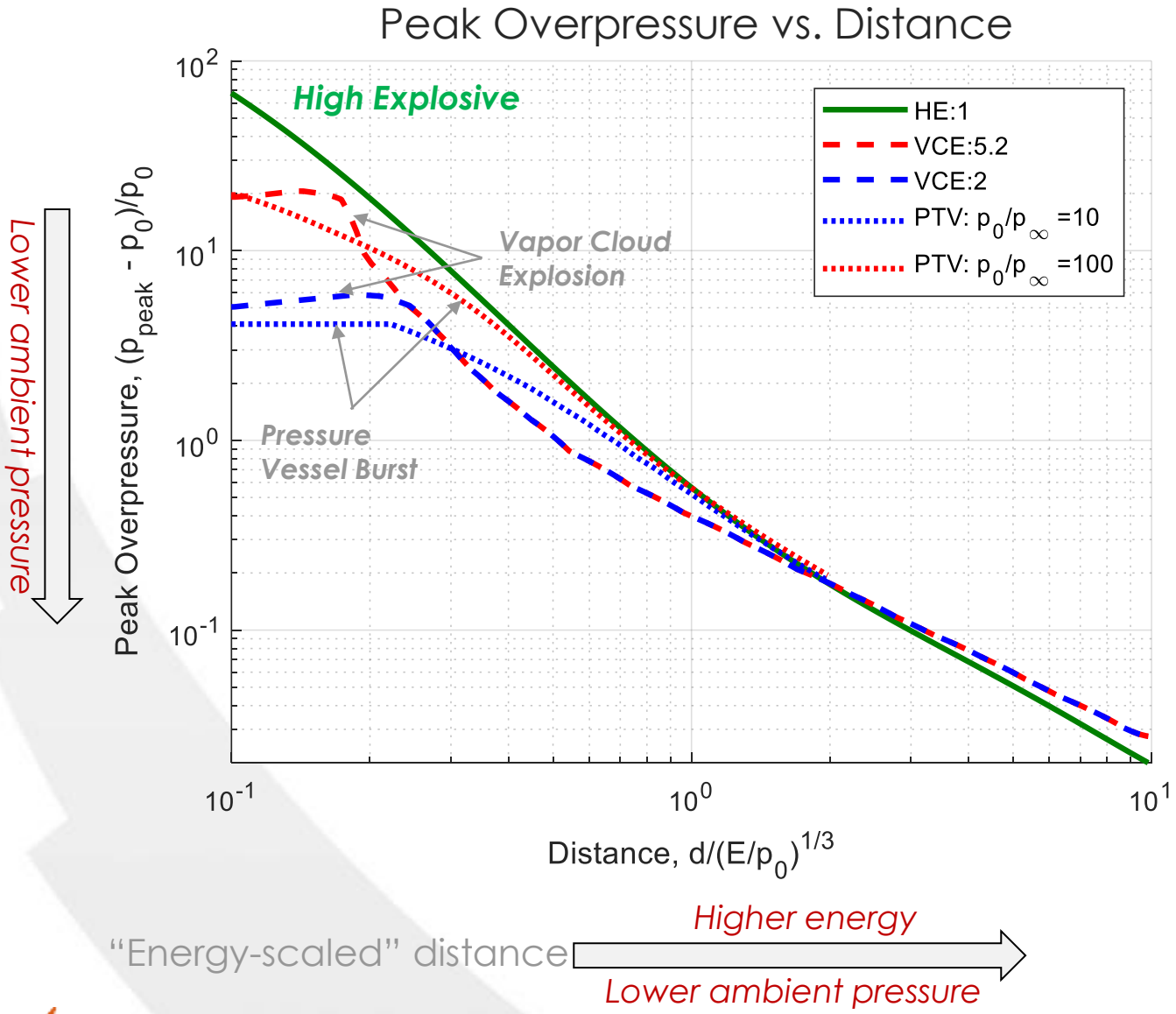
Blast simulation

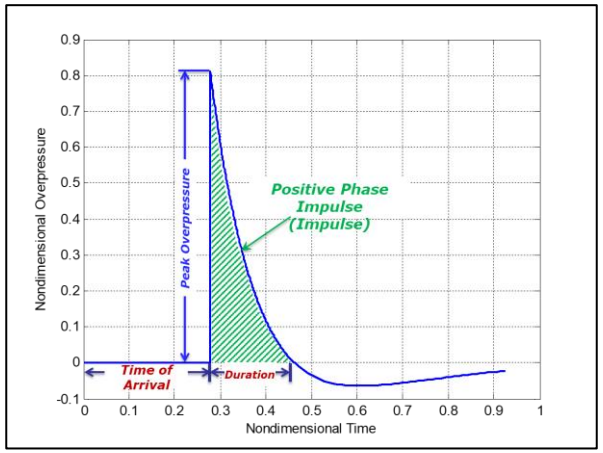
• Matlab Models	
– 1-D/spherical PV burst CFD	Matlab'd Brode model
– 1-D/spherical VCE simulation	Matlab'd WENO scheme w/ 1-eq chemistry and fitted interior flame
• Real CFD	
– Overflow	Headwind effects, fragment acceleration, PV burst physics
– CART3D	
– LOCI/Chem	1st principles flame propagation
• Hydro Codes	
– ALE3D	Non-spherical blast sources, blast interaction w/ geometry, coupled
– CTH	

