

Engineering Risk Assessment of Launch Vehicle Failure

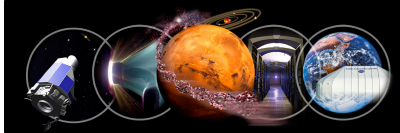
Ted A. Manning
Engineering Risk Assessment (ERA) Team
National Aeronautics and Space Administration (NASA)
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JAXA-Univ. of Tokyo Joint Symposium on Numerical Modeling of Rocket and Space Craft
JAXA Tsukuba Space Center
March 23, 2016

Outline



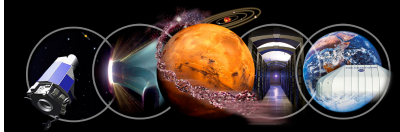
- Risk Assessment Framework
- Failure Propagation
  - Propagation Framework
  - Self Propagating Scenarios
- Blast Overpressure
- Debris Strike Risk
  - Debris Catalog Modeling
  - Fragment Acceleration



Engineering Risk Assessment (ERA) Team



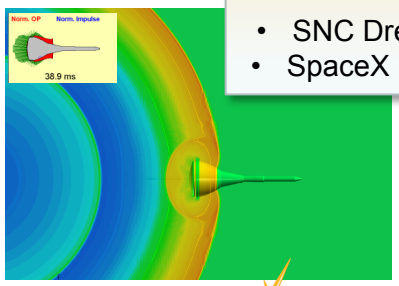
- Donovan Mathias
- Scott Lawrence
- Ken Gee
- Susie Go
- Ted Manning
- Darrel Robertson
- Lorien Wheeler

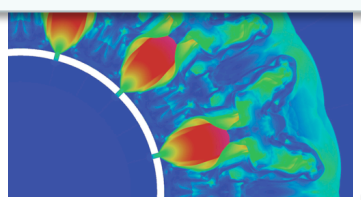


Engineering Risk Assessment Activity

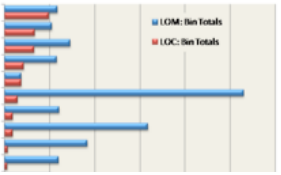
Crew Launch Vehicle Risk Assessment & Risk-Informed Design

- Ares I/V integrated LOM/LOC
- SLS abortability
- SNC Dream Chaser mission risk modeling
- SpaceX DragonRider ascent risk sensitivity

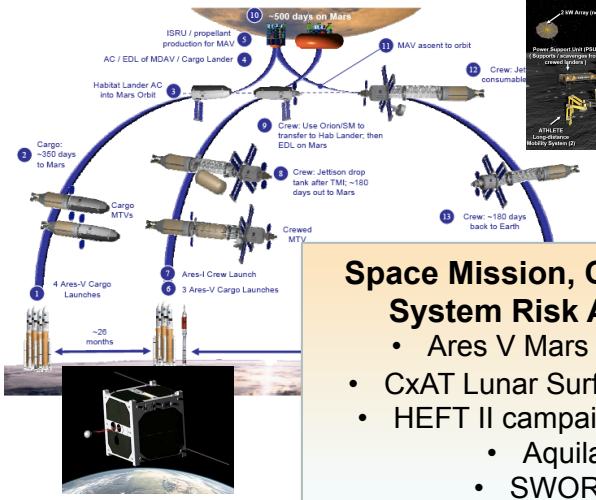


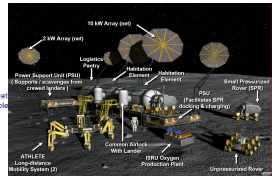






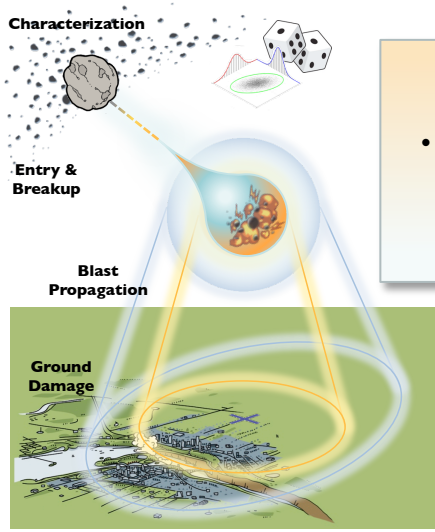






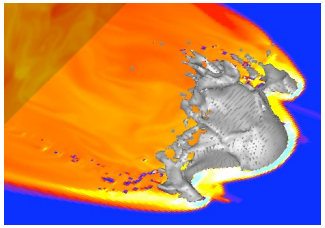
Space Mission, Campaign & System Risk Analyses

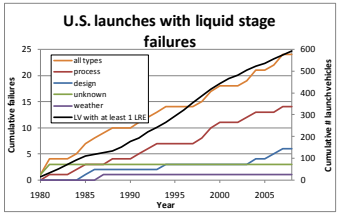
- Ares V Mars campaign
- CxAT Lunar Surface Systems
- HEFT II campaign to a NEO
- Aquila II
- SWORDS

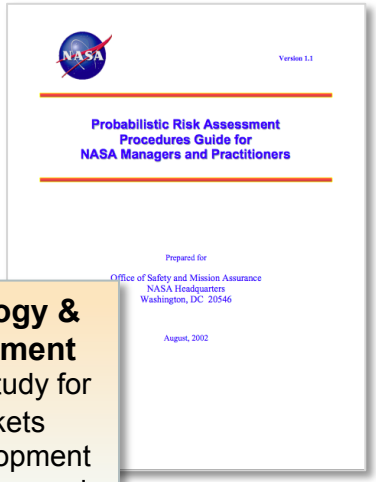


Asteroid Threat Assessment Project (ATAP)

- Physics-based impact risk model
  - Fragmentation/breakup
  - Crater-forming impact
  - Ground damage assessment







Agency Risk Methodology & Requirements Development

- Liquid/Solid Propellant Study for NASA's Study of Rockets
- CCP requirements development
- OSMA PRA guide chapters and training modules.

Outline

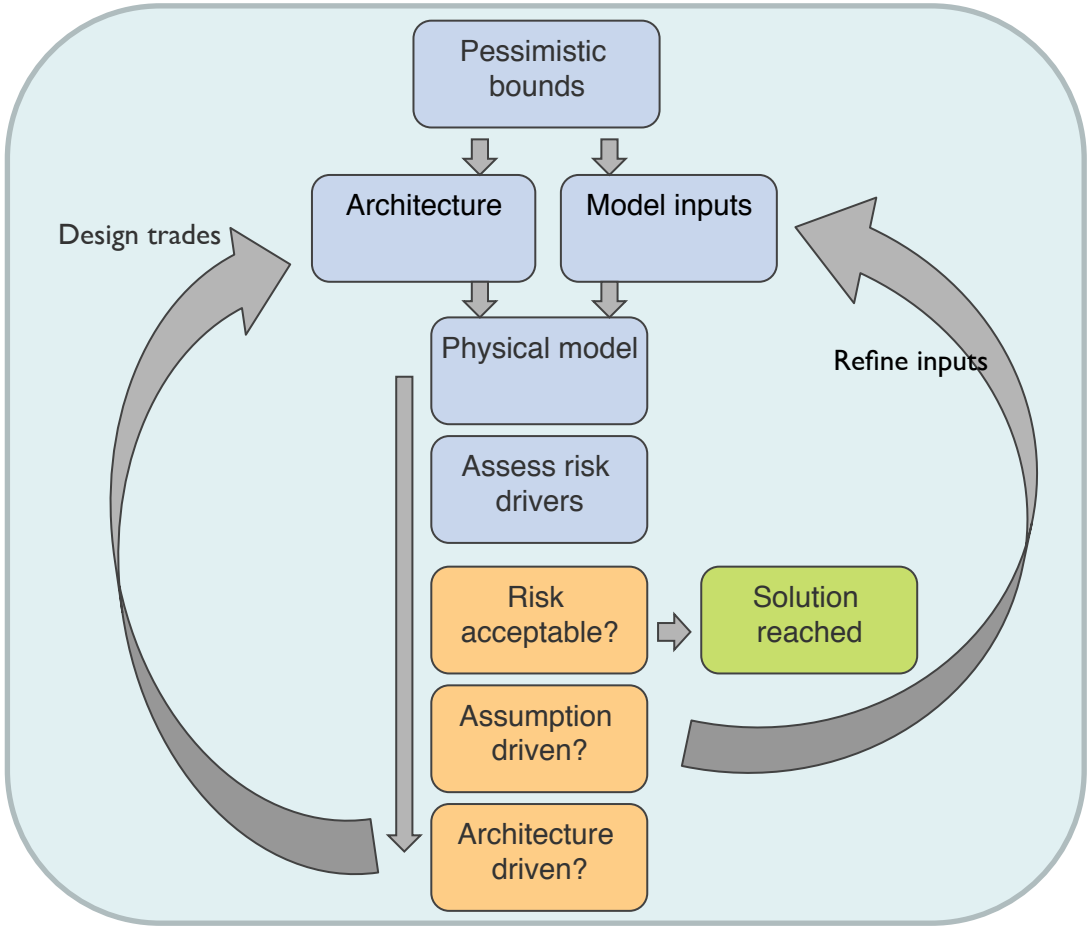


- **Risk Assessment Framework**
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Approach Application

- **Risk-informed decision support**
  - Requirement verification
  - Design optimization
  - Selection/procurement
- **PRA is informative, not predictive**
  - Provides quantitative answers to specific questions
  - Always driven by specific application
  - Based on traditional methods and extended as appropriate

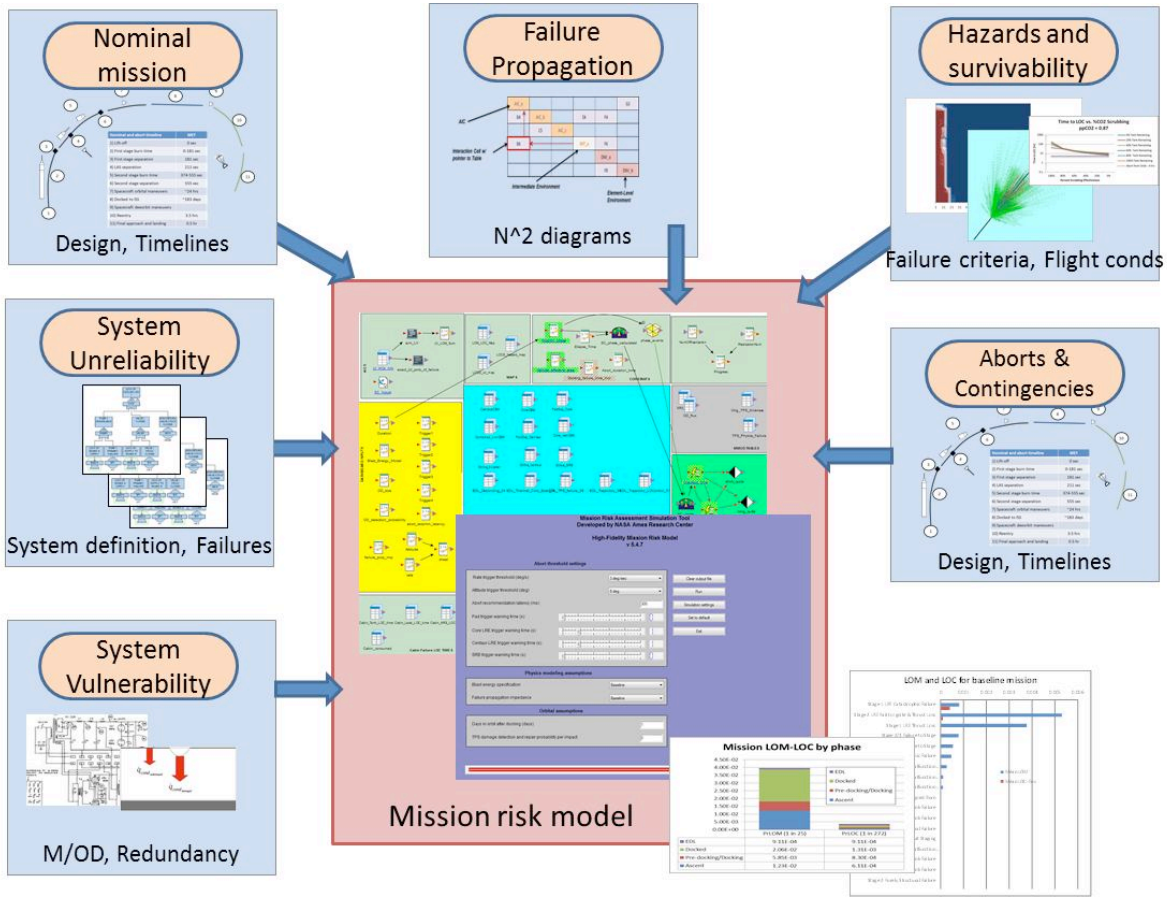
Iterative, responsive modeling approach



What is ERA?

Engineering Risk Assessment (ERA) extends traditional Probabilistic Safety/Risk Assessment (PRA/PSA) approaches to incorporate:

- **Physics-based analysis of key risk factors**
  - External hazards
  - Failure environments
- **Dynamic nature of failures**
  - Time dependence
  - State dependence
  - Interactive effects



Crewed Launch Mission



Launch Abort System



Crew Module
Service Module

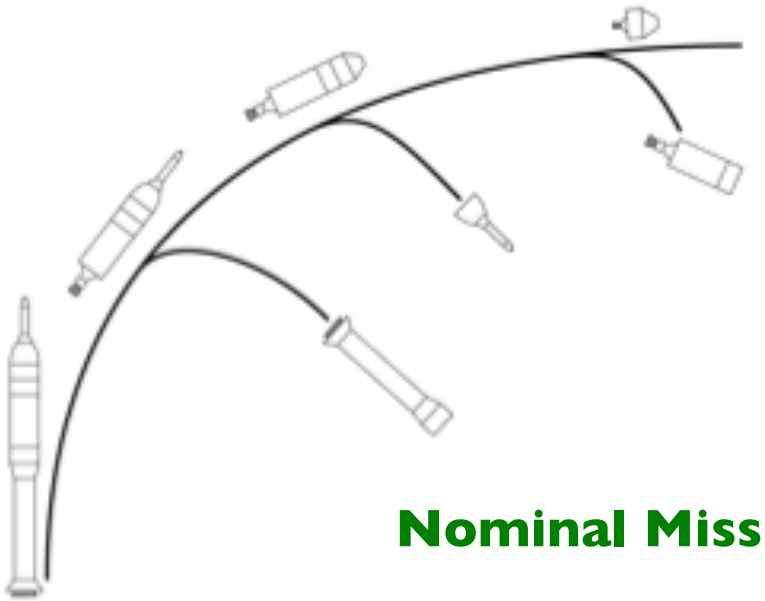


Second Stage

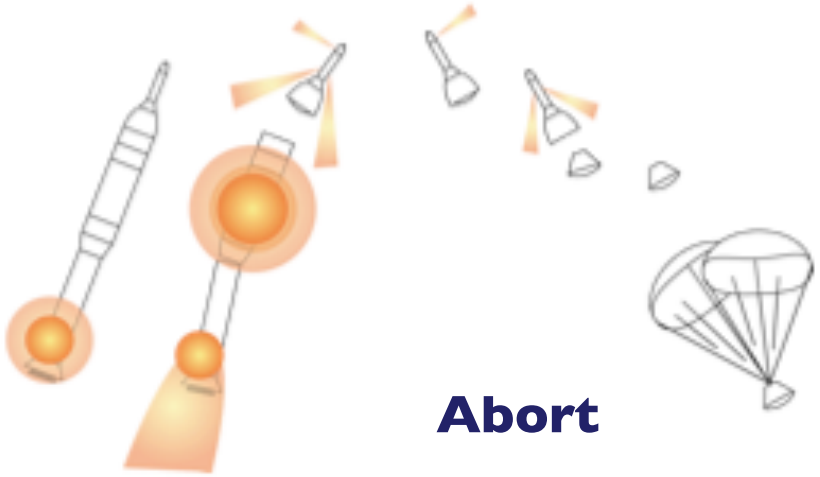
Upper Stage Engine



First Stage

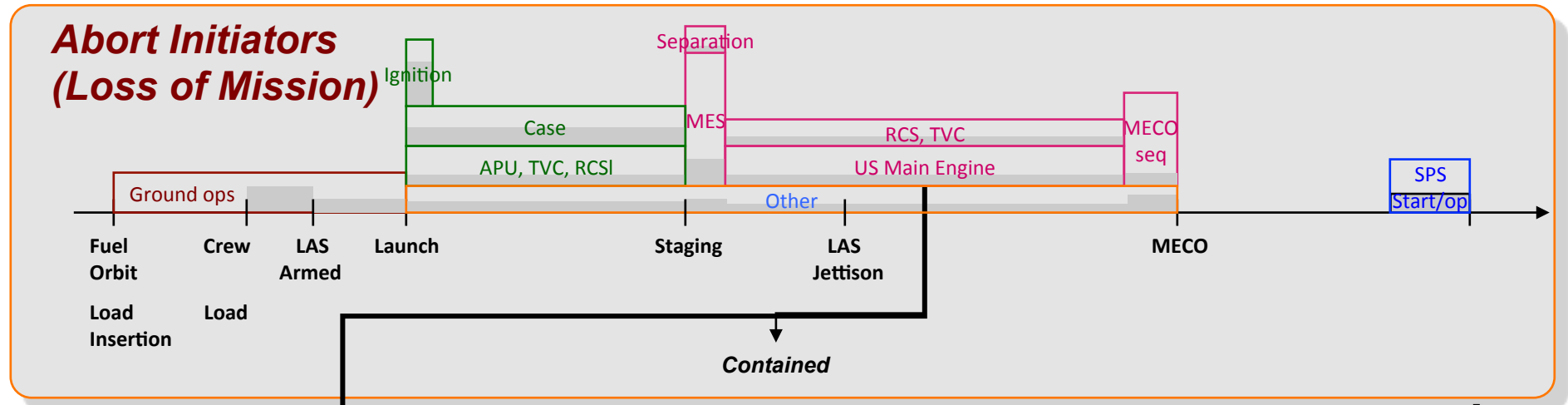


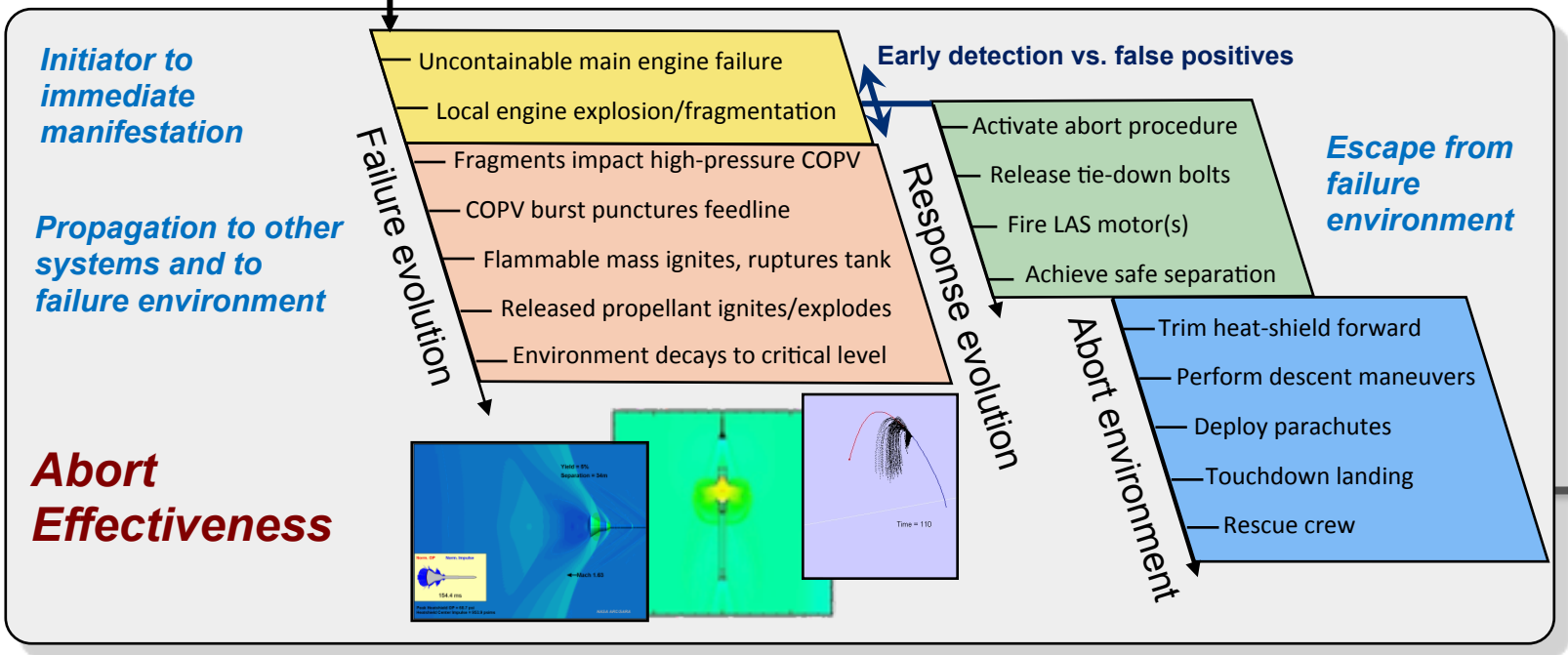
Nominal Mission



Abort

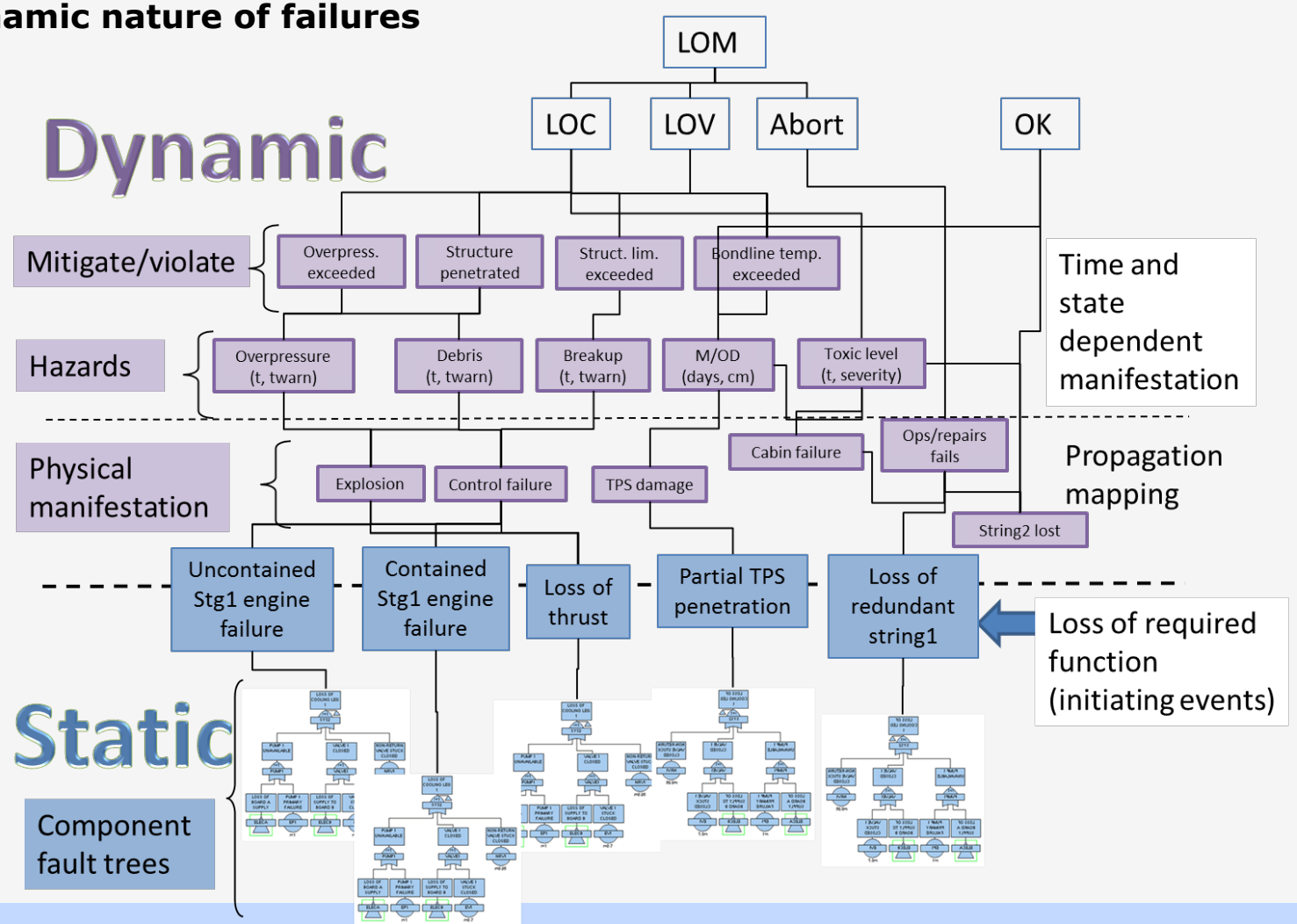
Integrated Ascent Risk Modeling



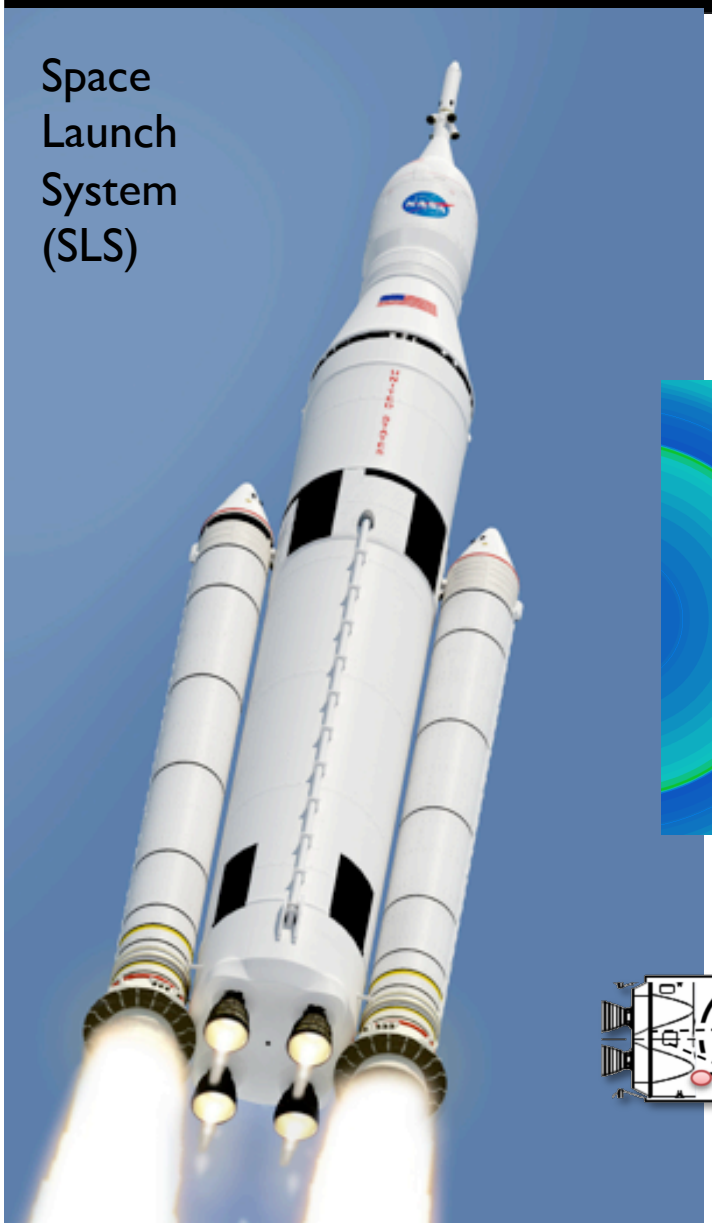


Hybrid Risk Modeling Approach

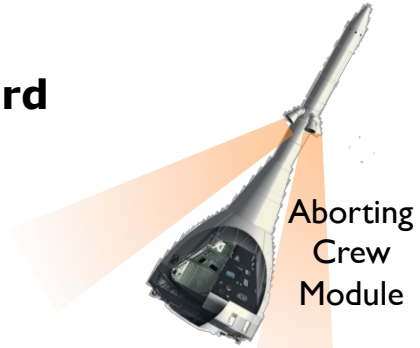
- Engineering Risk Assessment (ERA) extends traditional Probabilistic Safety/ Risk Assessment (PSA/PRA) approaches to incorporate:
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  - **Dynamic nature of failures**

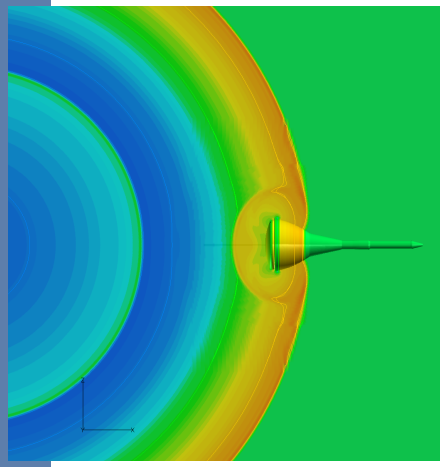


Launch Vehicle Explosion Risk Assessment



- Impact design by focusing physics-based analysis on risk driving **Hazard Environments**
- Launch vehicle stage explosion hazards to crew





Blast Overpressure



Fireball



Debris Strike



Failure Propagation

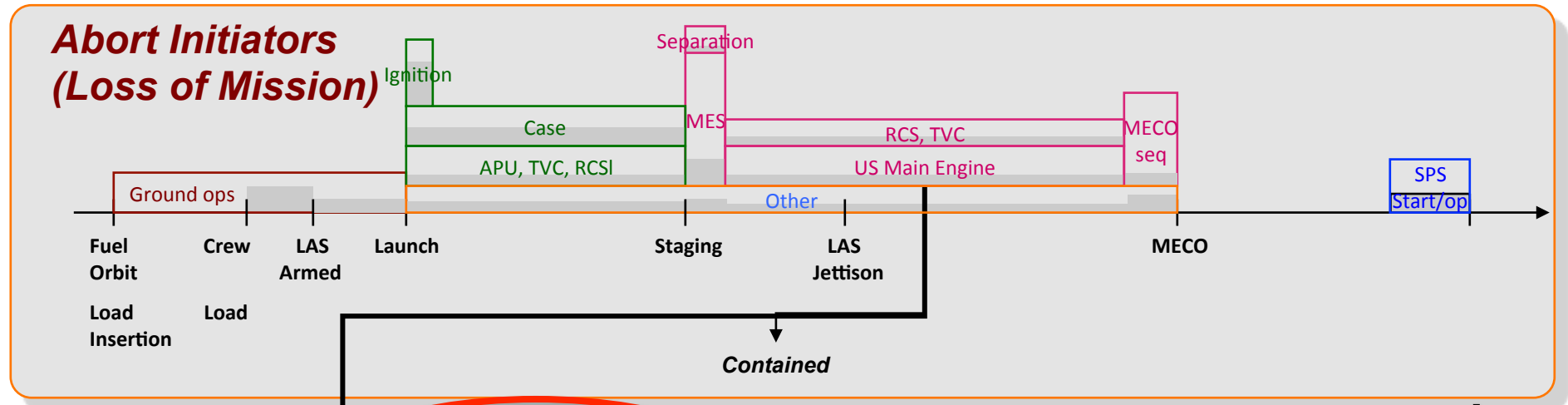
Outline

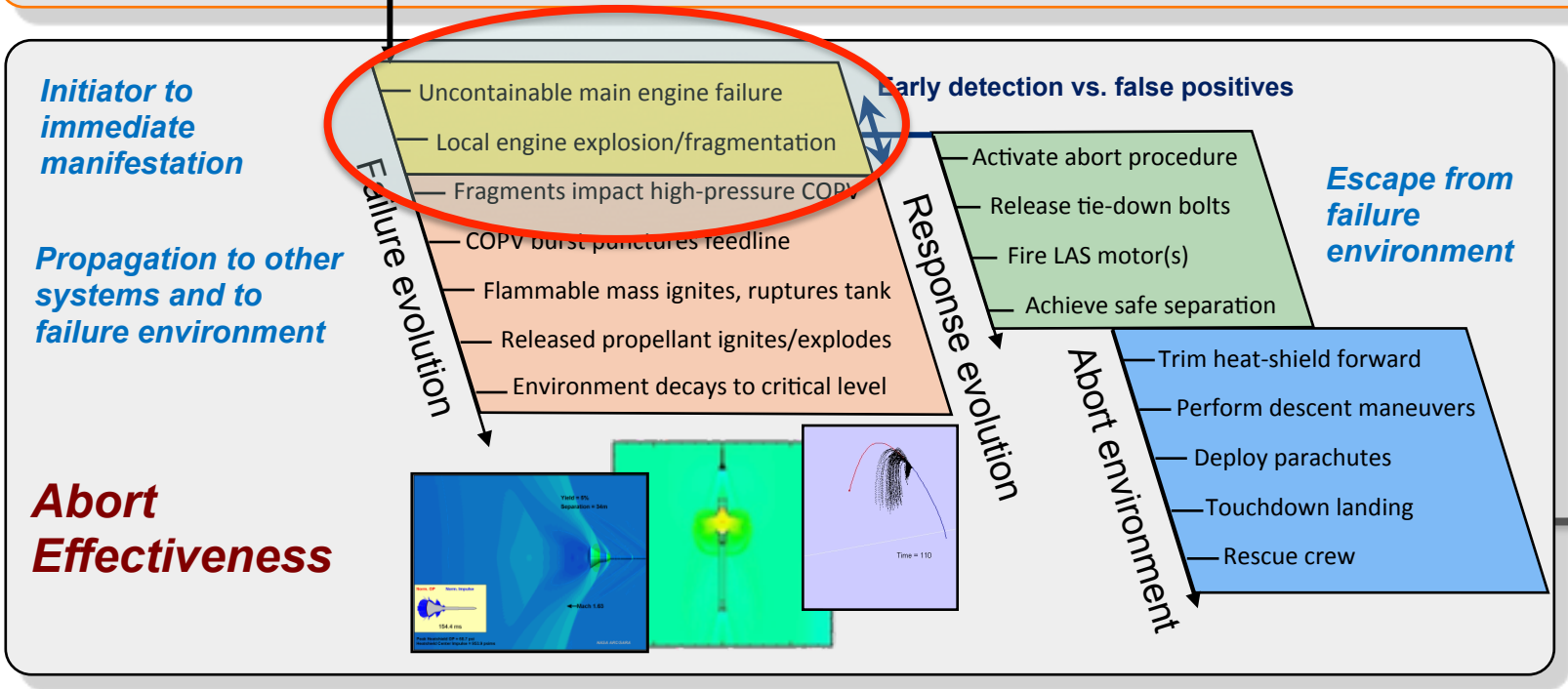


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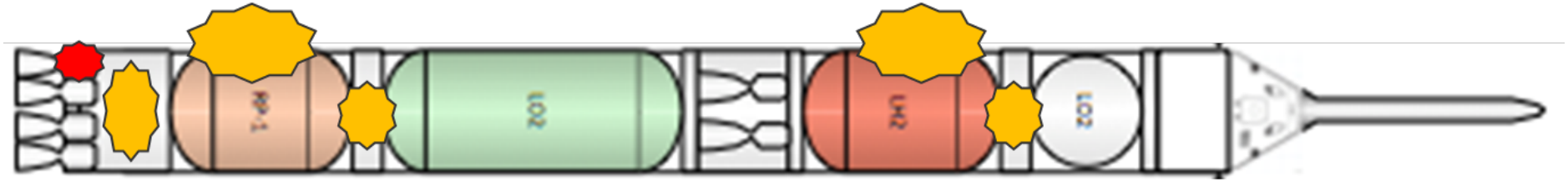

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Failure Propagation
Ref:
S. Lawrence, D. Mathias, K. Gee, "A Failure Propagation Modeling Method for Launch Vehicle Safety Assessment," PSAM 12, Honolulu HI, June 2014.
D. Mathias, S. Motiwala, "Simulation of Liquid Rocket Engine Failure Propagation Using Self-Evolving Scenarios," RAMS, Palm Harbor FL, January 2015.
NASA

Integrated Ascent Risk Modeling





Abortability Flow-Chart: Simple Example



For a given:
- Initial manifestation
- Mission phase
- Warning time

Initial Manifestation

Propagation
- Depends on phase
- Independent of WT

Two Explosions → **Abortable**

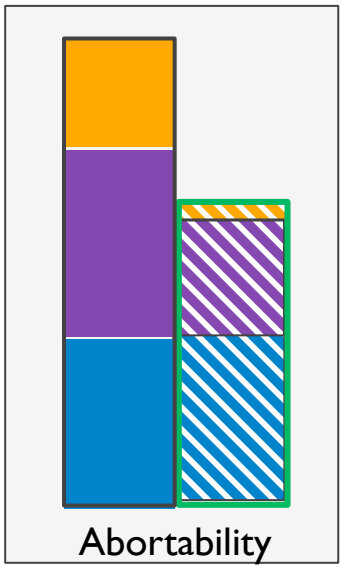
Loss of Crew (1)

Loss of Crew (2)

One Explosion → **Abortable**

Loss of Crew ***(Blast and/or Fragments)***

No Explosions → **Abortable**



Simple Propagation Matrix Example

Selected initiator: Stage 1 turbopump failure

Paths go horizontally and then vertically

Stage 1 TurboPump	0%	50%	15%			
	Stage 1 MCC Expl	70%	0%	5%	0%	
		Aft Skirt Explosion	10%	80%	0%	
		20%	HE Tank Explosion	10%	5%	
				Stage 1 Tank Rupture		50%
				100%	Stage 1 Intertank CBM	
						Stage 2 Tank Rupture

Transition Probabilities

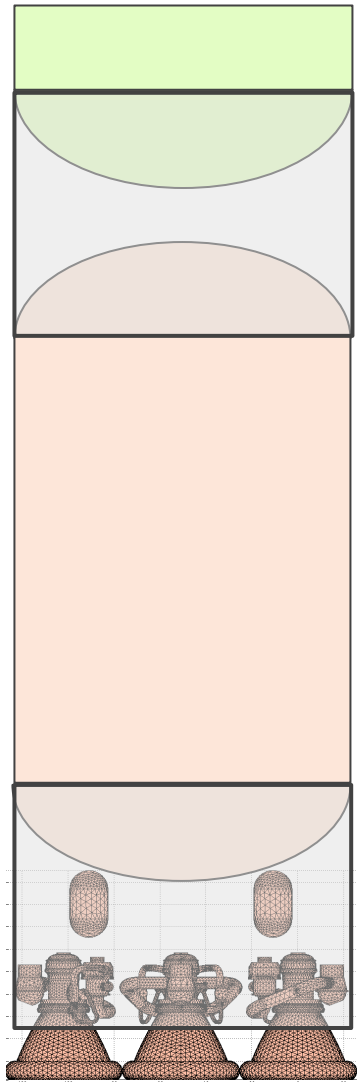
Initiators

Intermediate Environments

Failure Environments

Event Tree

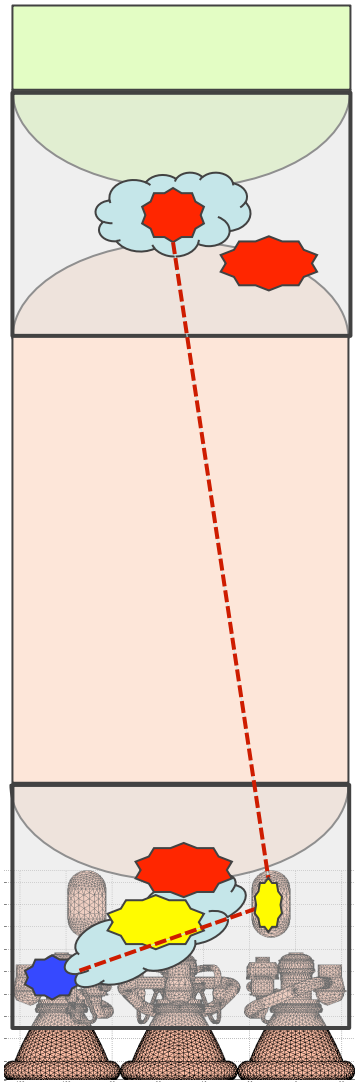
Stage 1 TP



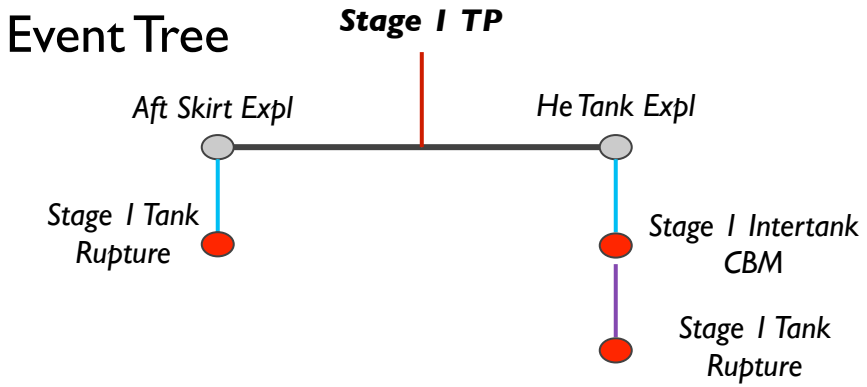
Simple Propagation Matrix Example

Stage 1 inter-tank CBM causes (overpressure) Stage 1 tank rupture

Stage 1 TurboPump	0%	50%	15%			
	Stage 1 MCC Expl	70%	0%	5%	0%	
		Aft Skirt Explosion	10%	80%	0%	
		20%	**HE Tank Explosion**	10%	5%	
				Stage 1 Tank Rupture		50%
				100%	**Stage 1 Intertank CBM**	
						Stage 2 Tank Rupture