Validation

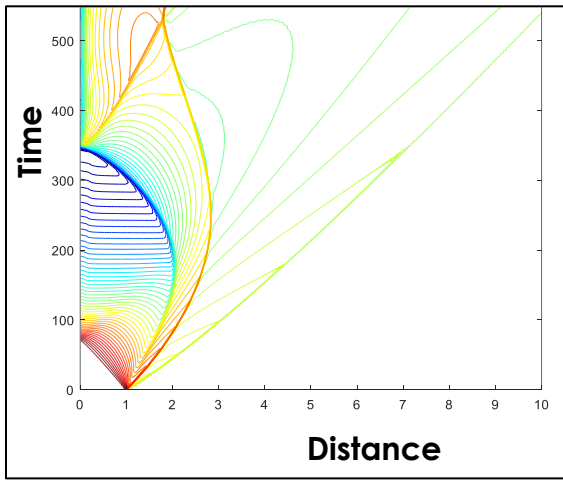
- Test data:
  - MSFC Hydrogen Uncontained Test Apparatus (HUCTA)
  - Fraunhofer test
  - Detonation tests
- Verification with published modeling & simulation

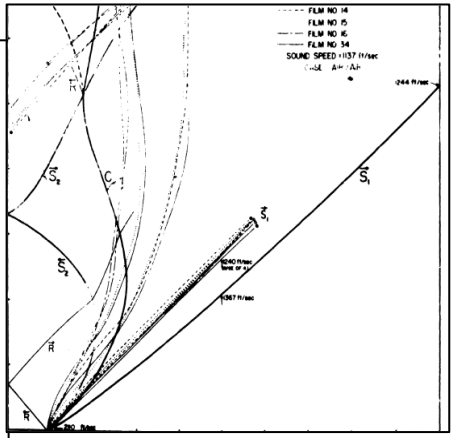
Blast Overpressure Parameters, Ramifications of Scaling