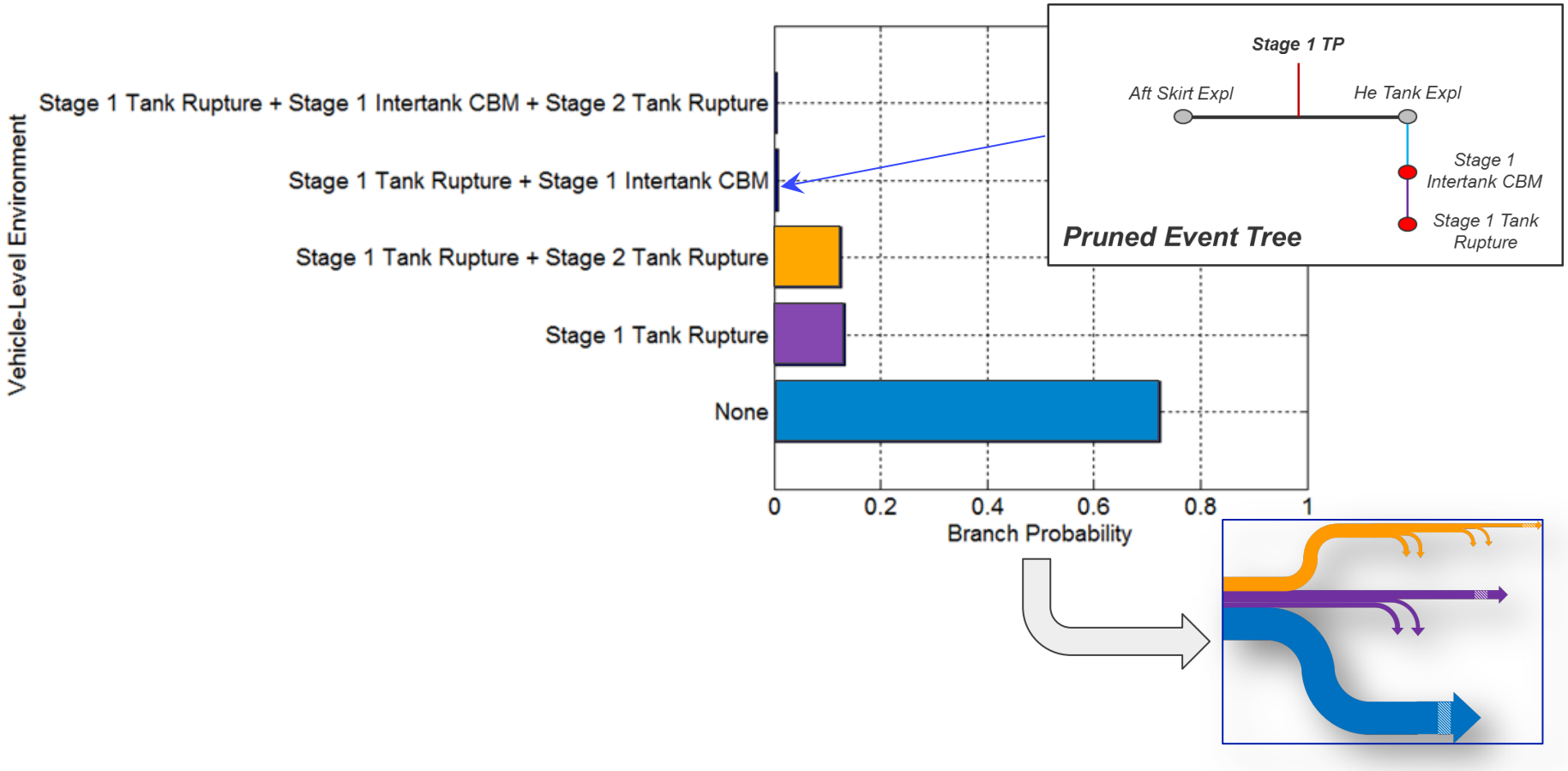


Event Tree



Sample Monte Carlo Results

Monte Carlo results are binned to produce the desired mapping (branch splits) between the initial manifestation and the explosion(s)

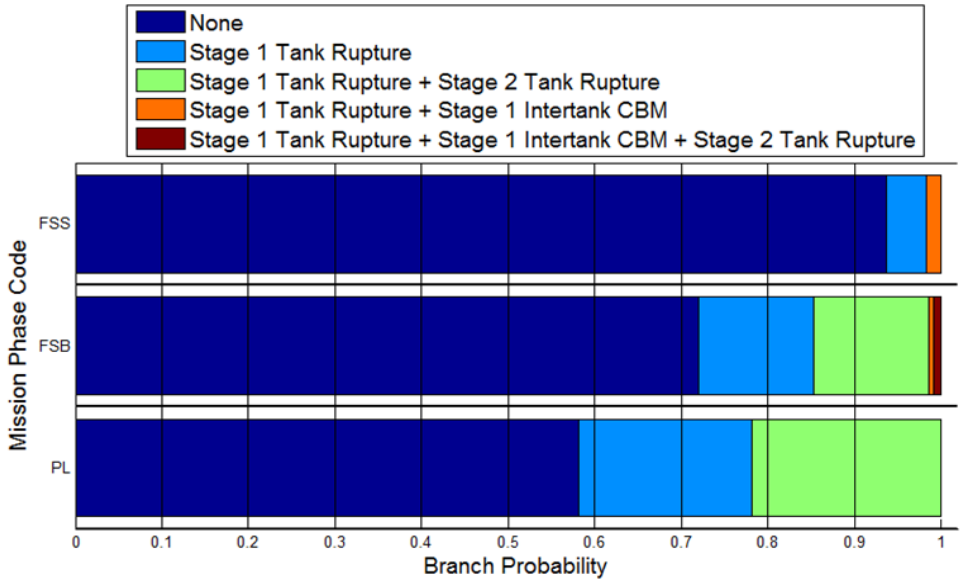


Implementation for Complex Cases

Transition Data Table Snippet

Phase and propagation resistance sensitivities

	Pre-Launch w/ LAS	First Stage Burn	Staging	Upper Stage Burn, w/ LAS	Upper Stage Burn, no LAS	Spacecraft Staging			
ID	PL	FSB	FSS	USL	USN	USS	Source	Target	Timing
E6	0/ 0/ 0	0/ 0/ 0	0/ 0/ 0	0//	0//	0//	Stage 1 TurboPump	Stage 1 MCC Expl	0.01/0.01
F6	90/50/15	90/50/15	90/50/15	0//	0//	0//	Stage 1 TurboPump	Aft Skirt Expl	0.1/0.1
G6	25/15/5	25/15/5	25/15/5	0//	0//	0//	Stage 1 TurboPump	HE Tank Explosion	0.1/0.1
F7	100/70/20	100/70/20	100/70/20	0//	0//	0//	Stage 1 MCC Expl	Aft Skirt Expl	0.1/0.1
G7	5/0/0	5/0/0	5/0/0	0//	0//	0//	Stage 1 MCC Expl	HE Tank Explosion	0.01/0.01
H7	100/15/0	15/5/0	0//	0//	0//	0//	Stage 1 MCC Expl	Stage 1 Tank Rupture	0.01/0.01
I7	0//	0//	0//	0//	0//	0//	Stage 1 MCC Expl	Stage 1 Intertank CBM	0.1/0.1



Mapping: Dependence on Phase

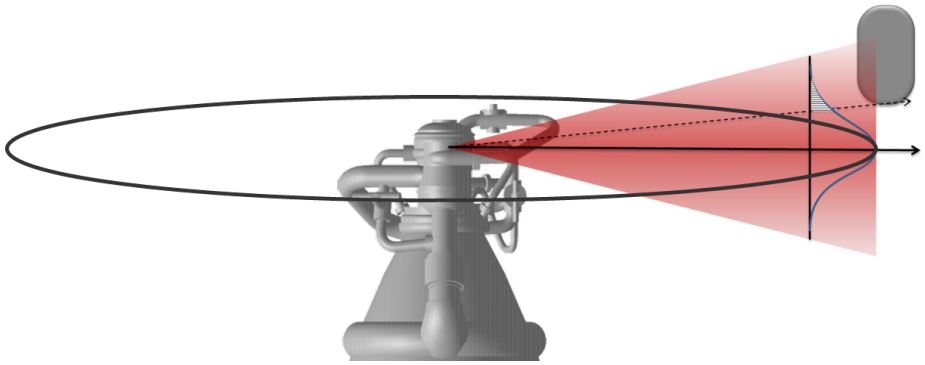
Stage 1 Shutdown/Separation

Stage 1 Boost

Pre-Launch

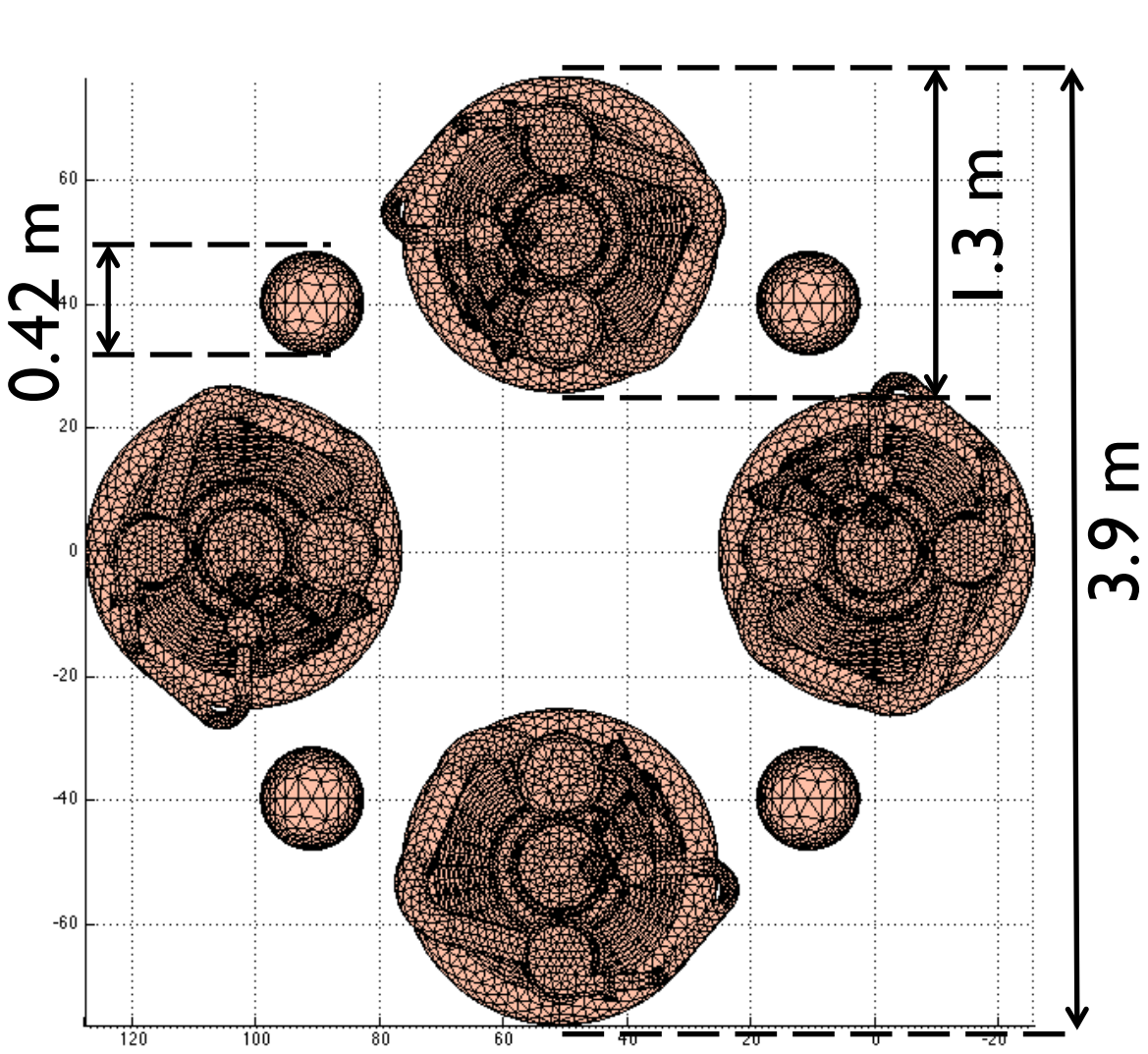
Transition Analysis Thought Process

- Energy Transfer Mode(s)
  - Overpressure
  - Kinetic Energy (Fragments)
  - Shock & Vibration
  - Environment (pressure, temperature)
  - Etc.
- Source Severity
  - Energy type: ***[KE]***
  - Magnitude: ***[Velocity and density]***
  - Uncertainties: ***[Velocity and density]***
- Target Vulnerability
  - Energy type: ***[KE]***
  - Magnitude: ***[Size, Location, Limit velocity]***
  - Uncertainties: ***[Limit velocity]***
- Energy Decay
  - Natural decay with distance: ***[1/d²]***
  - Obstructions: ***[%]***

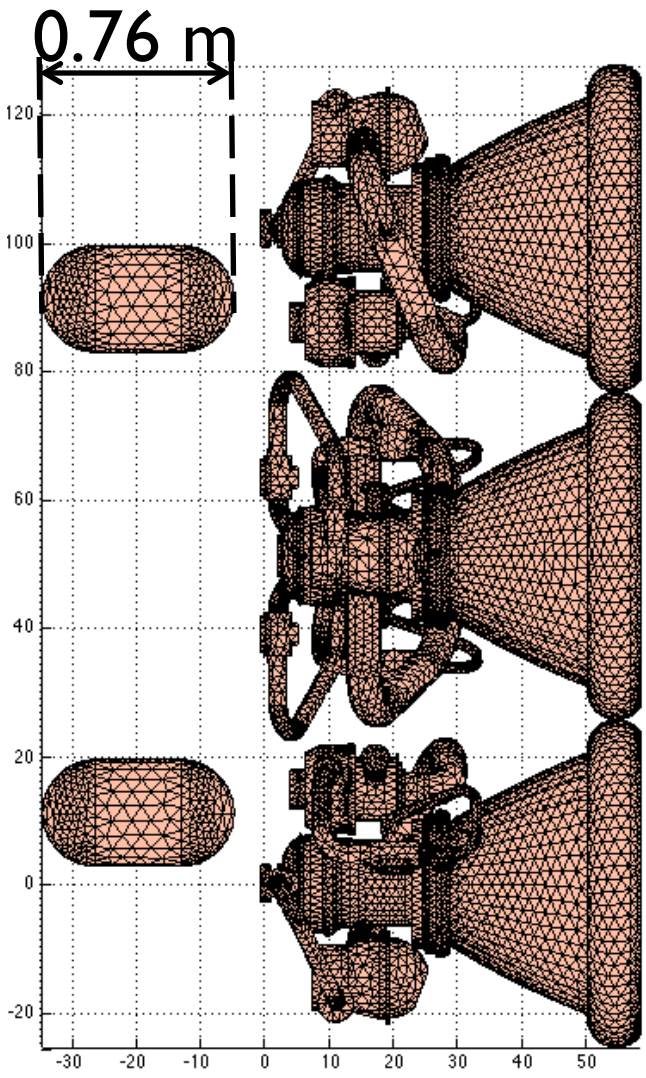


Example: TP Burst → He tank burst

Self Propagating Failure Scenarios



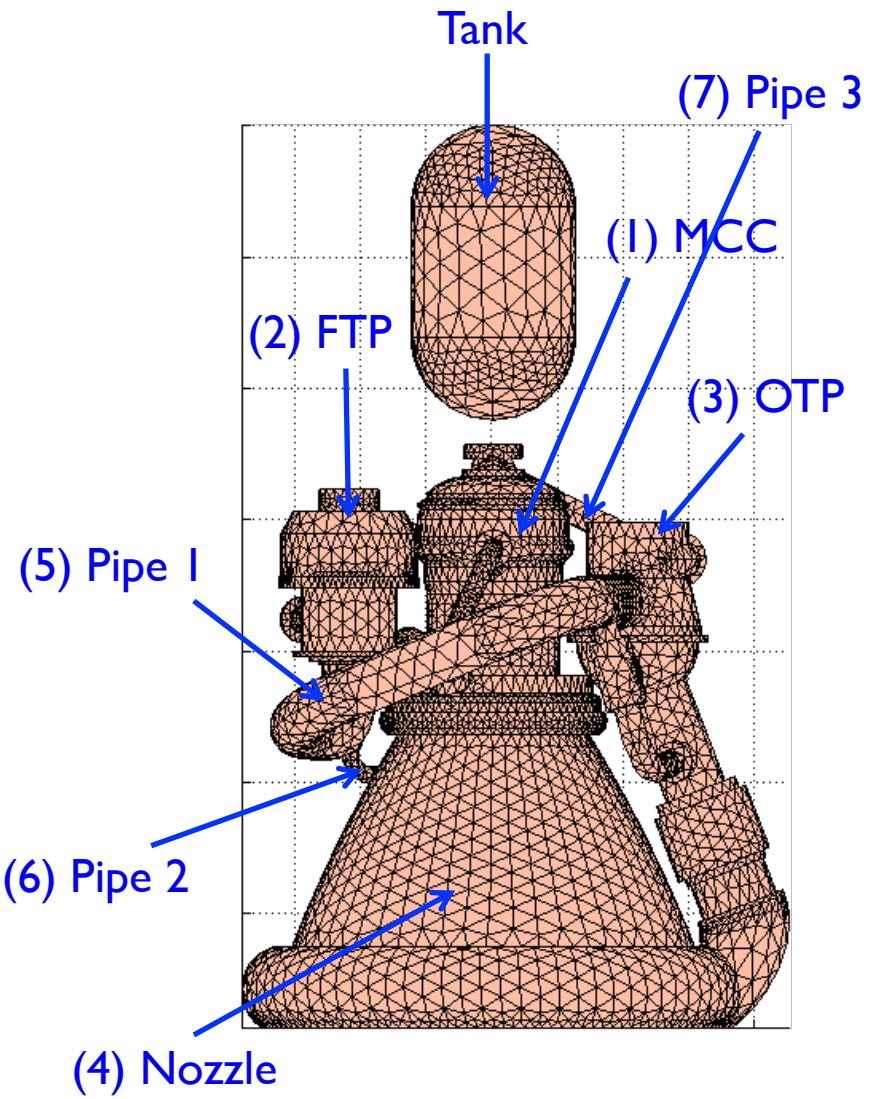
Top Down



Side

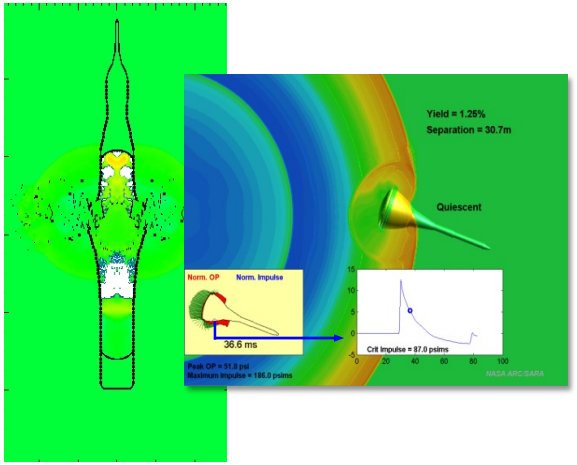
Test Case: 4 Engines + Tanks

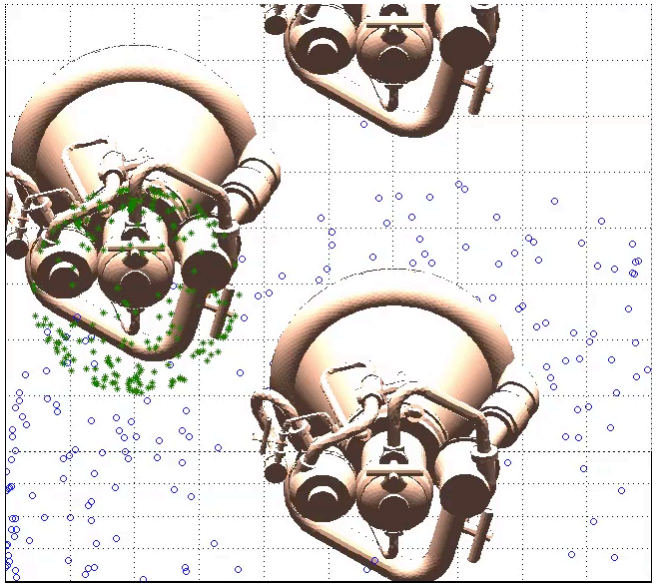
- Simple engine model for generic launch vehicle platform (derived from J2X)
- 32 components: 7 per engine and 4 tanks
  - Main combustion chamber (MCC)
  - 2 turbopumps: fuel (FTP) and oxidizer (OTP)
  - 3 pipes (fuel, oxidizer, hot gas)
  - Nozzle
- Between ~1k–6k triangles per component
- 3 different initiators: MCC, FTP, and OTP



Failure Propagation Model

- Models failure propagation of debris field and blast wave environments
- Consists of component-to-component interactions and behaviors given initial conditions
- Uses Monte Carlo framework developed in C++:
  - Execution begins by seeding a failure and letting it cascade until propagation ends
  - Results include probabilities of component vulnerabilities and scenario tracking
- 100,000 realizations run in ~2 minutes on laptop for current test case





LOM and LOC Probabilities

- Interested in specific end results that lead to loss-of-mission (LOM) or loss-of-crew (LOC) outcomes
- LOM outcome occurs with 2nd engine out – propagation leads to strike of a critical component in another engine

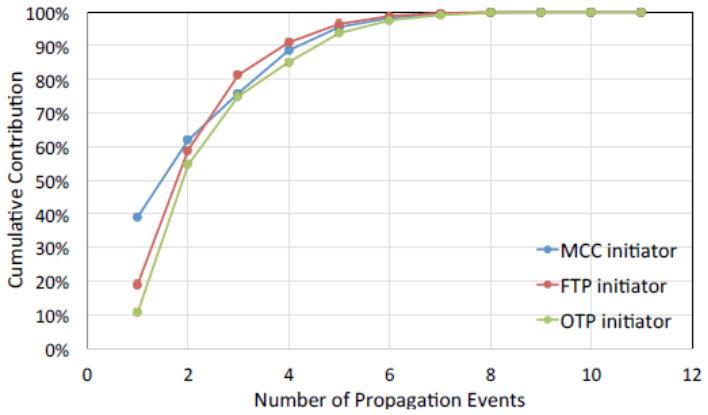
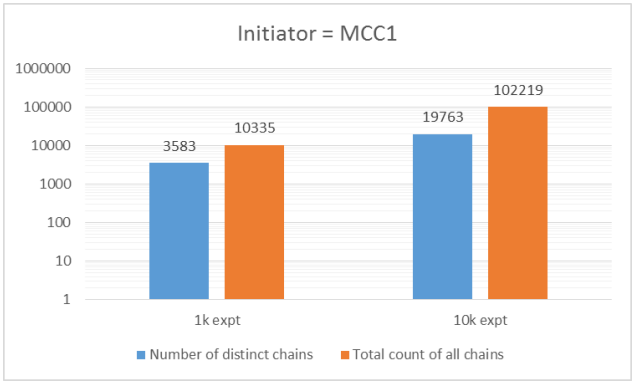
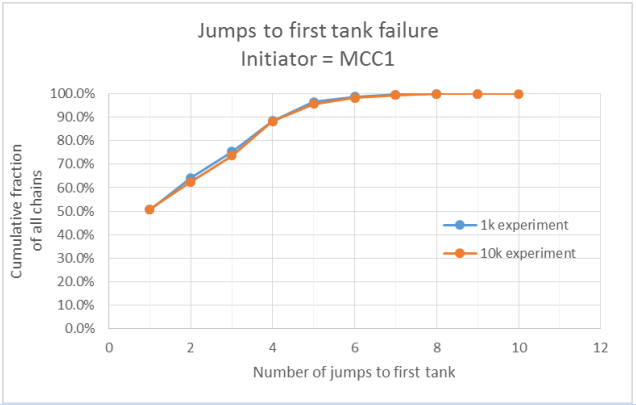


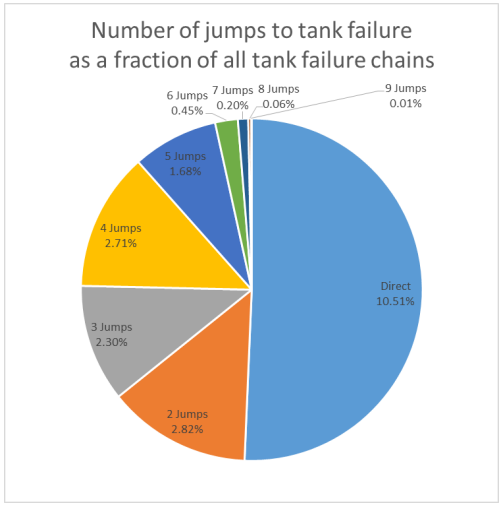
Figure 9 – Contribution of Propagation Events for First Tank Burst

Non-truncated MCC chains, 10k realizations





Average of 10 different failure propagation chains per realization.

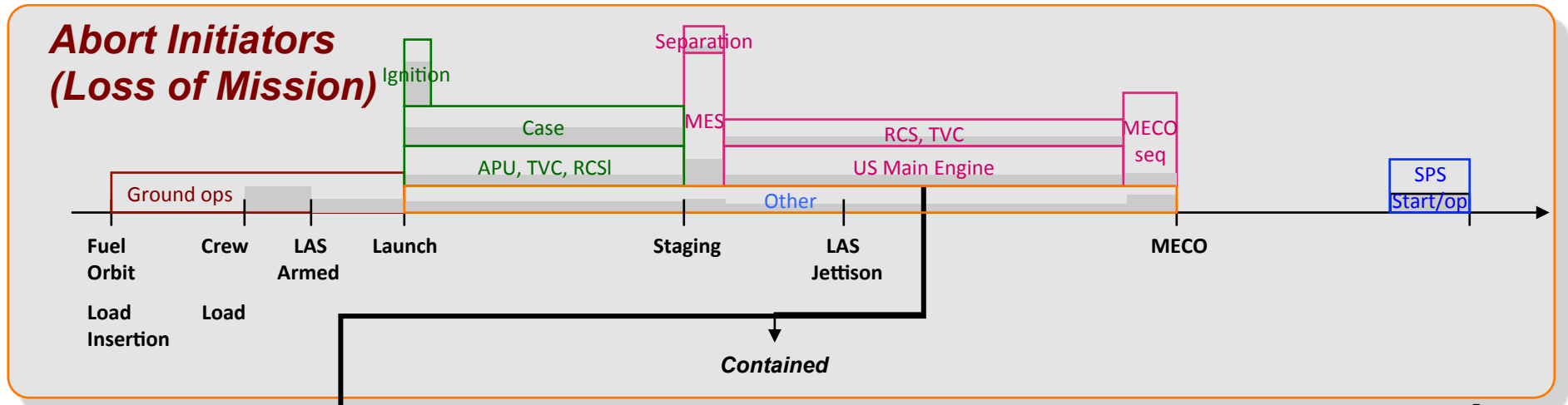


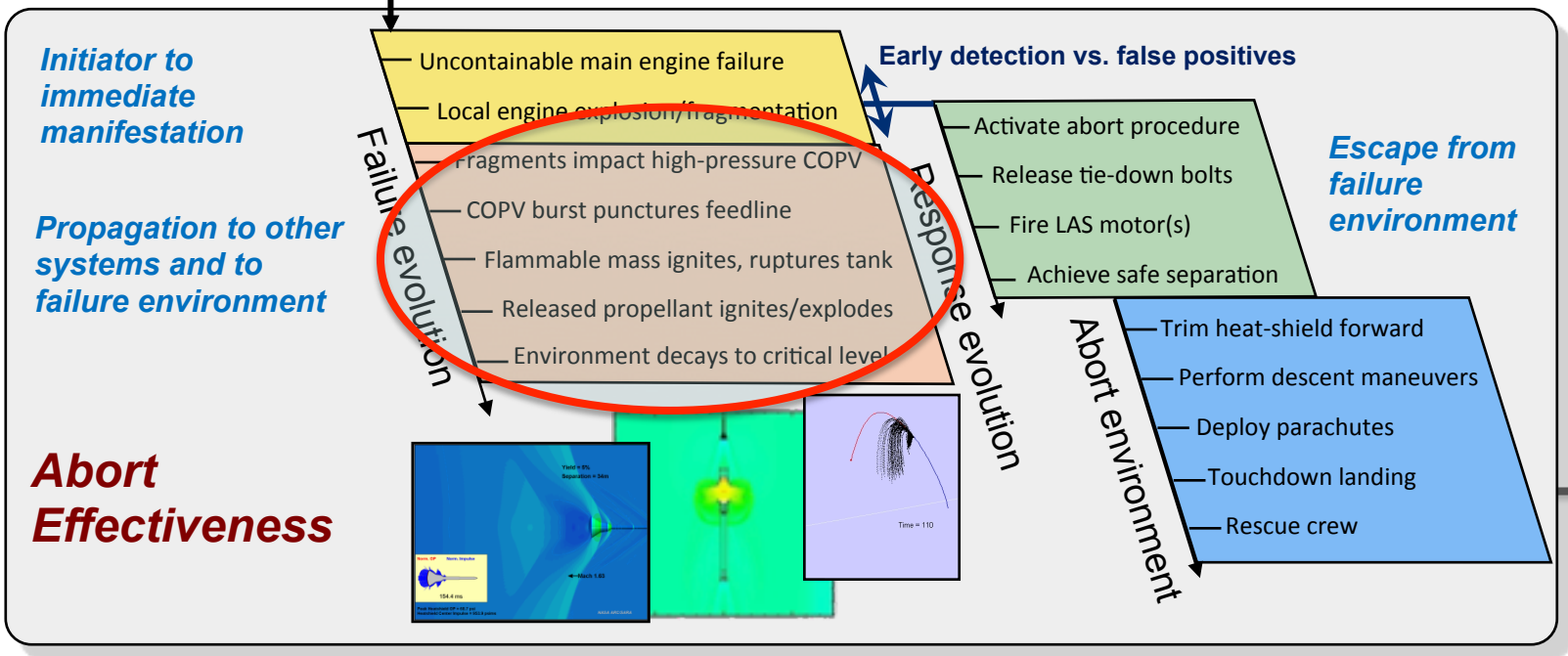
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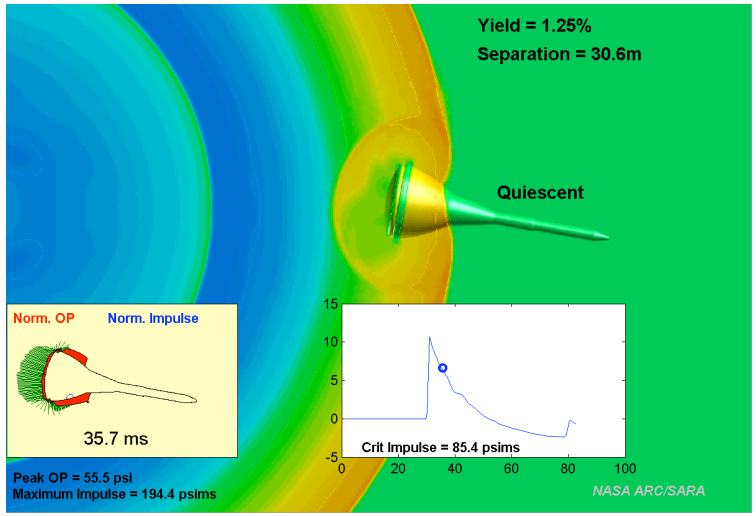
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  - Self Propagating Scenarios
- **Blast Overpressure**
- **Debris Strike Risk**
  - **Debris Catalog Modeling**
  - **Fragment Acceleration**

Integrated Ascent Risk Modeling

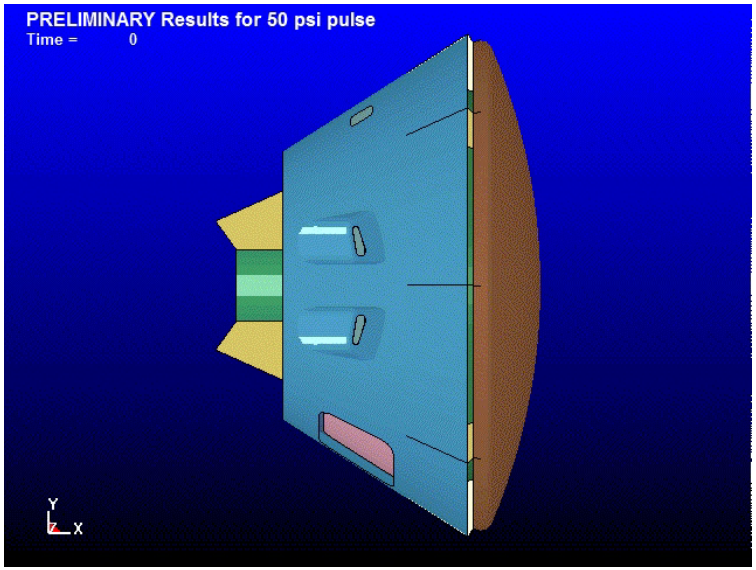


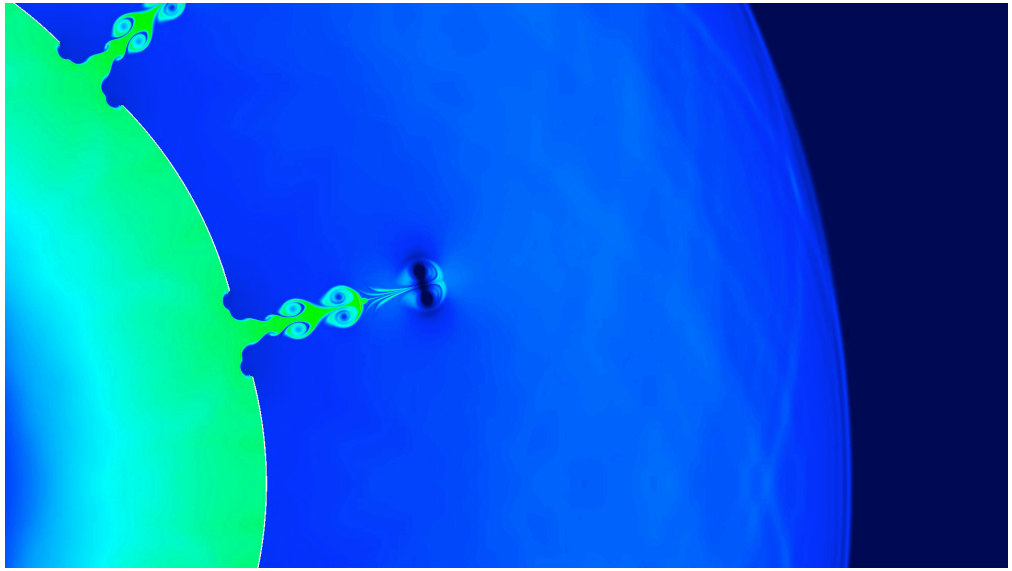


Blast & Debris Modeling

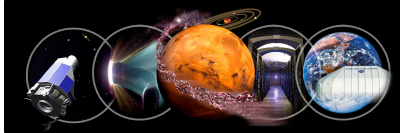


- **Engineering-level models:** quick, easily reconfigurable sensitivity and trade studies
- **CFD blast wave simulations:** more accurate blast propagation and interaction effects
- **CFD tank burst simulations:** launch vehicle tank failure scenarios
- **Structural response modeling:** effects of blast pressures on vehicle






NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Blast Overpressure
S. Lawrence, D. Mathias, K. Gee, M. Olsen, “Simulation Assisted Risk Assessment: Blast Overpressure Modeling, PSAM8, PSAM-0197, June 2006.
S. Lawrence, D. Mathias, “Blast overpressure modeling enhancements for application to risk-informed design of human space flight launch abort systems,” RAMS, January 2008.
NASA

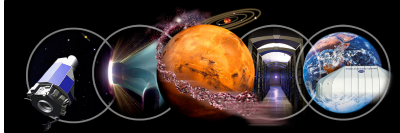


Blast Overpressure Modeling

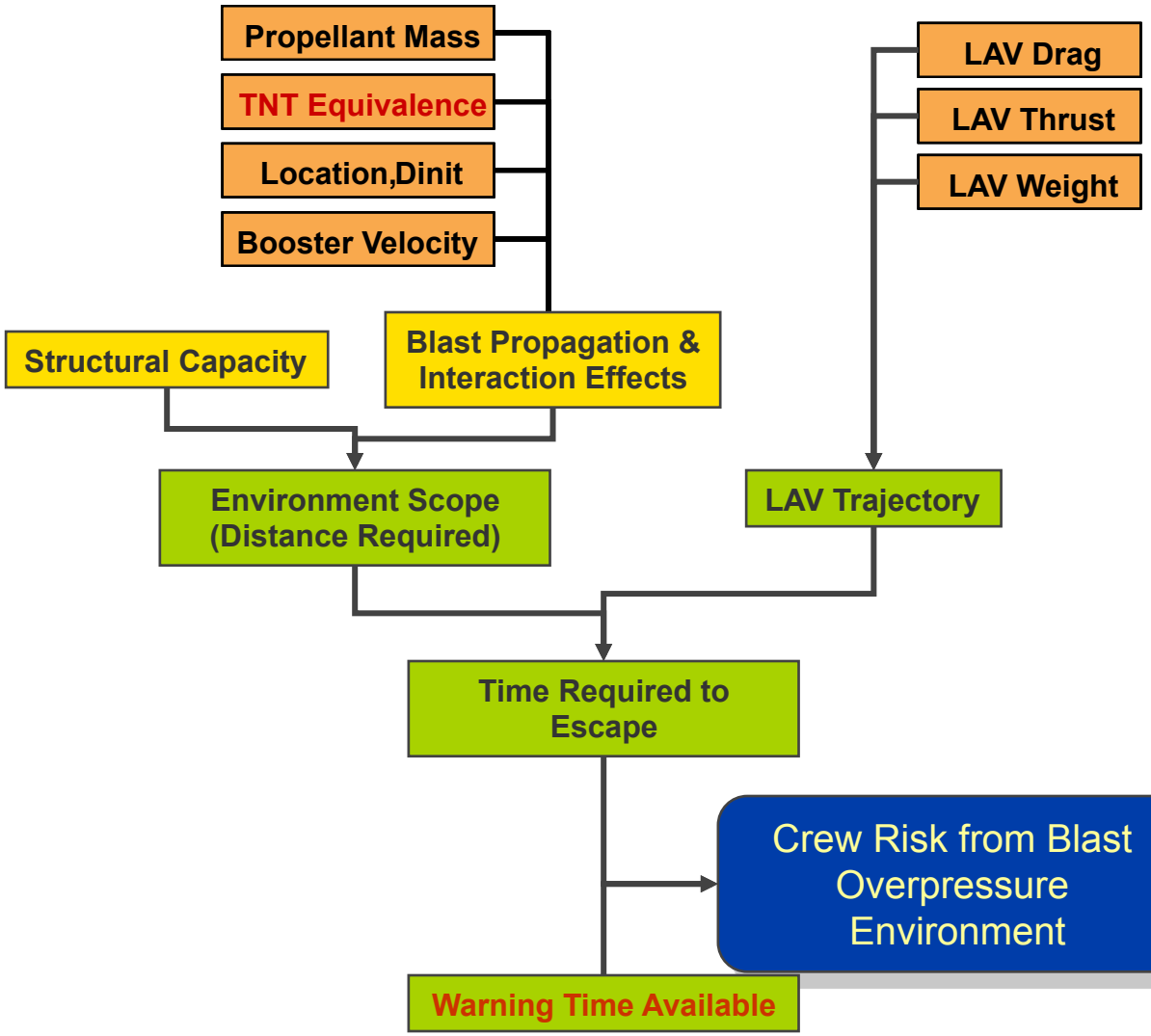
- Objectives:
  - Provide data to support requirement definition/refinement/ verification for structural survival of blast loading
  - For a given structure, provide data to support failure probability analysis
  - Provide risk information for use in integrated ascent/abort risk assessment

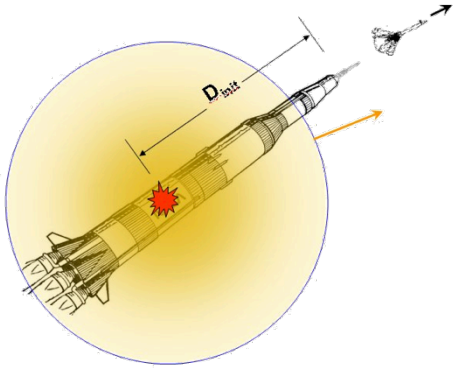
- Key problem elements:
  - Blast size specification (yield %)
  - Blast propagation, including vehicle velocity effects
    - Overpressure decay
    - Blast trajectory (time-of-arrival)
  - Interaction of blast with abort vehicle (LAV)
  - Response of structure to blast loading

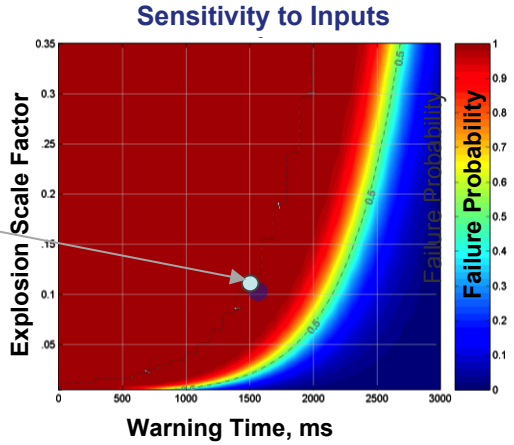
Explosion Modeling: Engineering-Level Model











Vapor Cloud Explosion (VCE) Modeling

- Engineering-level enhancement
- Blast behavior a function of:
  - Total energy (blast size)
  - Detonation Mach number (blast strength)
- TNT distribution replaced with 1-parameter (M_{flame}) family of distributions
  - Baker-Strehlow-Tang curve set: Developed from 1-D numerical simulations w/ simplified chemistry (heat addition)
- Model includes families of curves for positive-phase impulse as well as peak overpressure

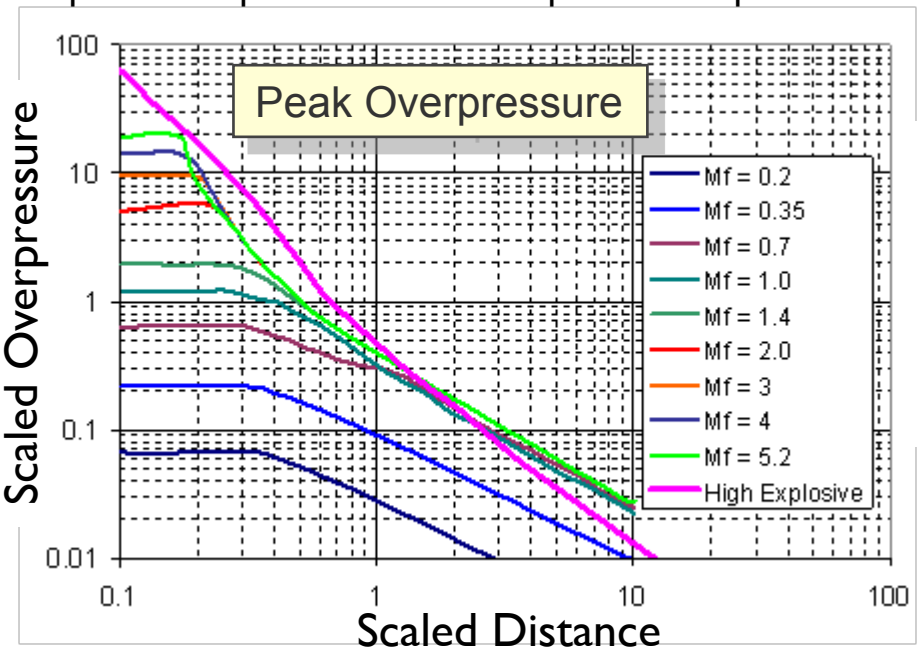
TNT Equivalency/Sachs Scaling:

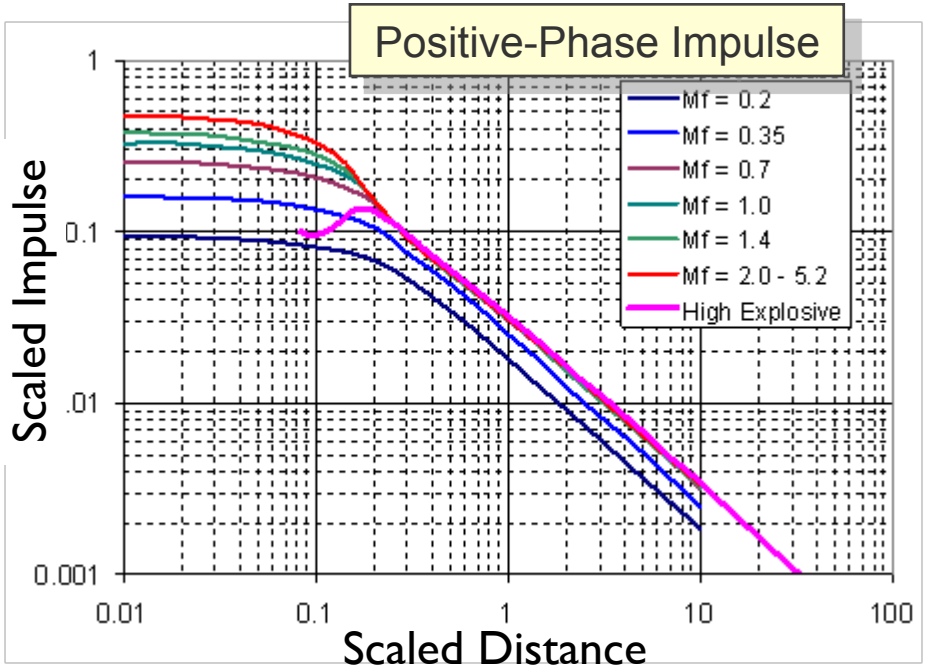
Overpressure: $OP = (p_{max} - p_\infty)/p_\infty$

Distance: $\lambda = x/\alpha$

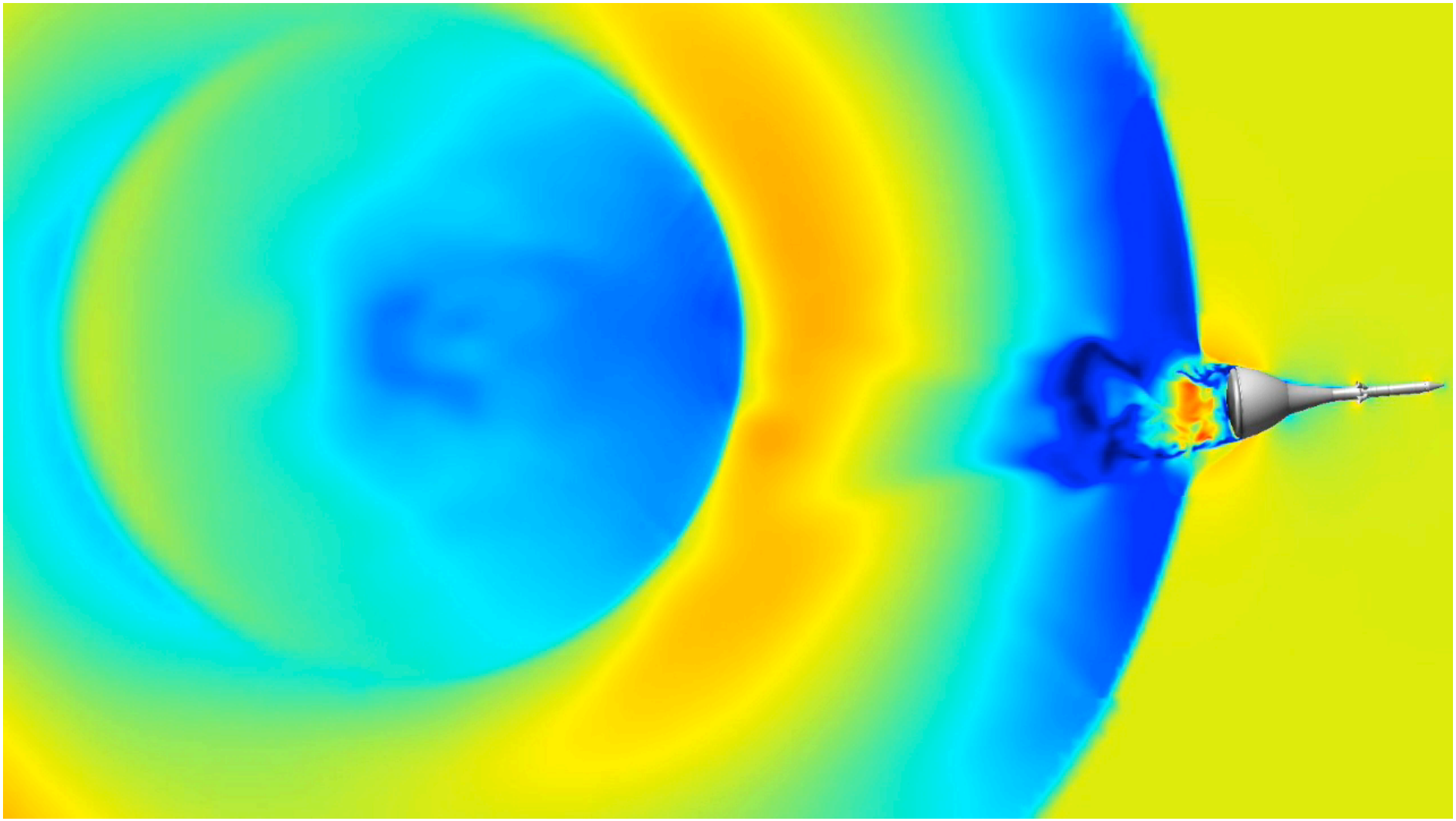
$\alpha = (E_{prop}/p_\infty)^{1/3}$

Time: $\tau = t\, c_\infty/\alpha$





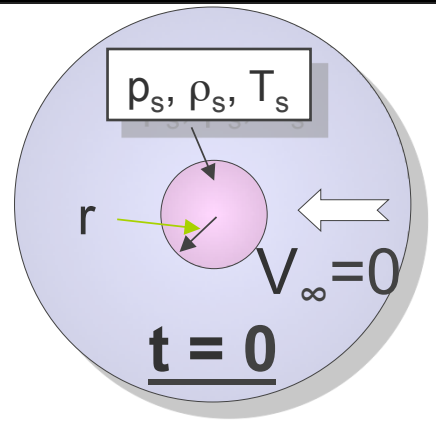
Blast Propagation Model



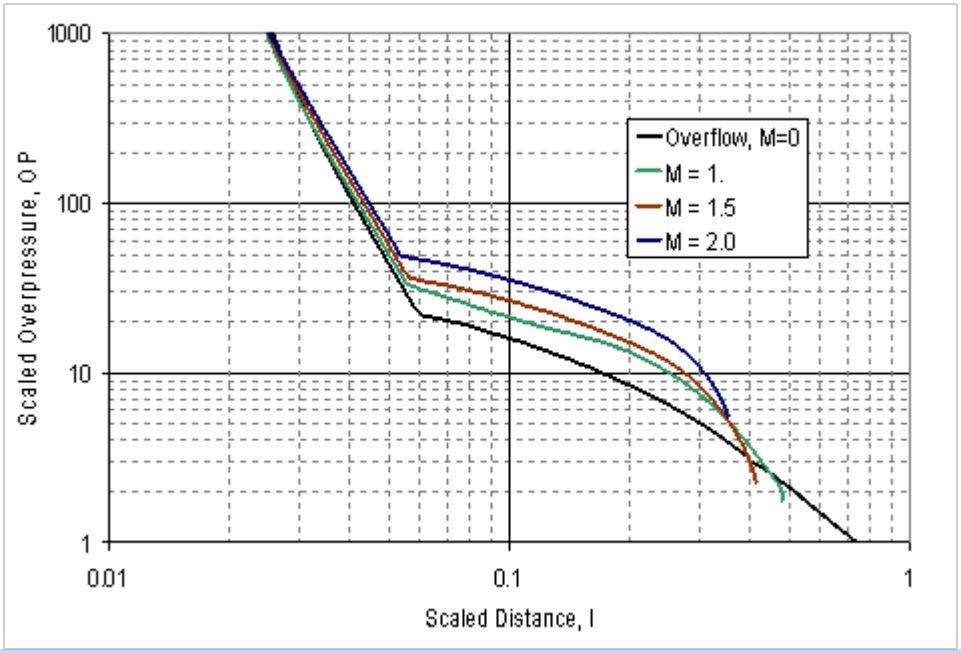
Headwinds: Navier-Stokes Simulations

Perfect gas simulations at selected conditions along ascent trajectory

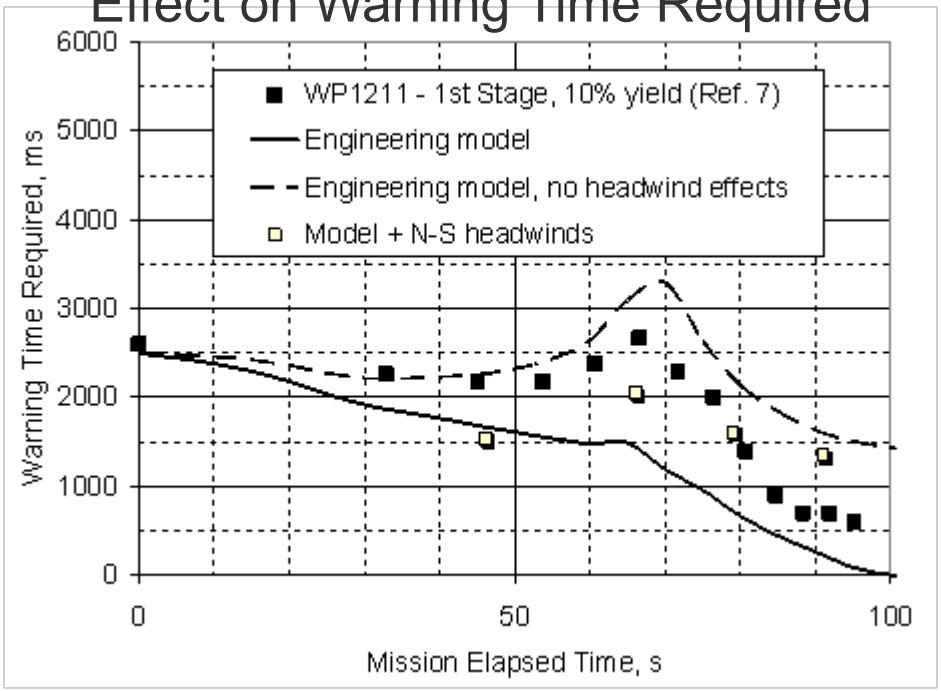
- Increase initial shock strength
- Increase penetration
- Sensitive to initial conditions



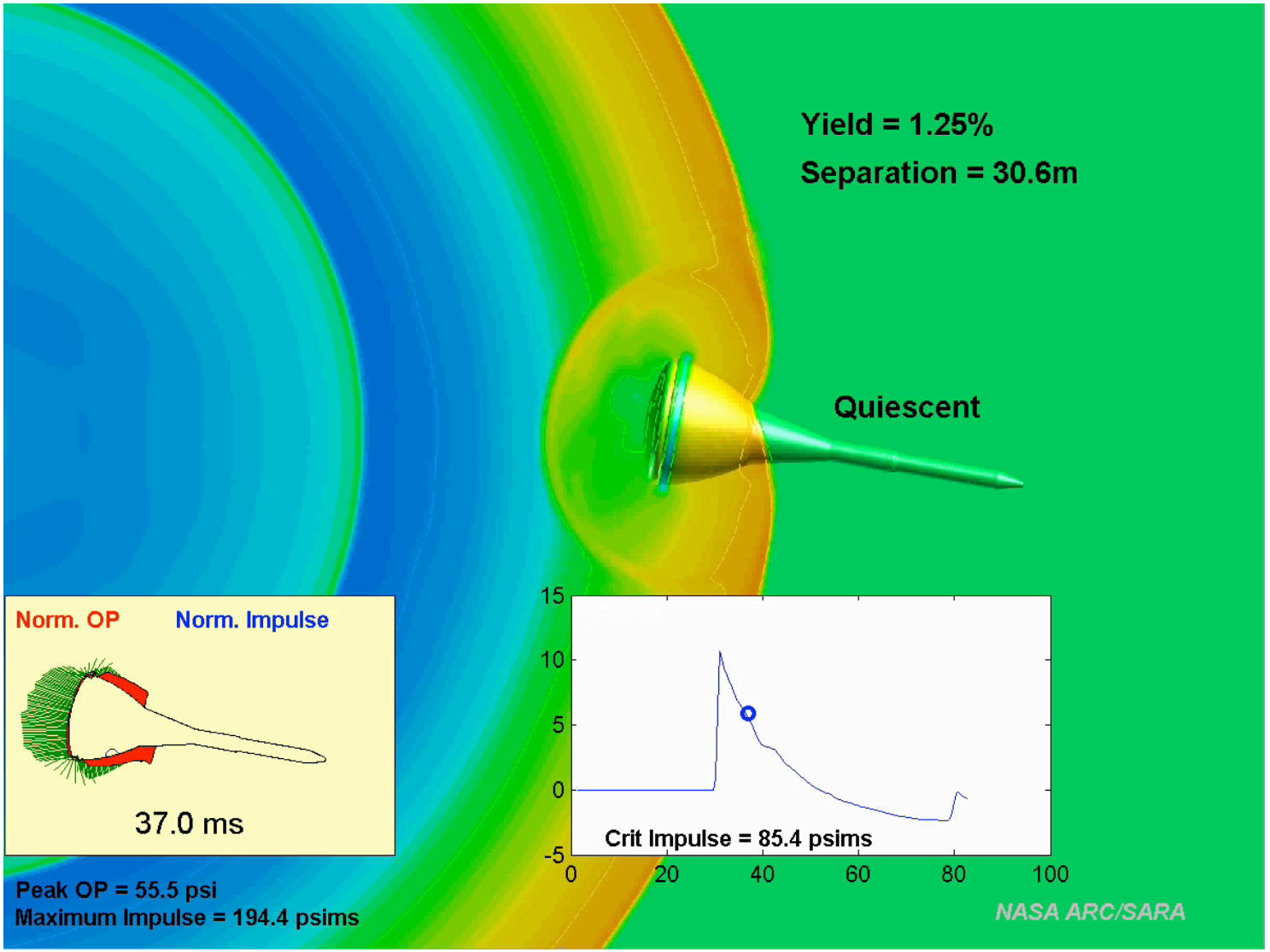
Overpressure Characteristics



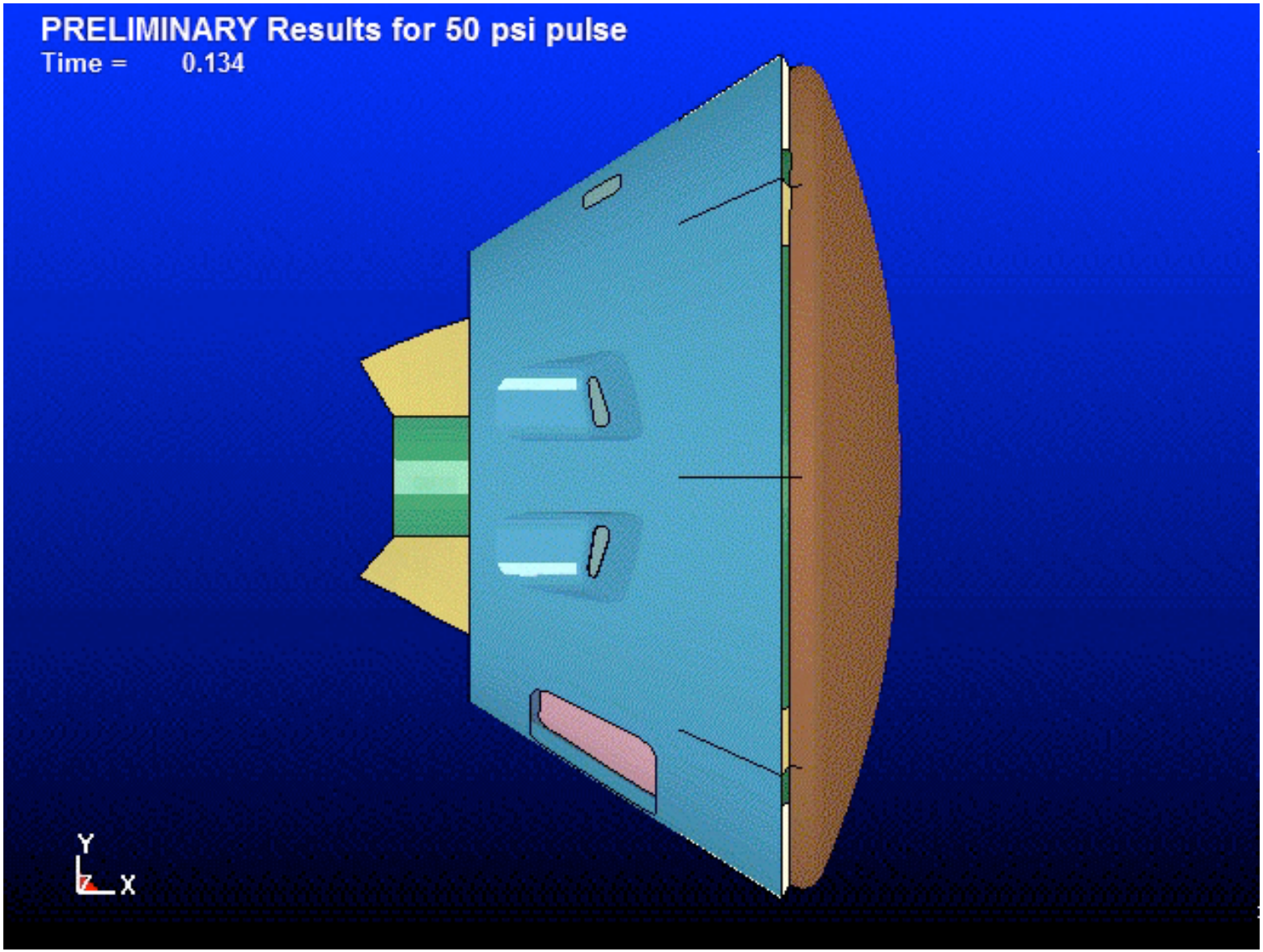
Effect on Warning Time Required



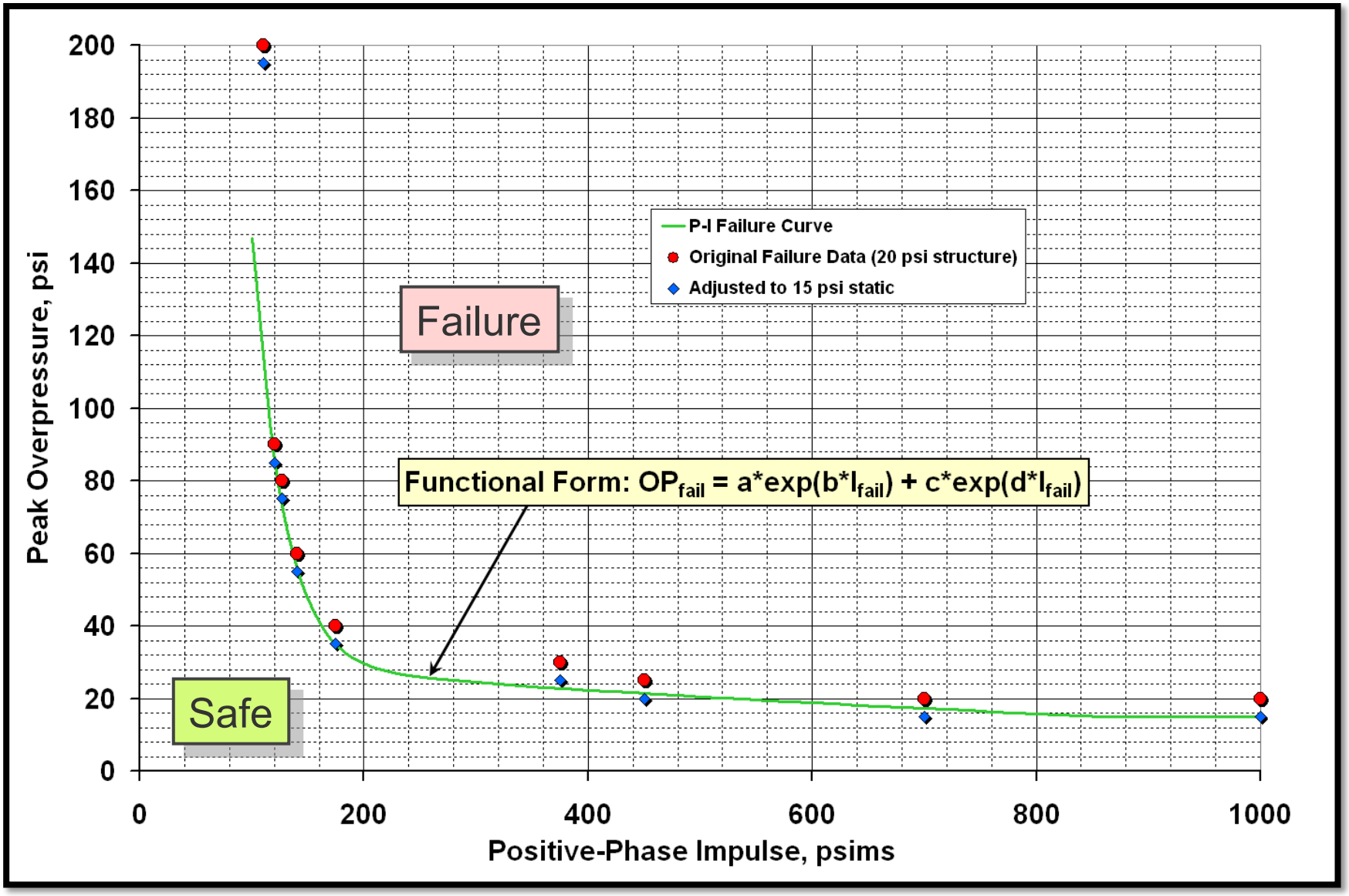
Blast Propagation Model



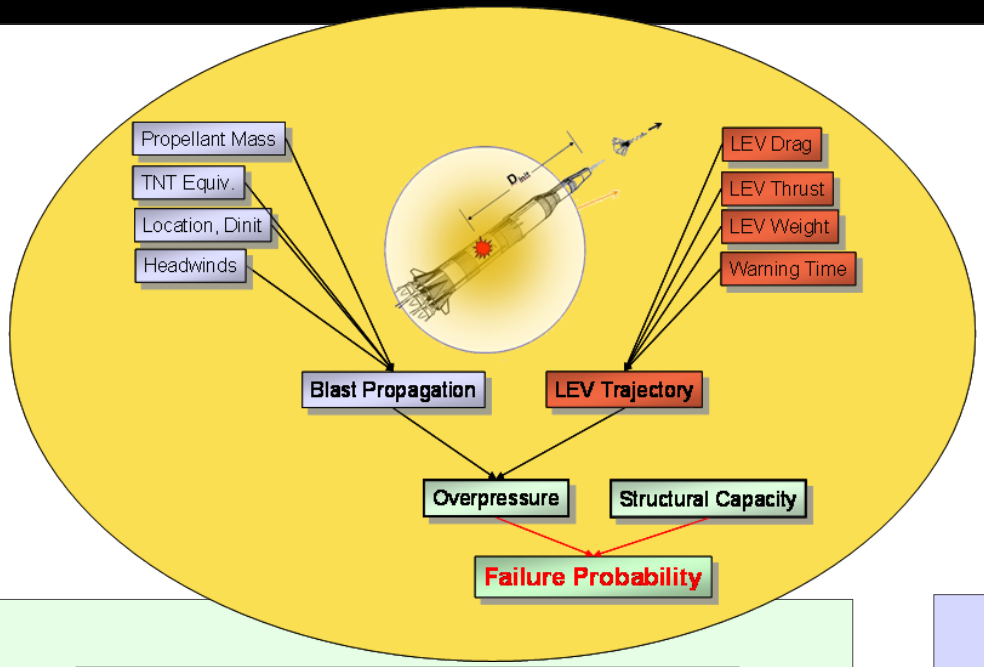
Structural Response Model



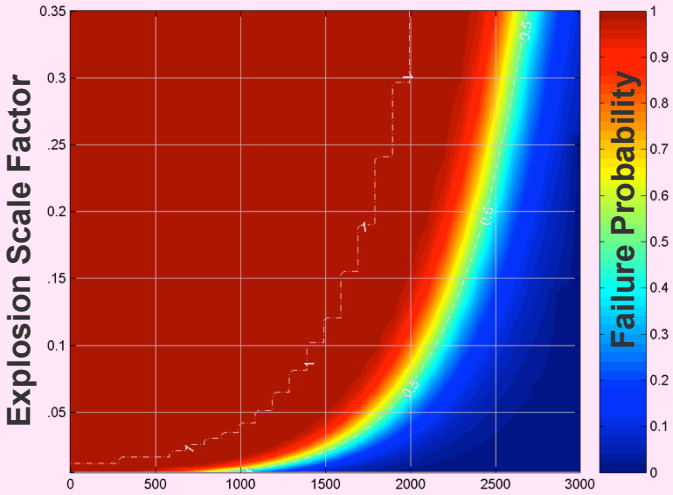
Overpressure-Impulse (P-I) Failure Criteria