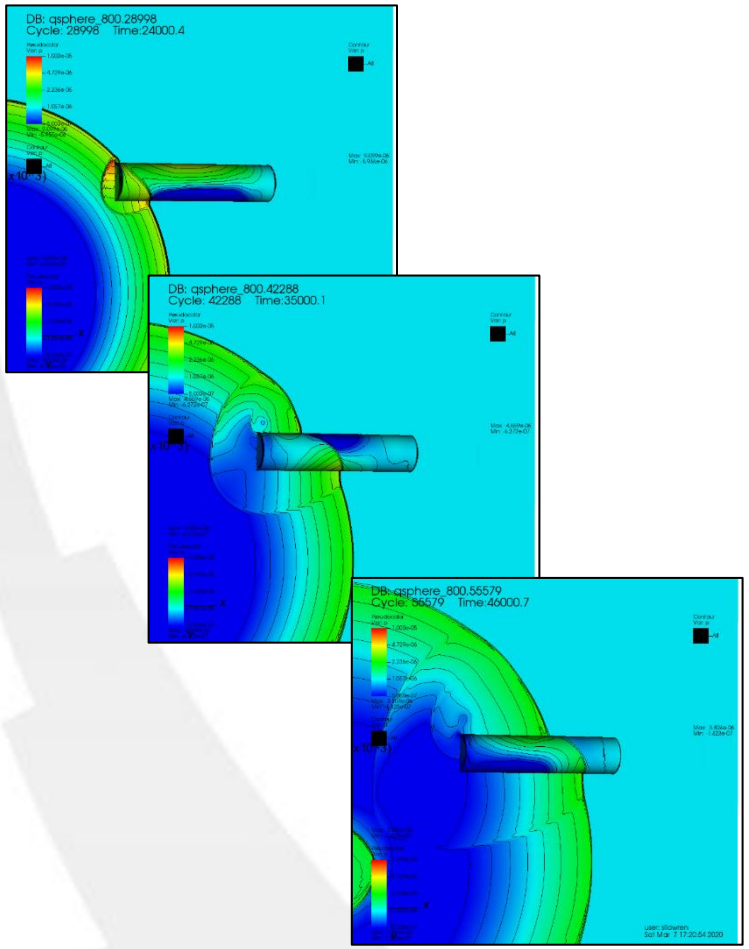
Pressure Vessel Burst





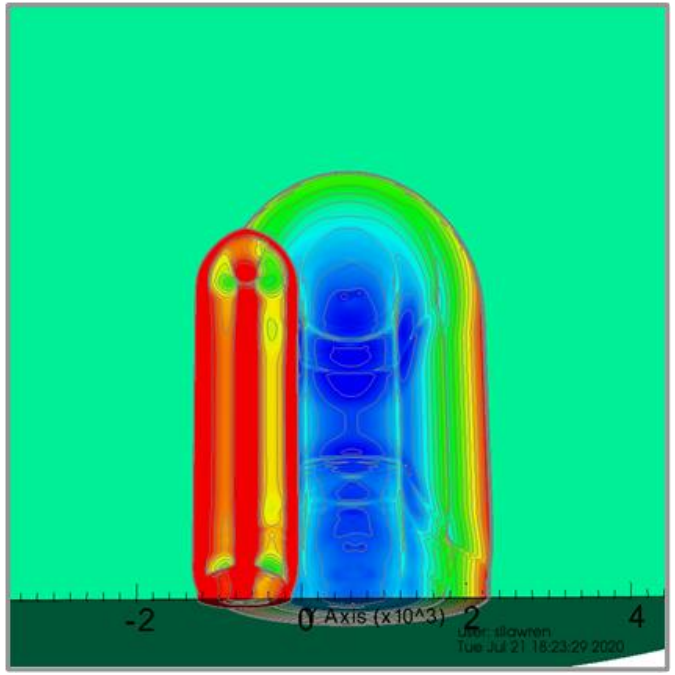
Boyer, et al:
Glass sphere burst

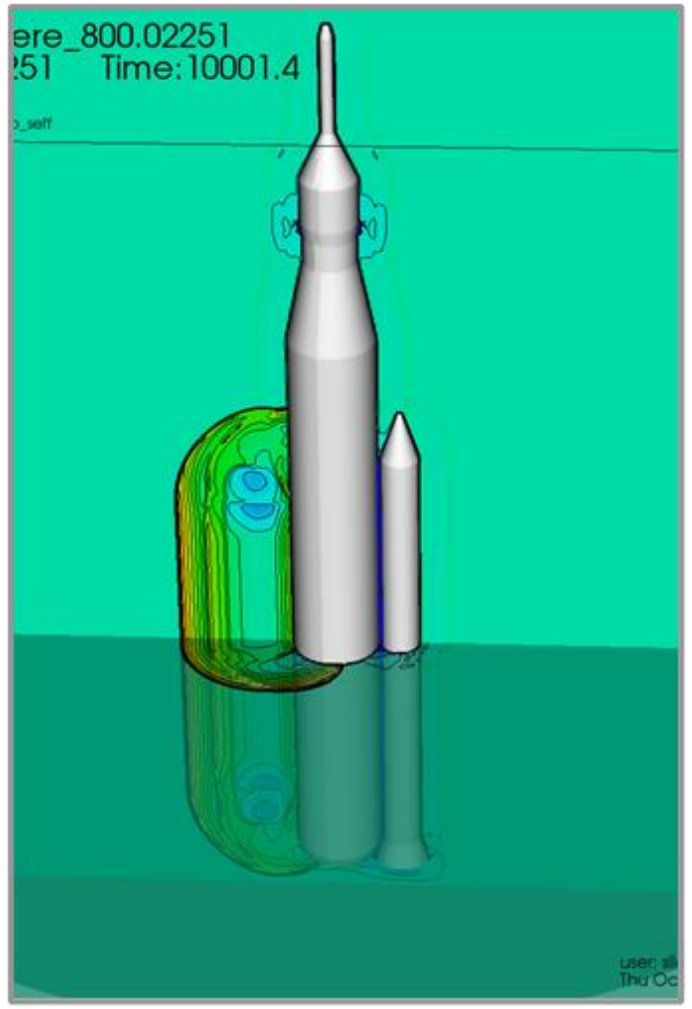
Other Miscellaneous Simulations (ALE3D)



Blast-Induced Torque?

Effects of Cylindrical Sources
&
Destruct Delays





Booster Burst w/ Core Geometry

Fragment Modeling & Simulation Tools

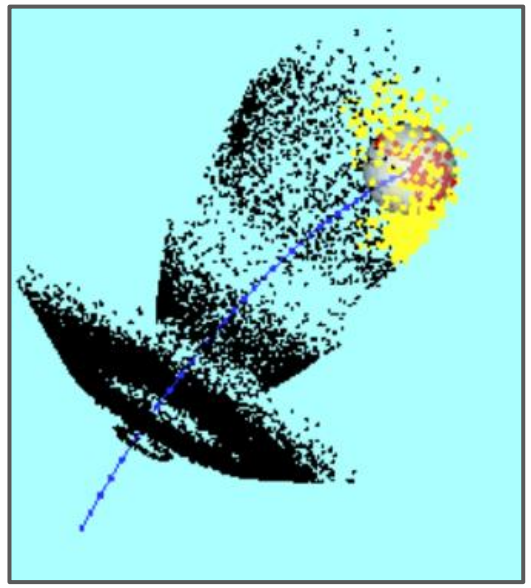
- **Debris catalog generation**
  - Scaled Shuttle
  - ERA Statistical Model
  - MSFC IE Team (LFOAM, SFOAM, Cannon Test Apparatus)
  - ALE3D fragmentation (Ted ribbed segments) & cannon simulations
  - Modified Baker model for fragment acceleration
- **Ken Gee strike probability model**
  - 3-DOF debris propagation
  - Abort trajectories
  - Statistical methods
  - Free-flyer booster trajectory integration
- **Failure propagation simulation code**
  - Application of the debris tracking modeling to service module abort

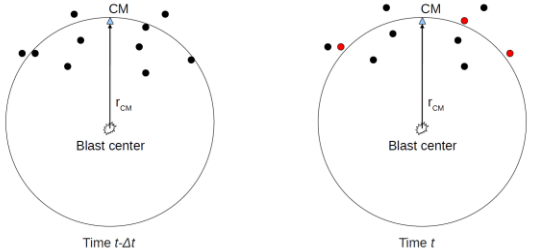
Ken Model

- **Debris initiation**
  - Debris catalog
  - Imparted velocity directionality assumptions
- **Debris propagation**
  - 3 degree-of-freedom trajectories (MISSION → OTIS)
- **Abort trajectory**
  - Provided by Orion
- **Debris counting/selection**
  - Evaluated during abort/debris position-time history
- **Cumulative strike probability**
  - Accumulated results of Poisson distribution

$$P_{strike} = 1 - \exp(-\sum \rho_{debris} A_{CM})$$

- **Sensitivities to**
  - Flight conditions (mission phase)
  - Warning time



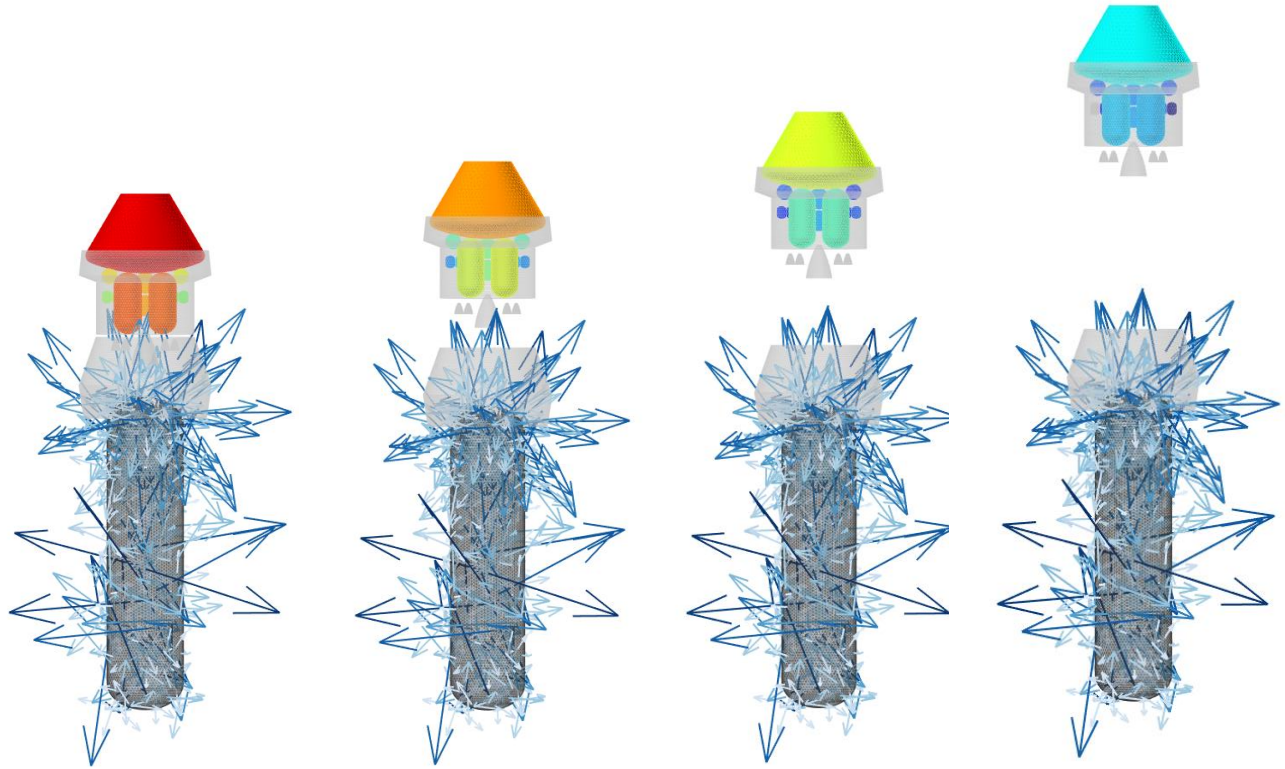


Debris Strike Modeling: SM Abort

- **Application of failure propagation debris tracking capability**

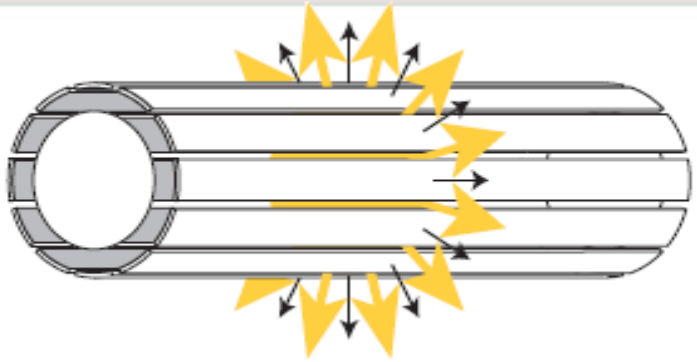
- **Abort Sep Geometric Model**
  - "ICPS" debris catalog geometry
  - MPCV adaptor
  - ESM components (26 total)
    - OMS nozzle (obstruction)
    - 8 aux nozzles (obstruction)
    - 4 prop tanks (pressurized, liquid)
    - 2 He tanks (pressurized, gas)
    - 6 H2O tanks (low pressure, liquid)
    - 4 N2-O2 tanks (pressurized, gas)
    - Enclosure (obstruction)
  - Forward adaptor
  - Crew module

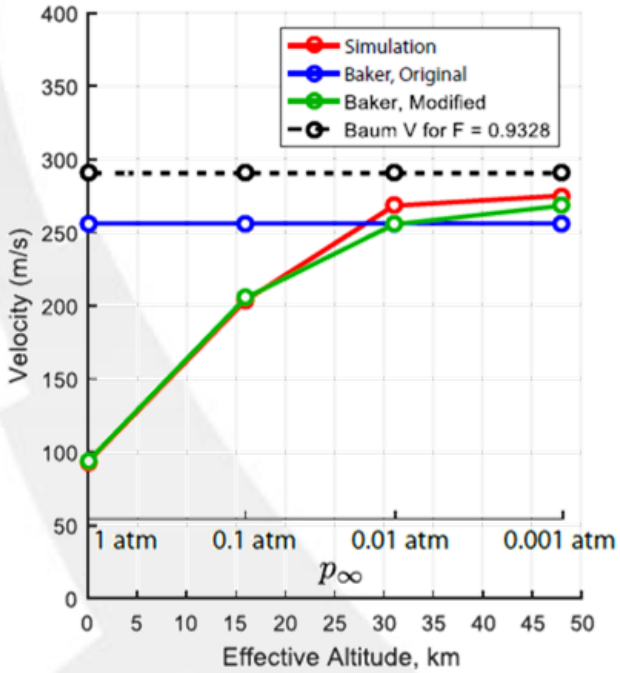
- **Process**
  - Series of static separation cases
  - Convert sep distances to ATWT
    - SM Abort Model
      - Spring-initiated→ hold→ aux motors
      - MET-dependent
  - Sensitivities → Variants
    - Input debris catalogs
    - Damage-to-failure
    - Debris direction spread