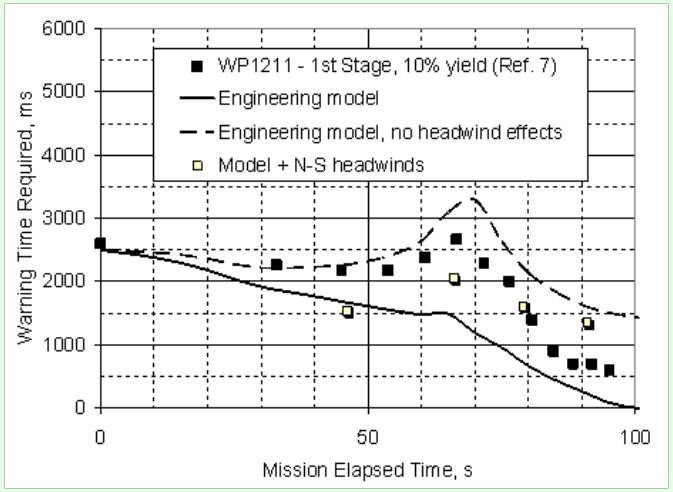


Blast Overpressure: Applications

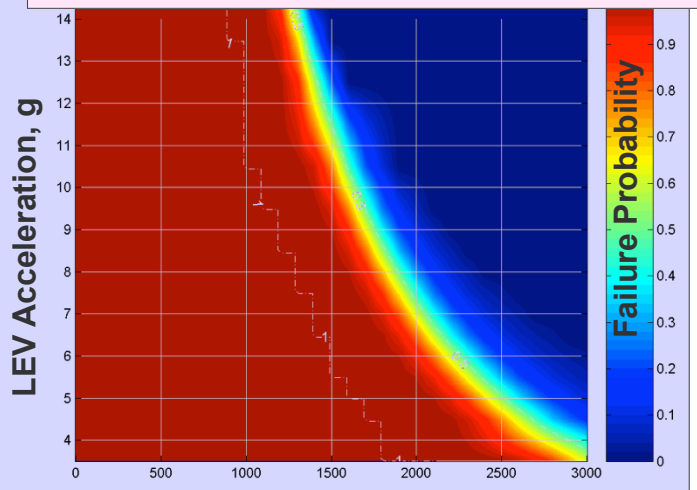


Sensitivity to Uncertain Inputs





Warning Time Requirements

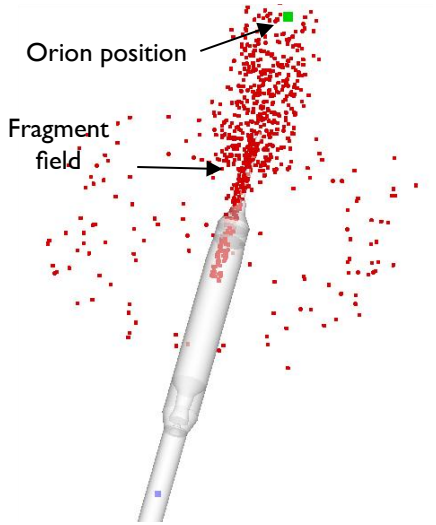


Sensitivity to Design Parameters

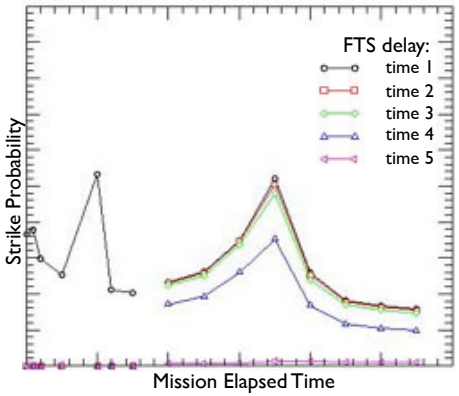

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Debris Strike Risk
K. Gee, S. Lawrence, “Launch Vehicle Debris Models and Crew Vehicle Ascent Abort Risk, RAMS, January 2013.
K. Gee, S. Lawrence, “Sensitivity Analysis of Launch Vehicle Debris Risk Model,” PSAM10, June 2010.
K. Gee, D. Mathias, “Assessment of Launch Vehicle Debris Risk During Ascent Aborts,” RAMS, January 2008.
NASA

Debris Model

- Debris propagation
  - Three degrees-of-freedom (3DOF) trajectory integration using MISSION code
  - Trajectories calculated for:
    - Launch vehicle
    - Crew module
    - Each fragment of potentially dangerous size
- Initial debris conditions ("Debris Catalog")
  - Mass distribution based on experimental data
  - Velocity distribution
    - Experimental and historical data
    - Computed results
- Debris Impact risk determined from intersection of CM and debris trajectories

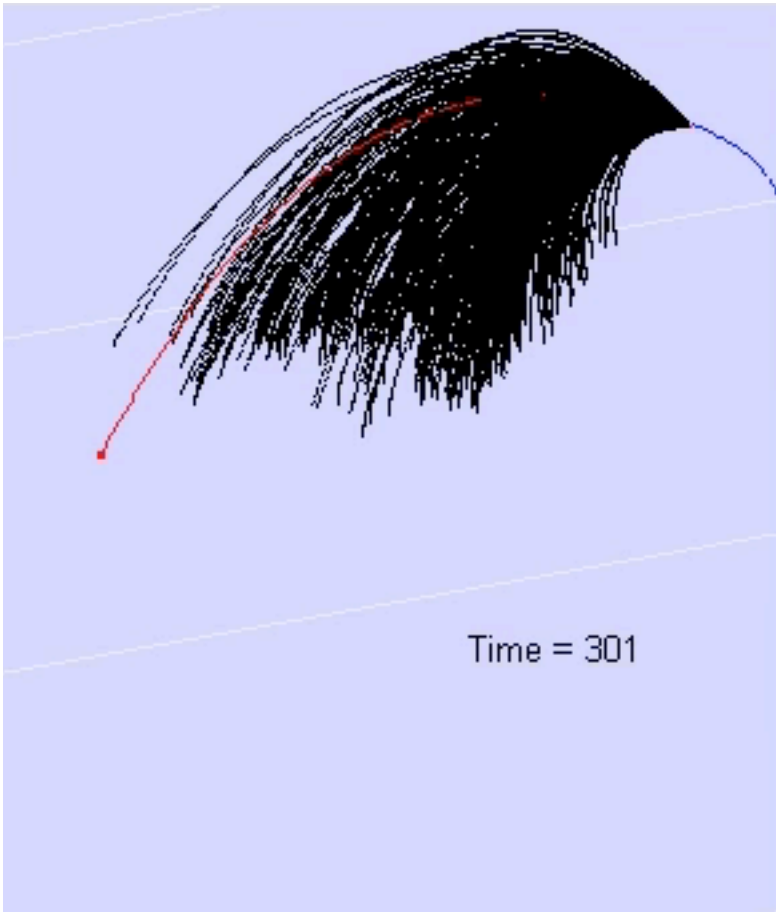


Debris field caused by fragmentation of the Ares I CLV during ascent



Strike probability as a function of MET with penetration criterion

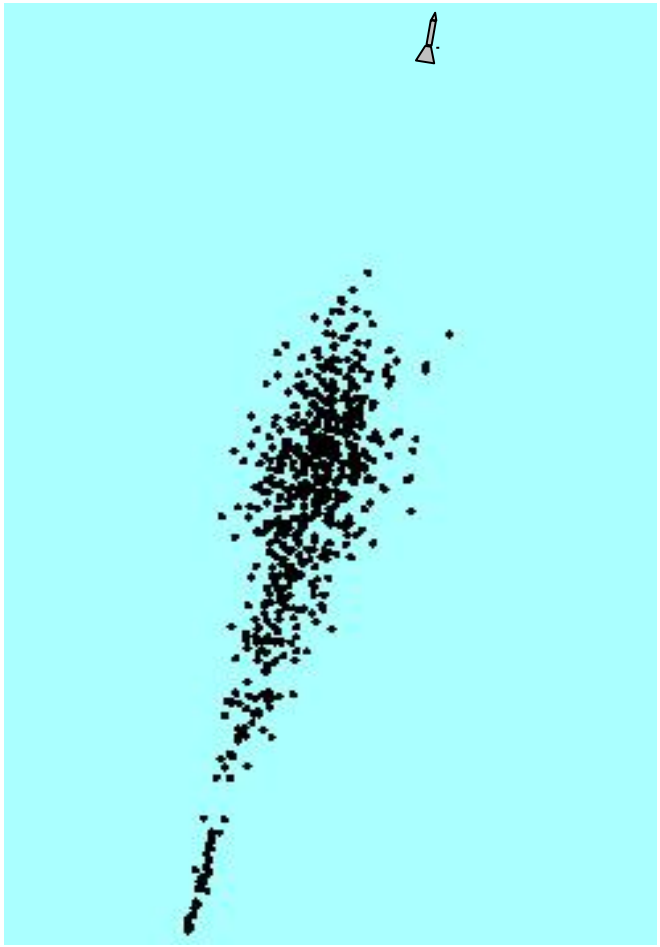
Debris Propagation Model



Analysis of Debris Strike Probability

- Debris catalog generation
  - Generate debris field based on vehicle dimensions and failure mode
  - Assess sensitivity of strike probability to debris field parameters
- Response surface approach to predicting strike probability
  - Full Monte Carlo analysis can be computational expensive and time-consuming
  - Investigated accuracy and speed of response surface approach

Launch Vehicle Debris Catalog



- Number of pieces
- For each piece
  - Mass
  - Reference area
  - Aerodynamic characteristics
  - Imparted velocity

Debris Catalog Model

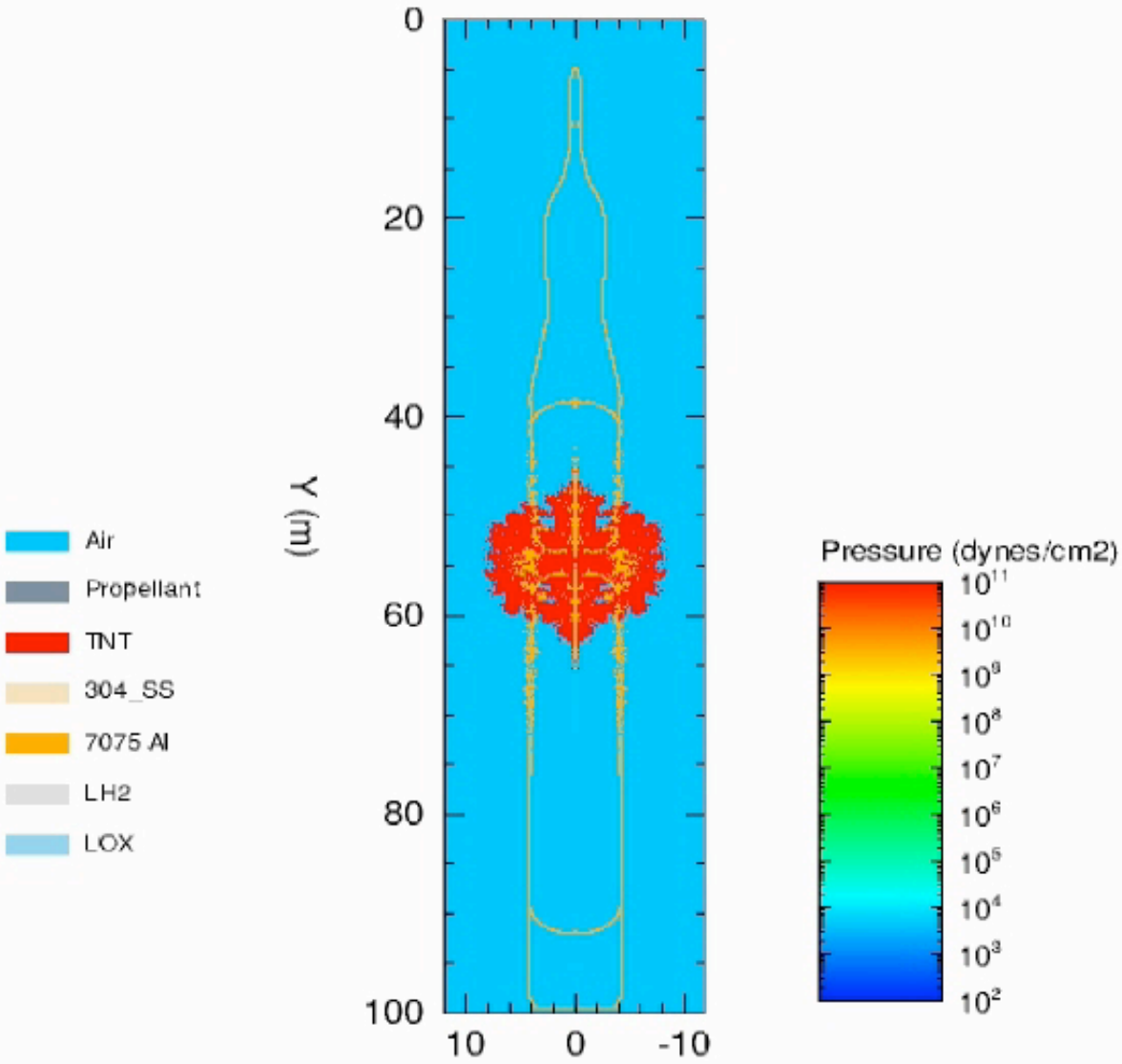
- Number of pieces and mass distribution
  - Based on analysis of explosion of cylinders
  - Controlled by average mass of debris pieces

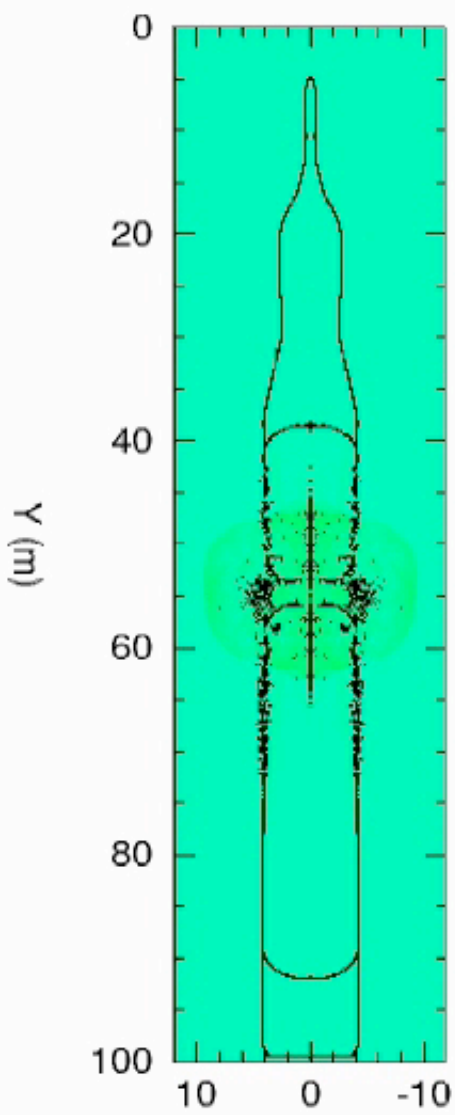
Sternberg 3-part exponential distribution

- Imparted velocity
  - Flight termination system (FTS)
    - Activation of linear shaped charges
    - Controlled by tank pressures and crack/hole size (venting)
  - Explosion
    - CTH solution
    - Controlled by equivalent mass of TNT

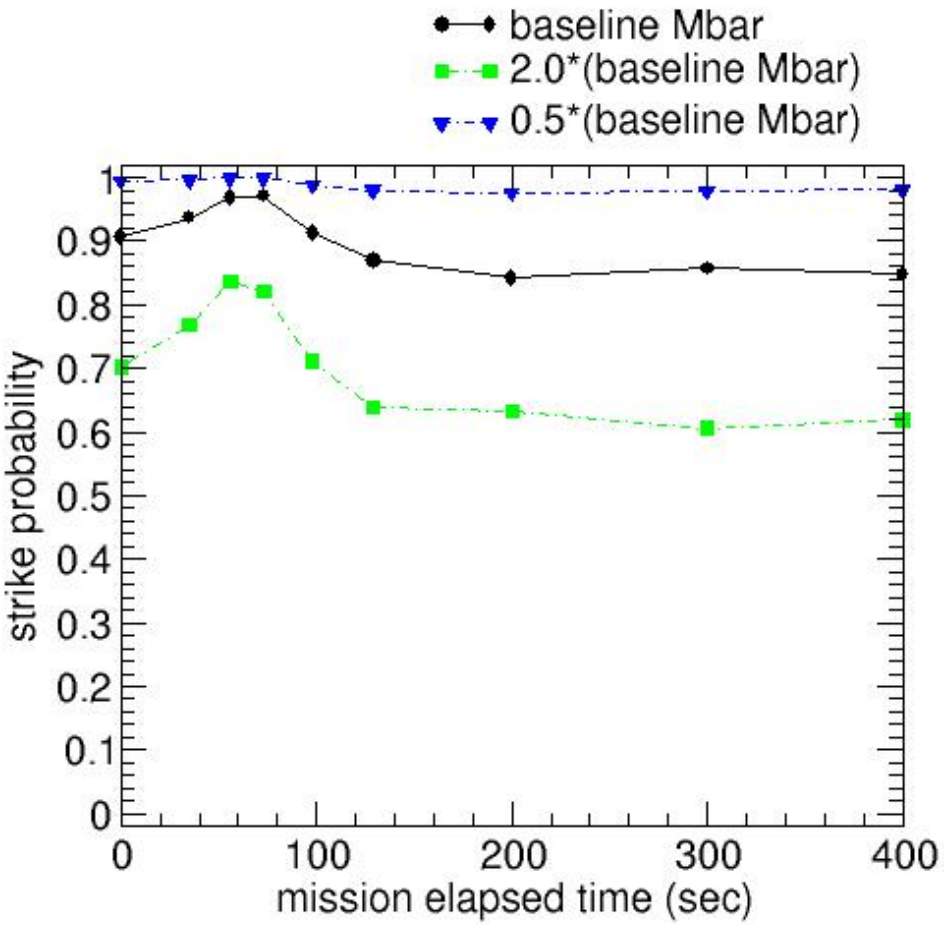
Johnson-Cook fracture
Grady-Kipp fragmentation