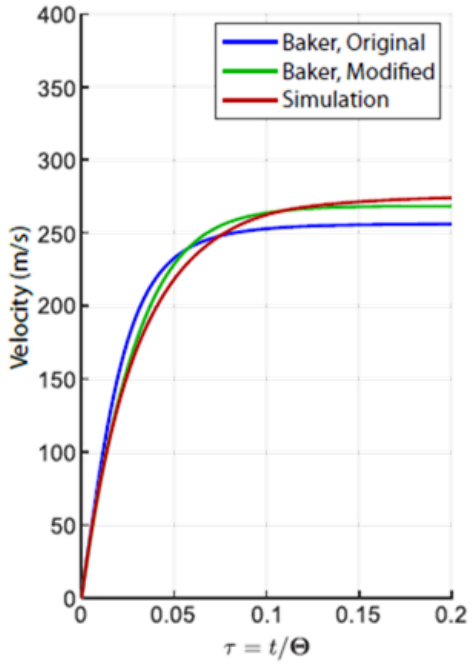
Sensitivity to Separation Distance

Fragment Acceleration Model & Simulation: Propellant Tank Burst

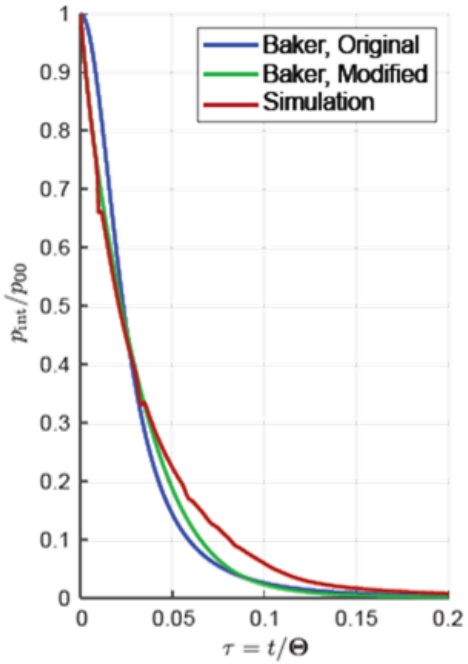




(a) Peak velocity sensitivity to external pressure

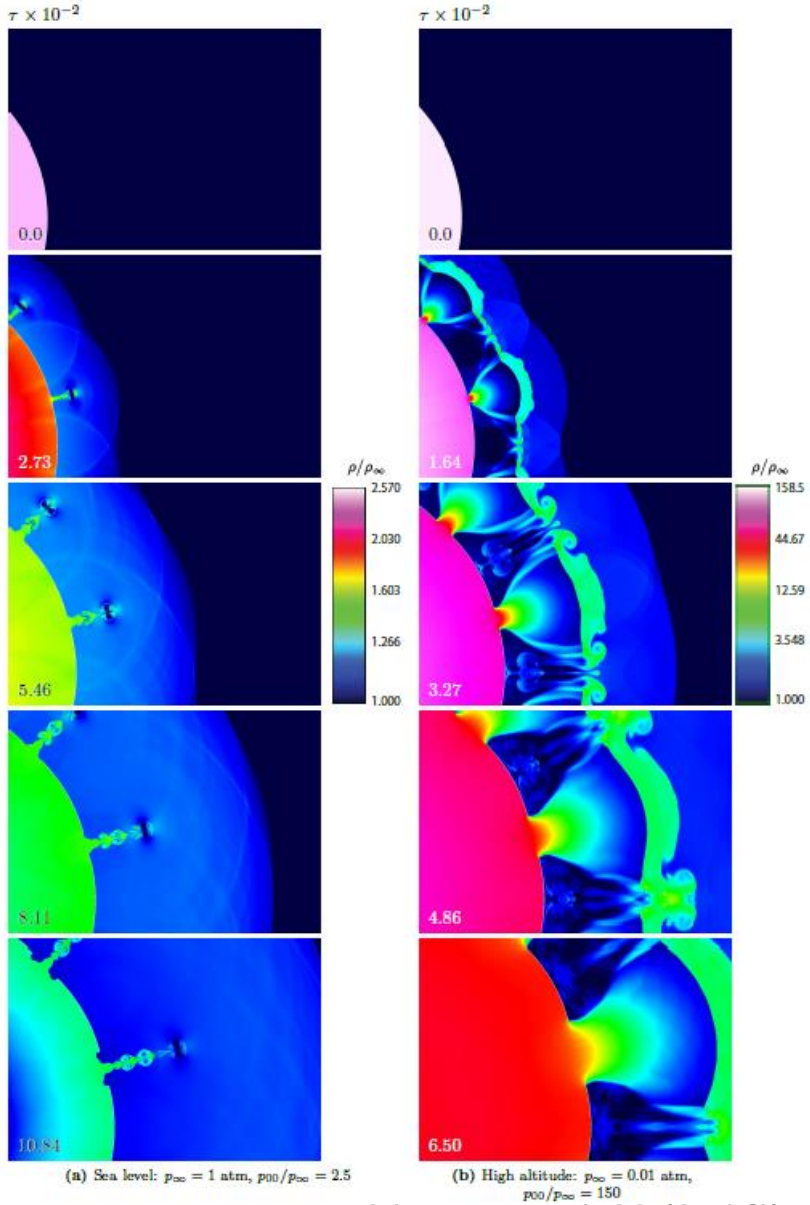


(b) Velocity at $p_\infty = 0.001$ atm



(c) Internal wall pressure at $p_\infty = 0.001$ atm

J. Spacecraft & Rockets

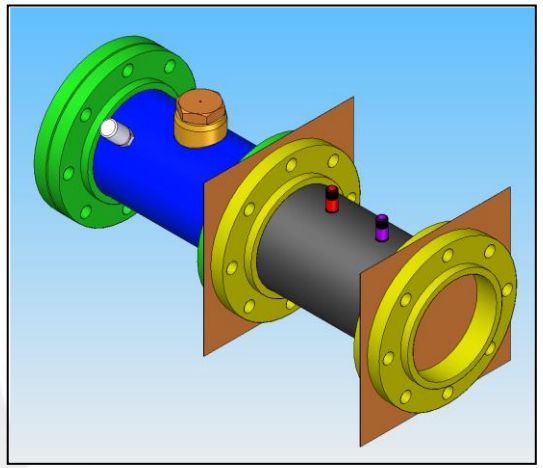


(a) Sea level: $p_\infty = 1$ atm, $p_{00}/p_\infty = 2.5$ (b) High altitude: $p_\infty = 0.01$ atm, $p_{00}/p_\infty = 150$

S/L Pressure S/L Pressure/100 (31 kft)

Fragment Formation: ALE3D Simulations for BEi Cannon

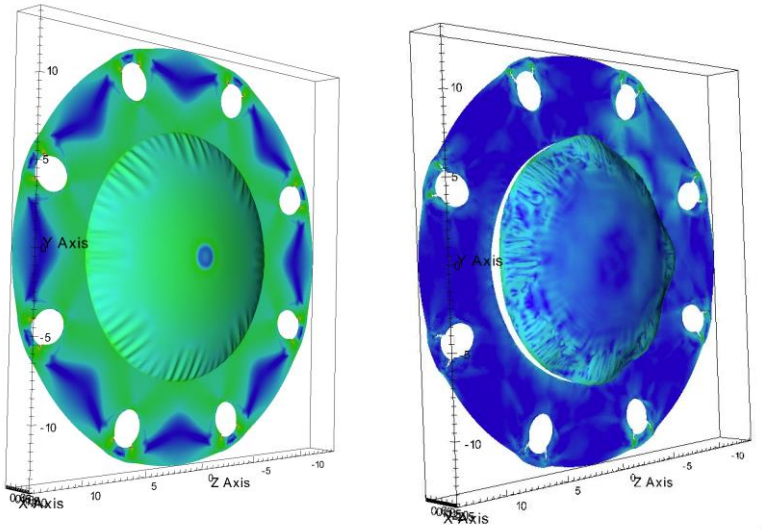
- **At MSFC by Bangham Engineering**



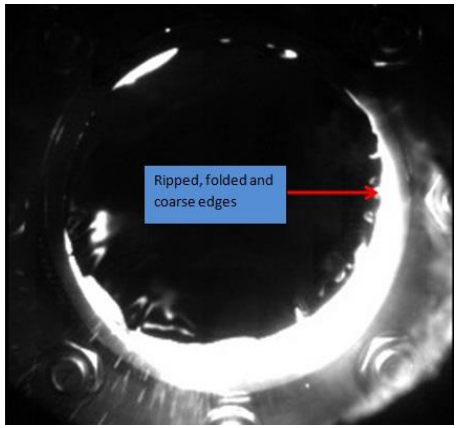


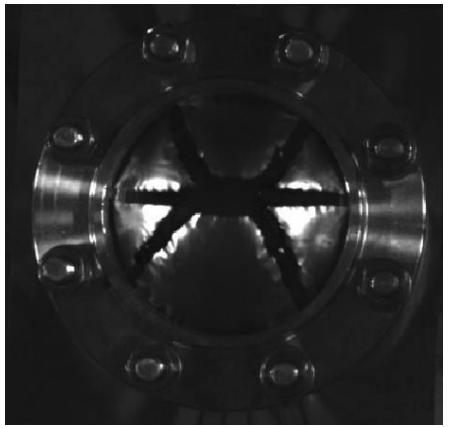
Source: Bangham Engineering Inc./NESC

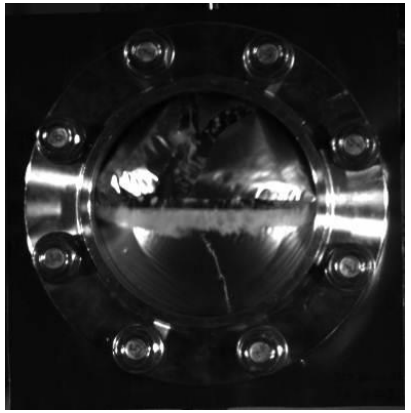
ALE3D Simulations



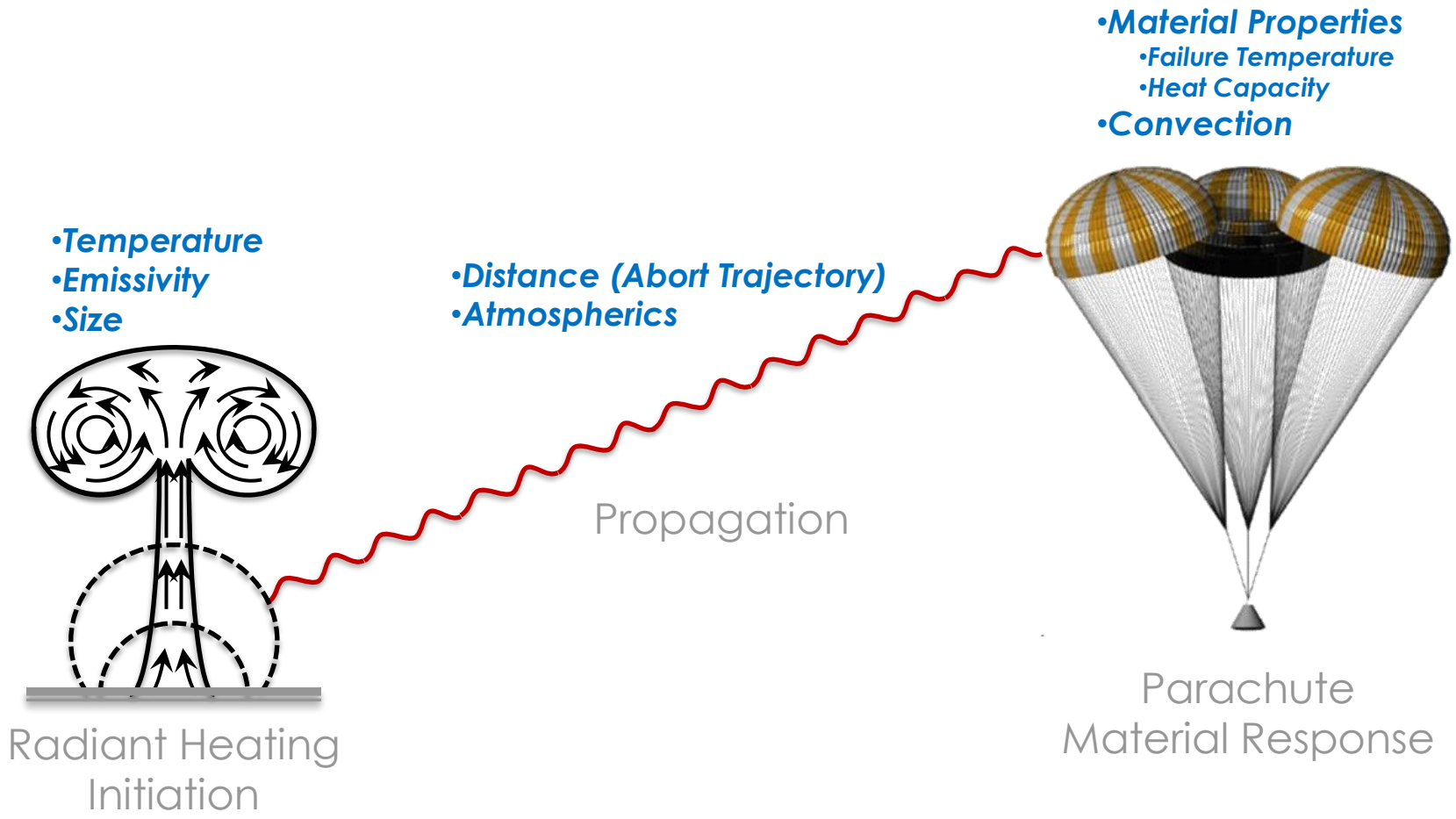
Cannon Test Result







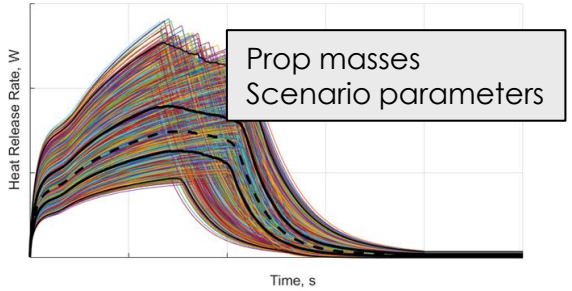
Fireball Problem Components