Vehicle-level Explosion Model II





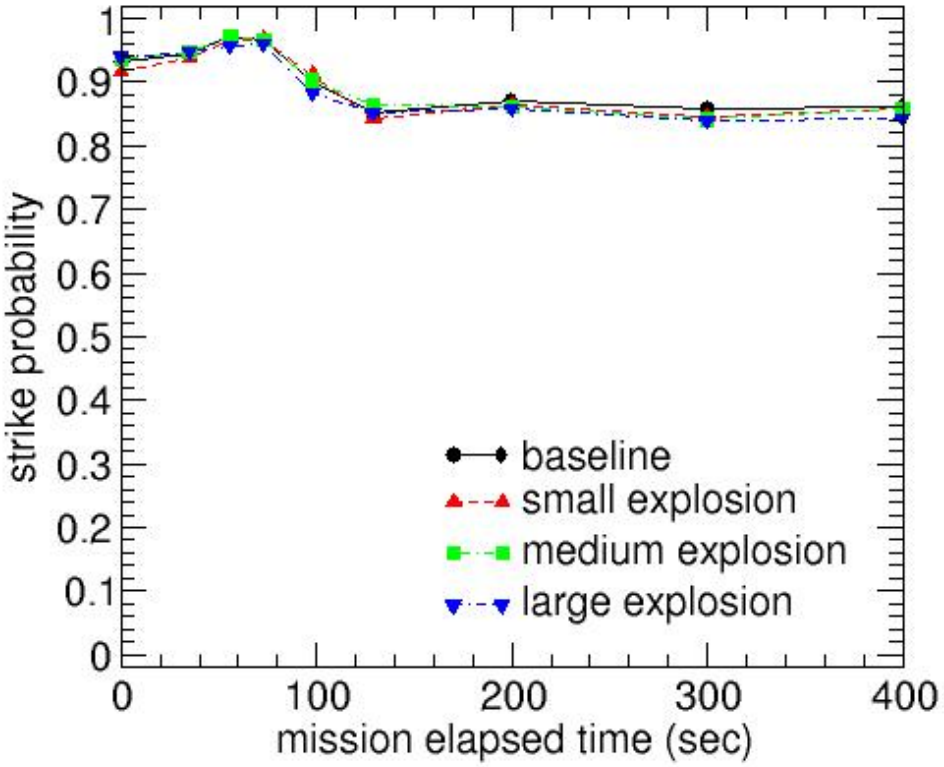
Debris Strike Sensitivity



- Current model
- Effect of number of debris pieces
- Warning time = 0.5 sec

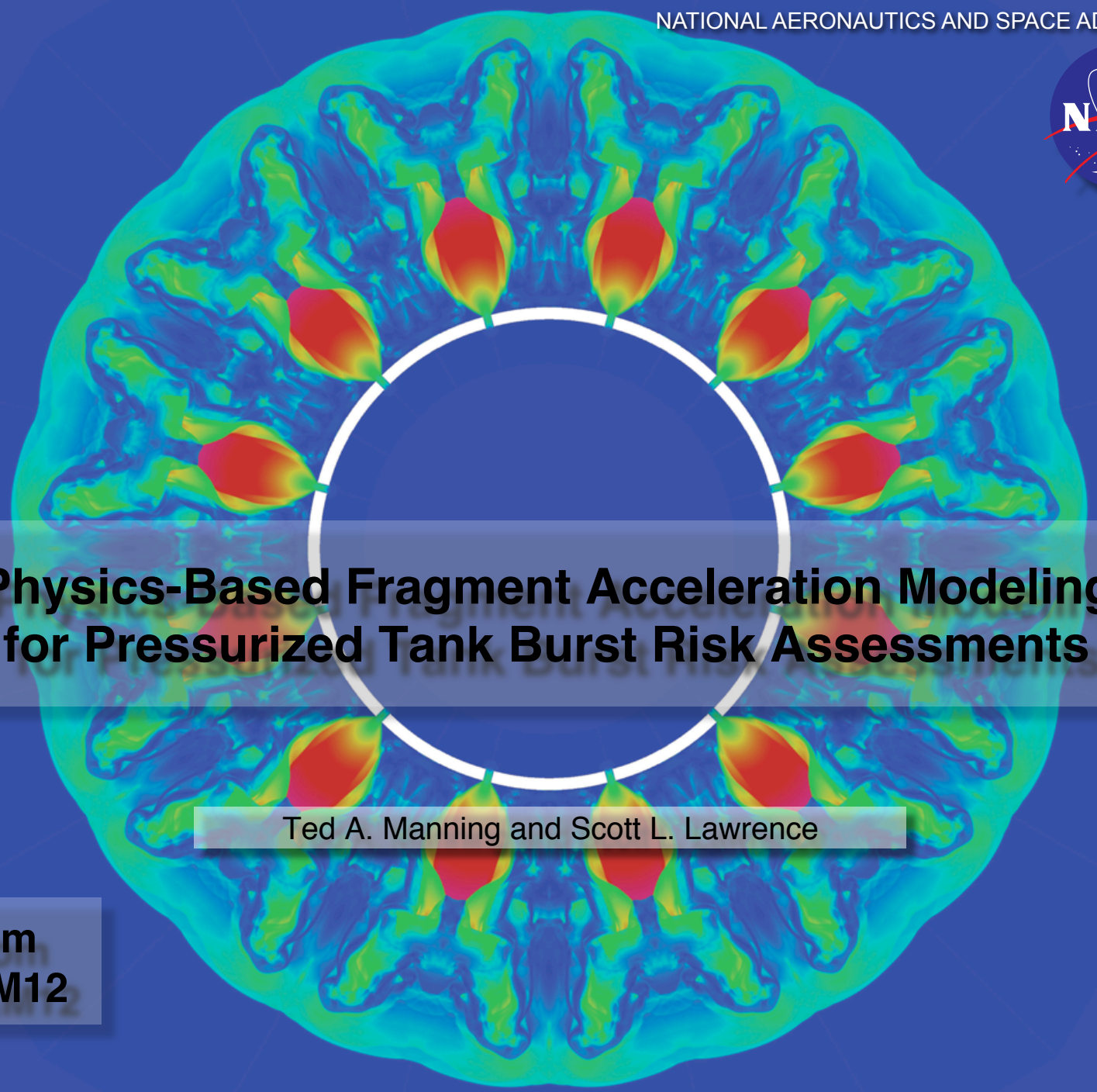
Space Shuttle ET debris model

Debris Strike Sensitivity



- Current model
- Effect of imparted velocities
- Warning time = 0.5 sec

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



Physics-Based Fragment Acceleration Modeling for Pressurized Tank Burst Risk Assessments

Ted A. Manning and Scott L. Lawrence

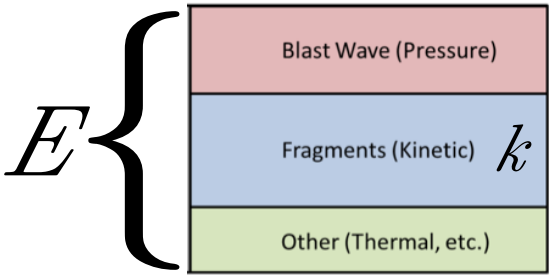
From PSAM12

Fragment Acceleration Modeling



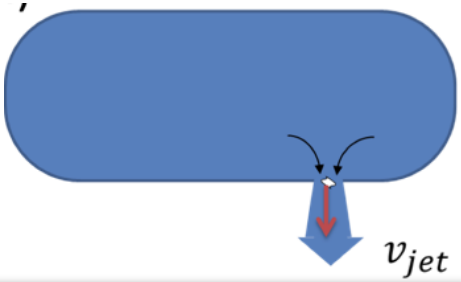
STS-51-L (Challenger)

- Energy Partition



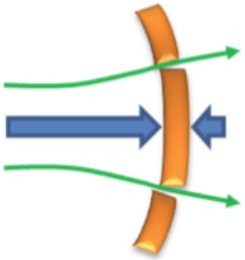
$$v_i = \sqrt{\frac{2kE}{m}}$$

- Momentum Conservation



$$v_i = v_{\text{jet}}$$

- Force Driven



Differential Pressure

Baker Model (1977)

$$v_i = \int \frac{F}{m} dt$$

Problem Statement

- Problem
  - Baker (1977) tank burst velocity model may not be suitable for low yield, lower altitude tank explosions due an external vacuum assumption
- Objective
  - Evaluate / Improve the Baker model
- Approach
  - Focus on Pressure Burst (no combustion)
  - Run high fidelity fluid/rigid-body simulations (Overflow CFD)
  - Add and/or modify terms in Baker model
  - Compare, Adjust, Iterate



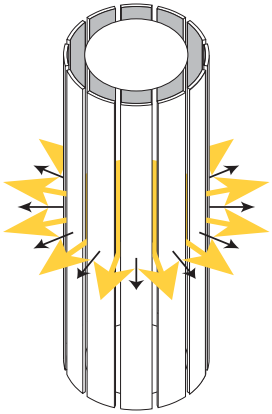
OVERFLOW CFD

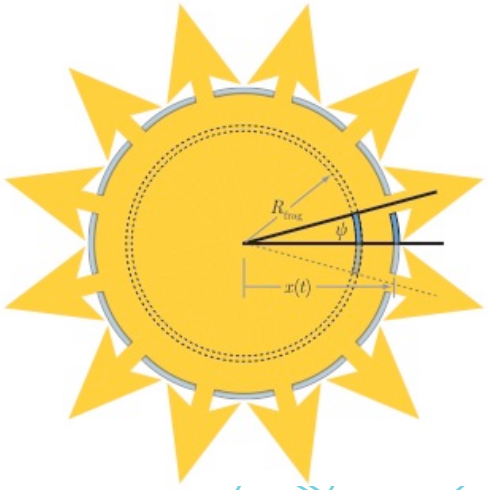
Original Baker

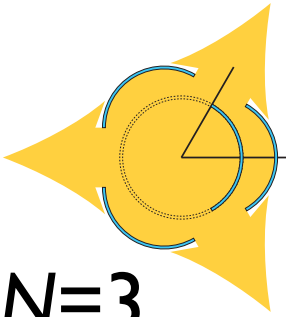
Modified Baker

Framework for Tank Burst Modeling

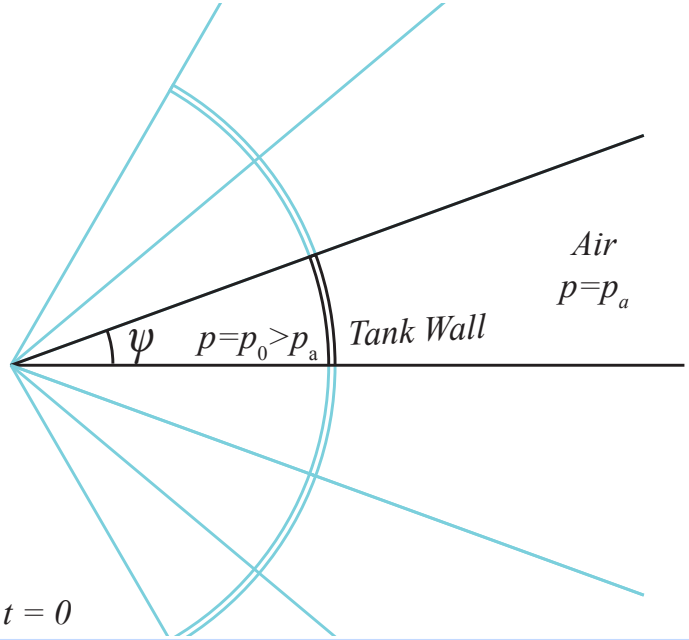
Infinite Cylinder: 2-dimensional expansion of gas, with gap leakage, *N* fragments

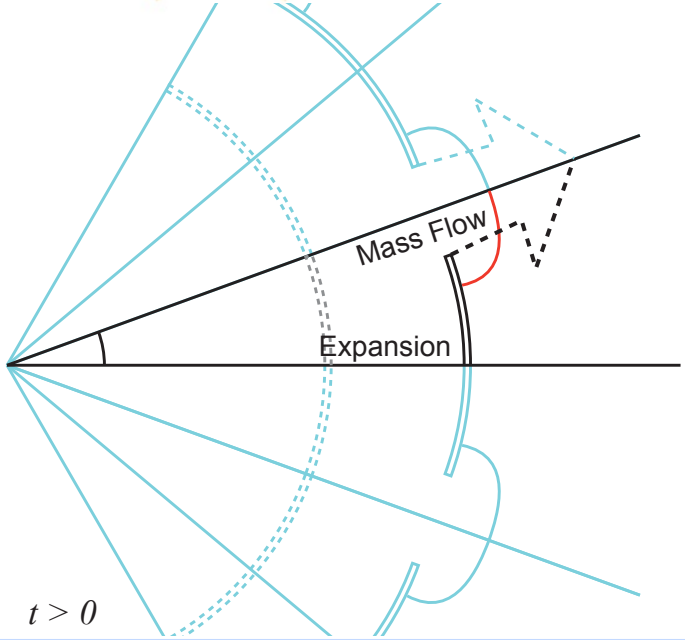


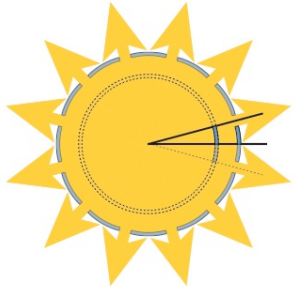




N=3



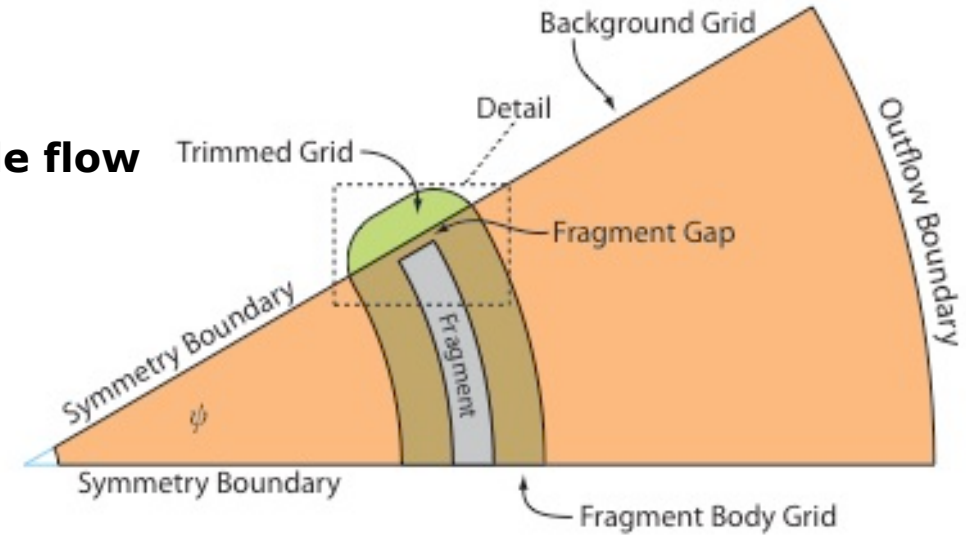




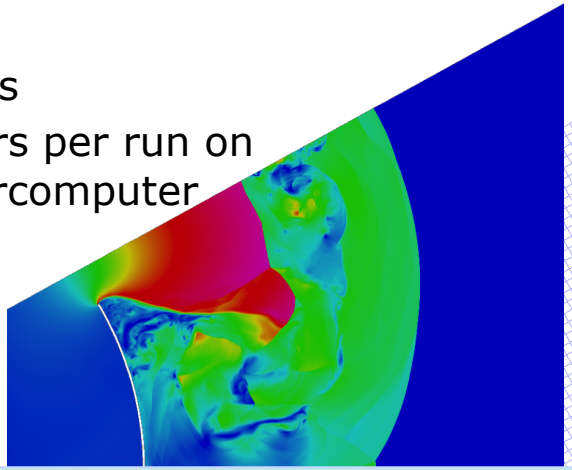
N=12

Computational Fluid Dynamics (CFD) Simulations

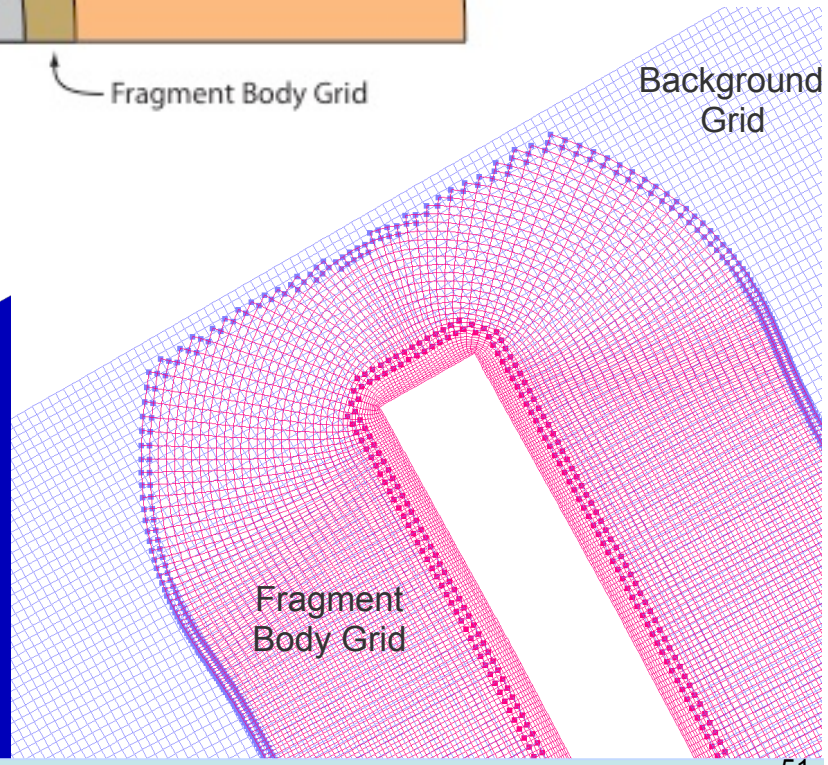
- OVERFLOW 2.2
  - **Unsteady compressible flow**
  - **Rigid body dynamics**
  - Finite difference
  - Structured overset grids
  - Multi-species fluids
  -
- For Tank Burst
  - **2-D with symmetry BC**
  - **Inviscid**
  - 1-DOF rigid body dynamics
  - 2 Overset grids
  - 2~10 million vertices
  - Up to 6000 cpu hours per run on NASA Pleiades supercomputer



N=6
ψ=30°

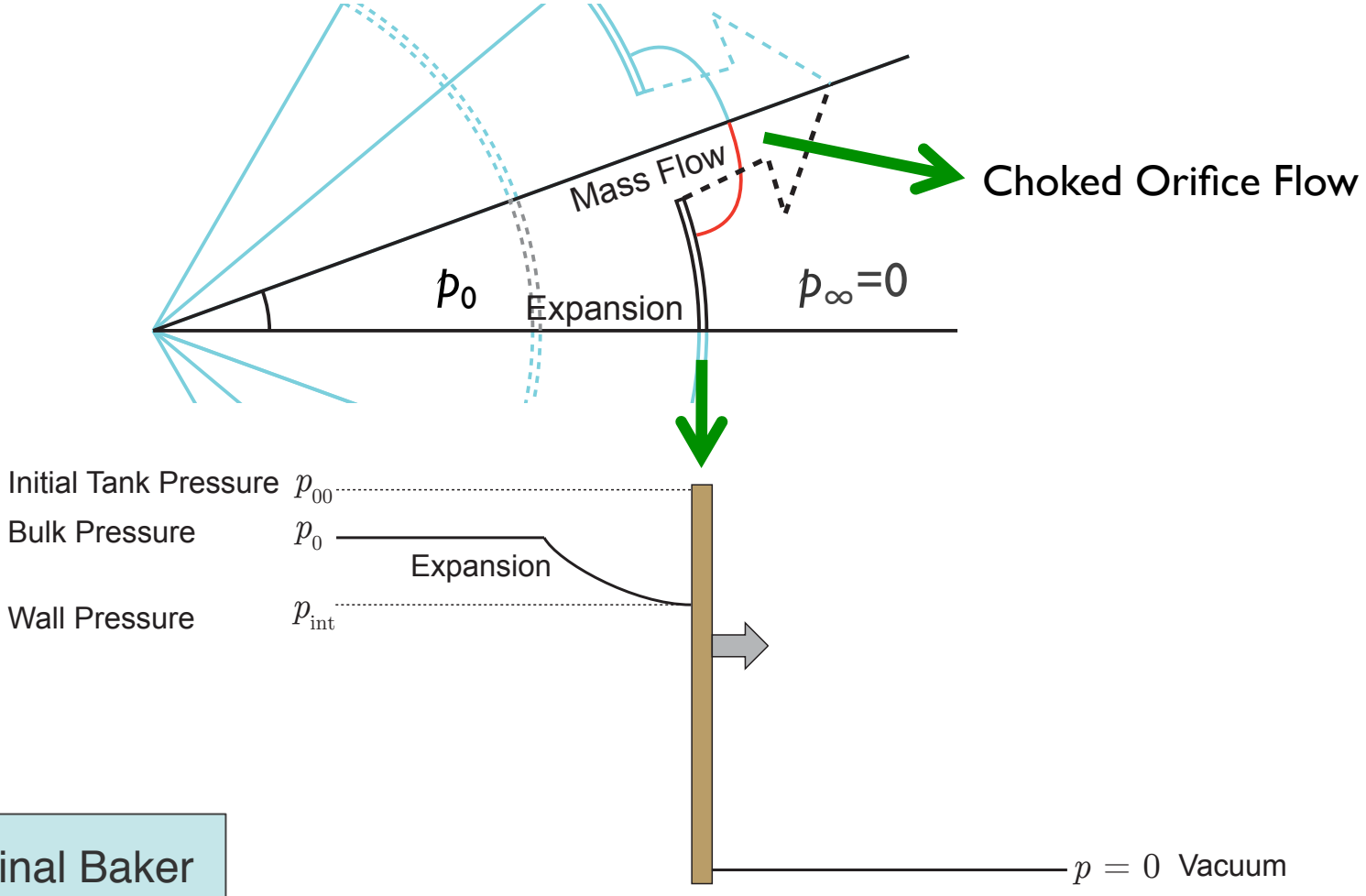


OVERFLOW CFD



Tank Burst Engineering Model (Baker Model)