Parachutes must be deployed to be threatened → Fireball hazard is minimal unless conflagration occurs well after abort

Fireball Model Components

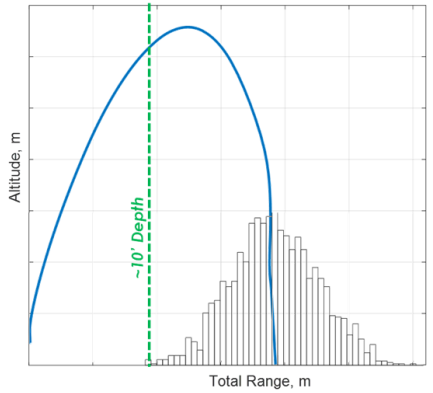
Fireball Heat Release (Sandia Fireball Model)



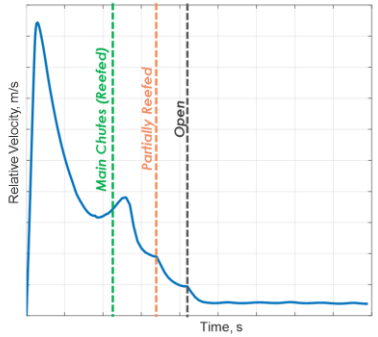
Atmospheric Transmissivity

$$Q = 2.02(RH \times P_v \times d)^{-0.09}\left(\frac{r_{FB}}{d}\right)^2 \dot{q}_{FB}$$

Abort Trajectory (Orion + dispersions)

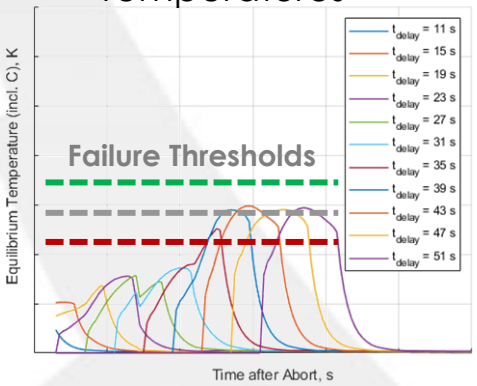


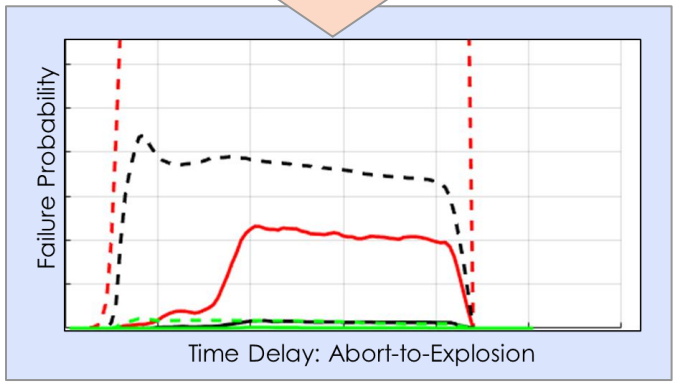
Chute Operations



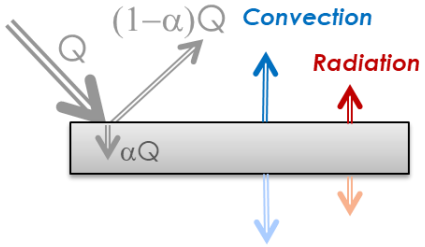
Monte Carlo Failure Status

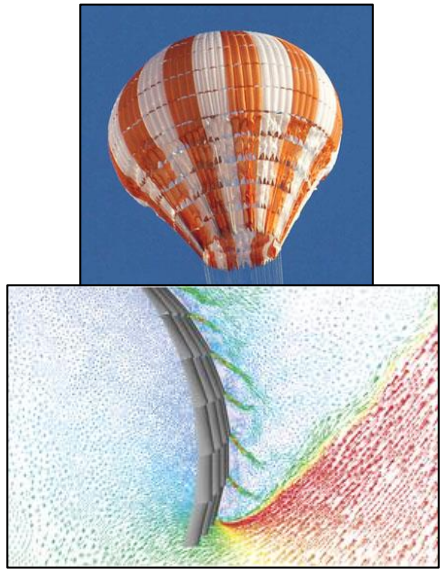
Parachute Equilibrium Temperatures





Parachute Heating Model

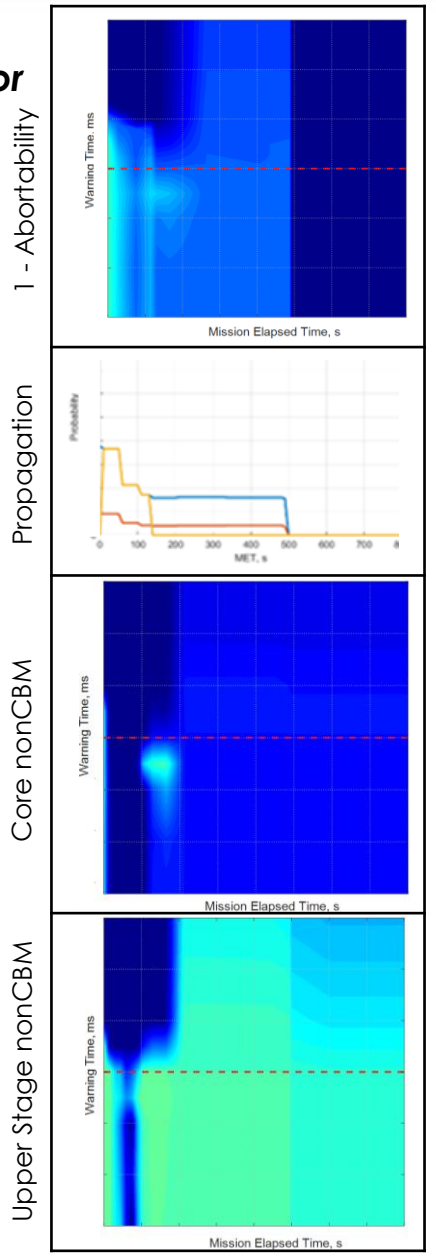




Abortability Calculation

- **Example explosion types**
  - Core intertank confined explosion
  - Core stage unconfined explosion
  - Booster burst
  - Interstage confined explosion
  - Upper stage unconfined explosion
  - Free-flyer booster
  - …
- **For each explosion type, compute estimates of failure probabilities for**
  - Blast overpressure
  - Fragment strike
- **Convolve these to produce explosion environments for each explosion type**
- **For each failure class (initial failure manifestation, e.g., Core engine TP Burst)**
  - Run propagation to estimate probabilities of one or more explosion types
- **Perform weighted average of the environment failure probabilities**
  - Weightings provided by propagation analysis

Example:
Core Stage Initiator



Abortability Sensitivities

- **Failure type (initial failure manifestation, e.g., TP burst, MCC burst, …)**
  - 19 classes considered
- **Mission phase (flight conditions at time of failure)**
  - 21 mission phases included
- **Warning time provided (early detection)**
  - 220 values of warning time (100ms increments)
- **Modeling assumptions**
  - Failure propagation
  - Explosion characterizations
  - 3 sets of each used