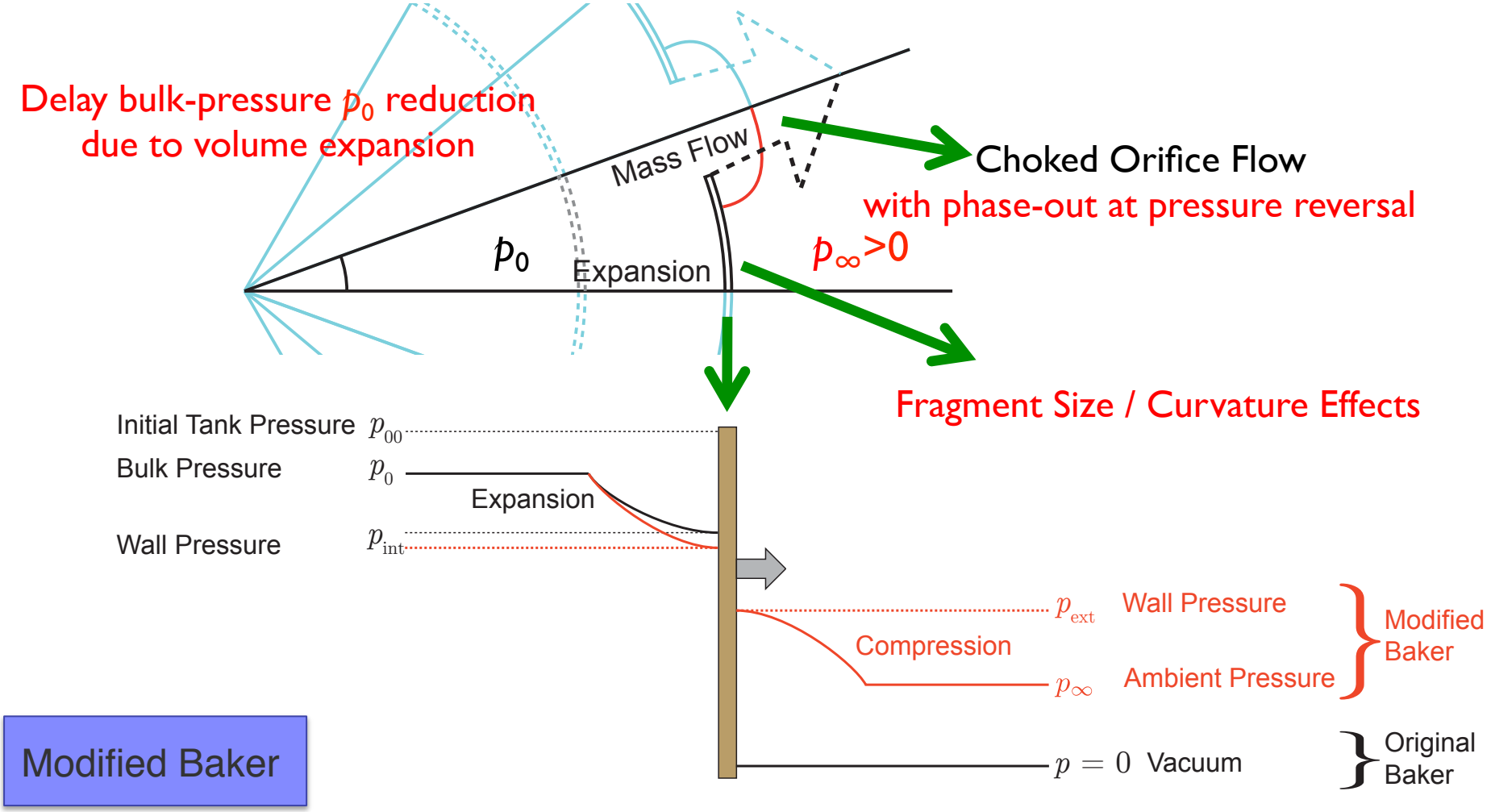
- "Original Baker" (Baker 1977): Isentropic Expansion with Orifice Plate leakage



Original Baker

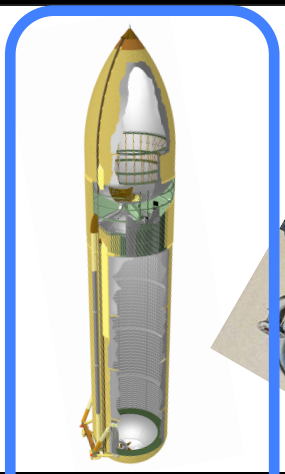
Modifications to Baker Model

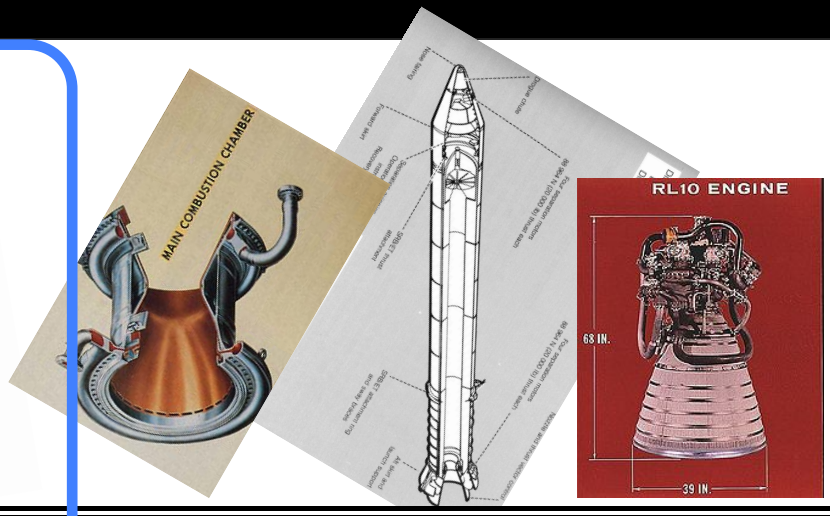
- Modified Baker: 1-D Piston Model with Orifice Plate leakage

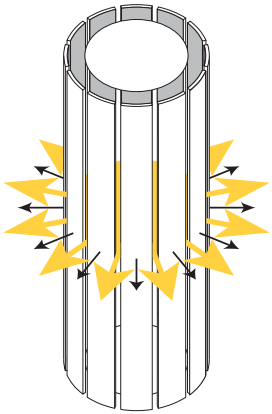


Tank Burst Cases



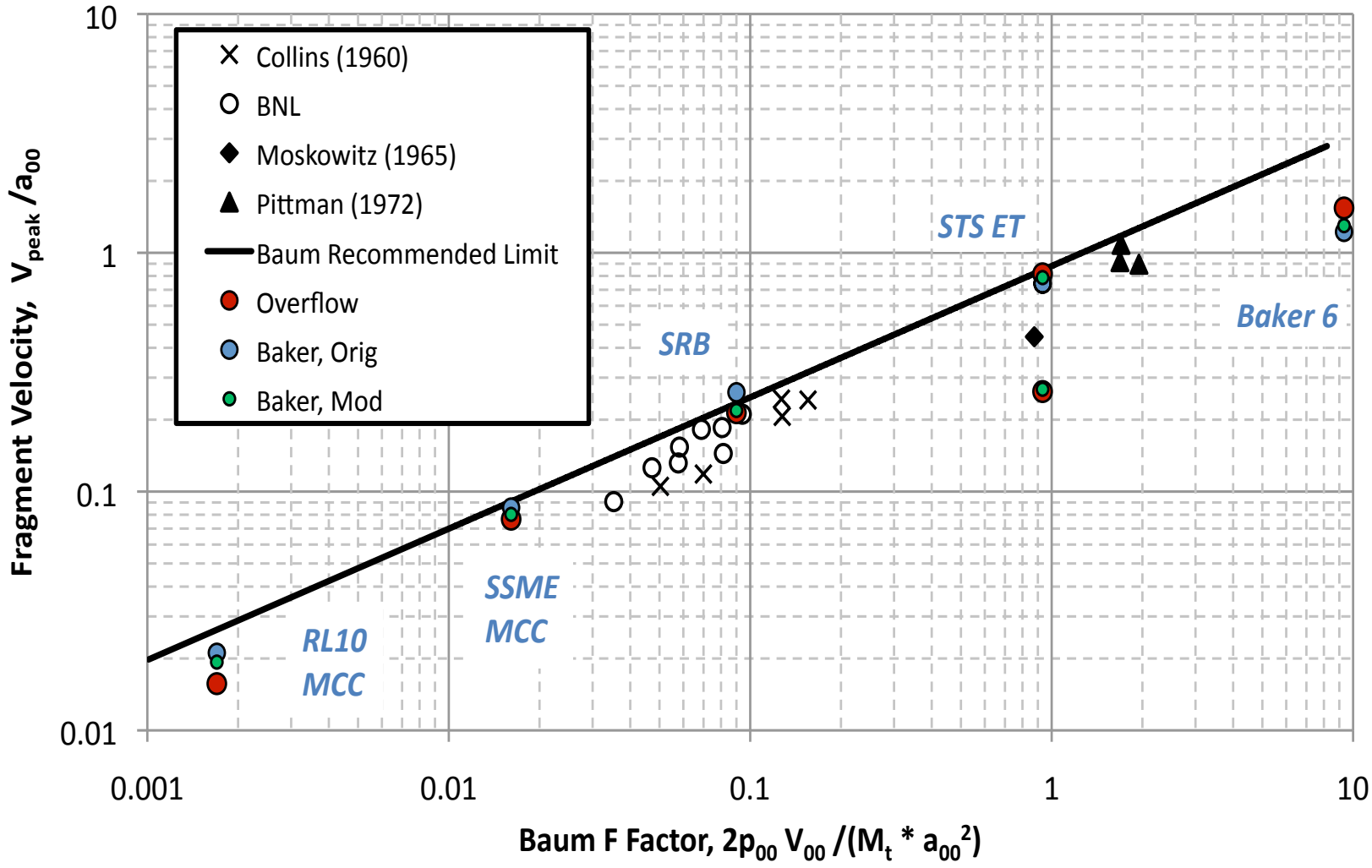






	STS ET	SSME MCC	SRB	RL10 MCC	Baker 6
Tank contents	Air	H_2, O_2, H_2O	APCP gas	H_2, O_2, H_2O	Air
Tank material	Aluminum	Inconel	Steel	Inconel	Aluminum
Radius (cm)	420	22.3	184	11	25.4
Thickness (cm)	0.21	1.24	1.2	1.17	0.68
p_{00} {Δp} (psi)	{22}	3000	800	500	10,000
T_{00} (K)	293	3400	3430	3400	272
p_∞ (atm)	0.001~1.0	1	1	1	1
Pressure Ratio	1500~2.5	205	54	9	680
Internal spec. heat ratio γ	1.4	1.37	1.155	1.37	1.4
Fragment count: N	3~24	3~24	4~24	3,12	3~24
Phase-in $\Delta t\ a_0/\psi\ R_{frag}$	1	0.1	1	1	1
Phase-in factor n	8	8	8	8	8
Discharge coeff. C_d	0.8	0.8	0.8	0.8	0.8

Compared to Baum Velocity Limit



Original Baker | Modified Baker | OVERFLOW CFD

STS External Tank: External Pressure Effect

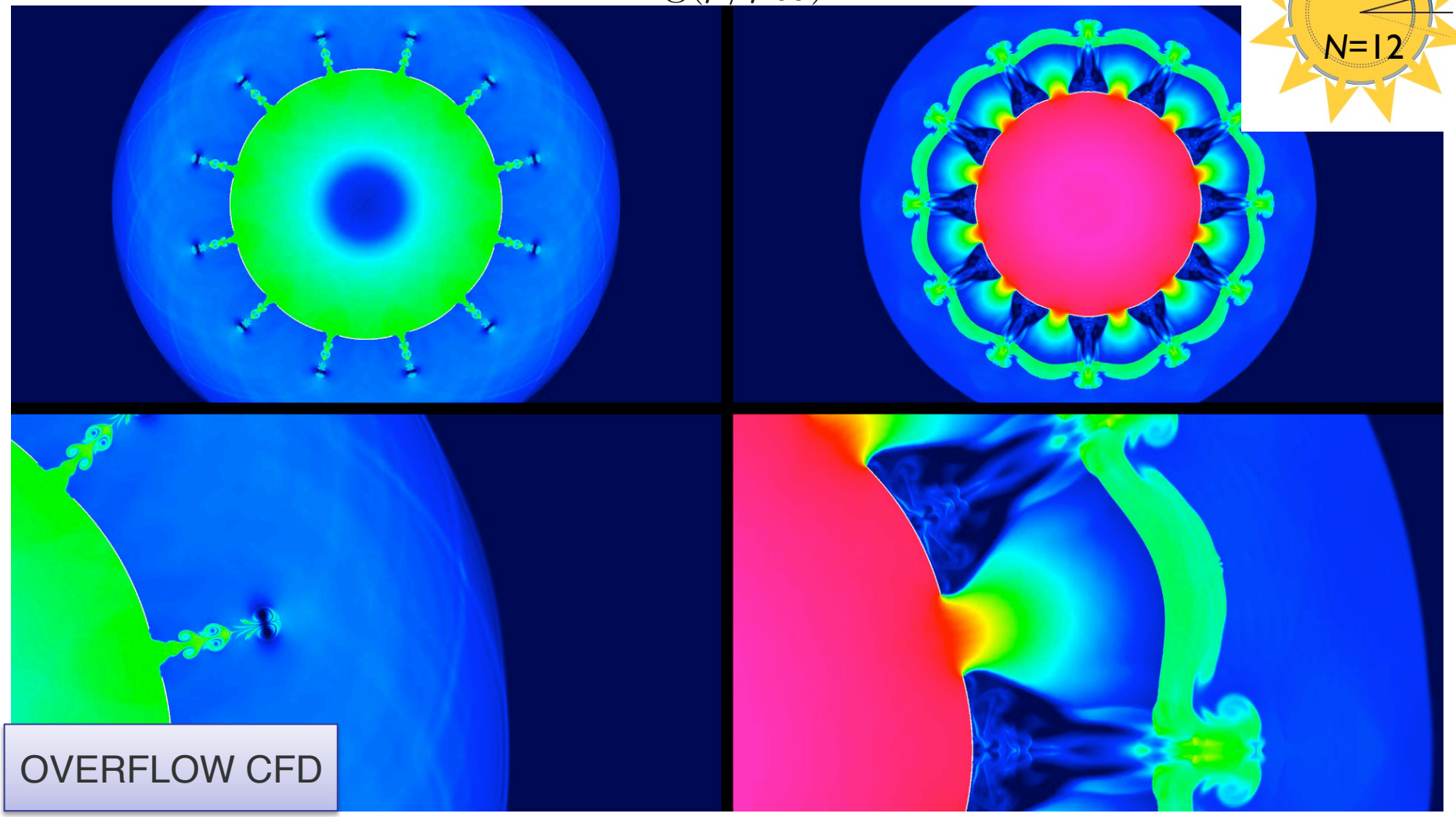
p_∞ = 1 atm

Δp = 1.5 atm

$\log(\rho/\rho_\infty)$

p_∞ = 0.01 atm



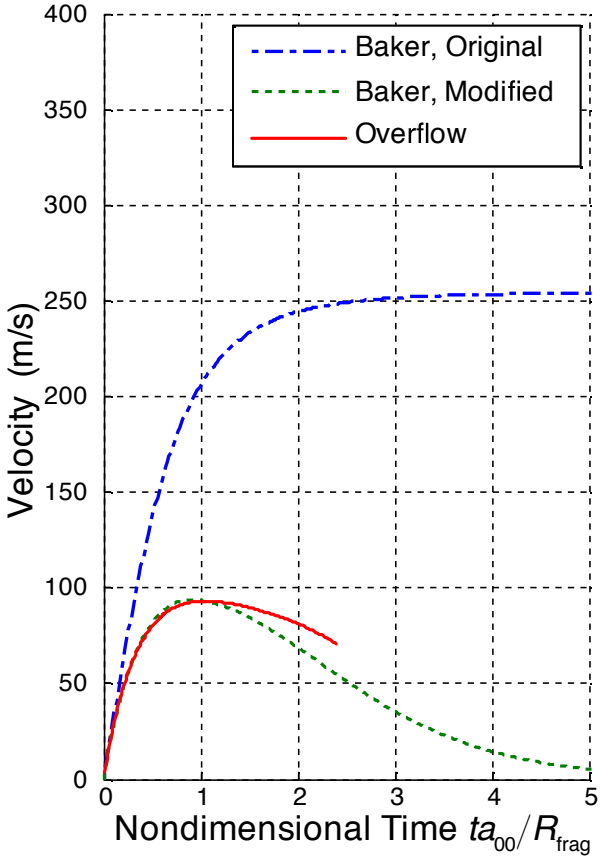


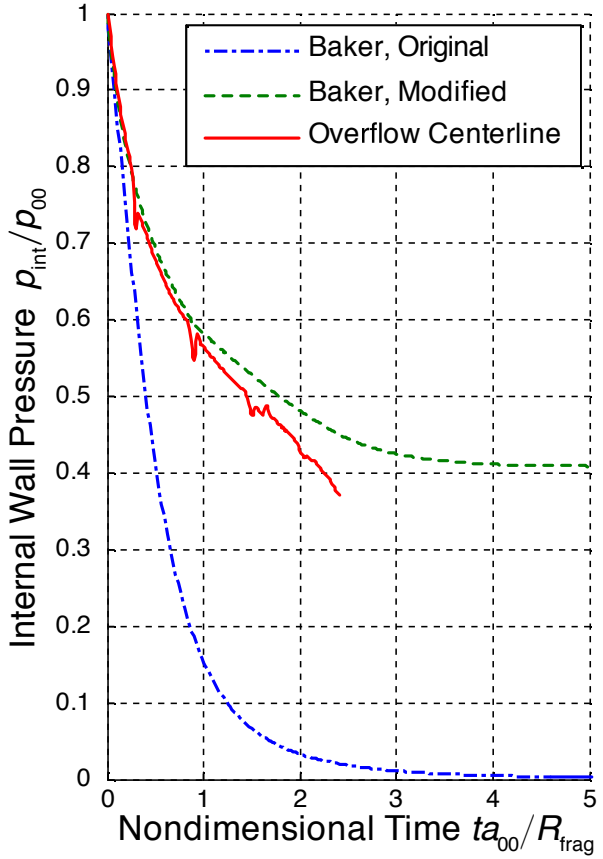
OVERFLOW CFD

STS External Tank: Sea Level

T_{00}=293K, Δp=22 psi, γ_{00}=1.4 (Air), R_{gas00} = 287 J/kg K p_∞=1 atm



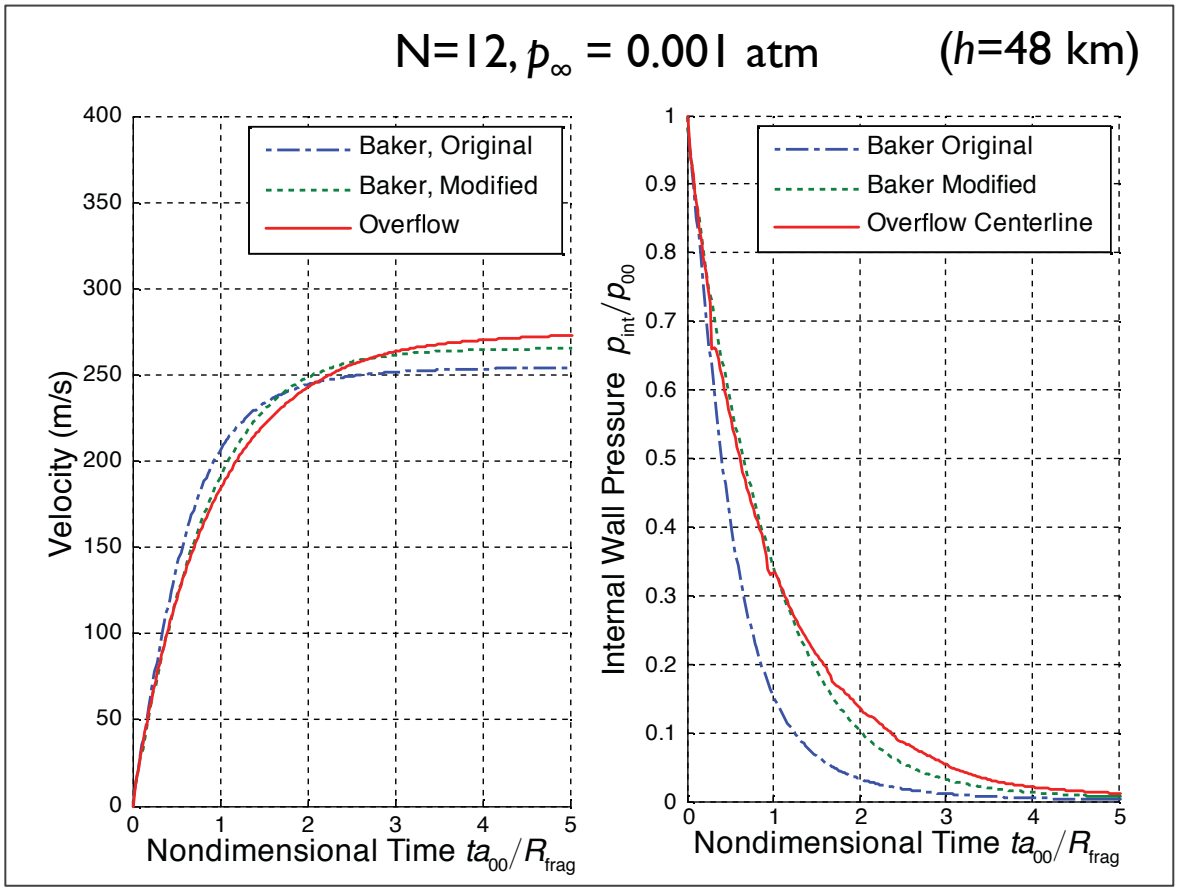




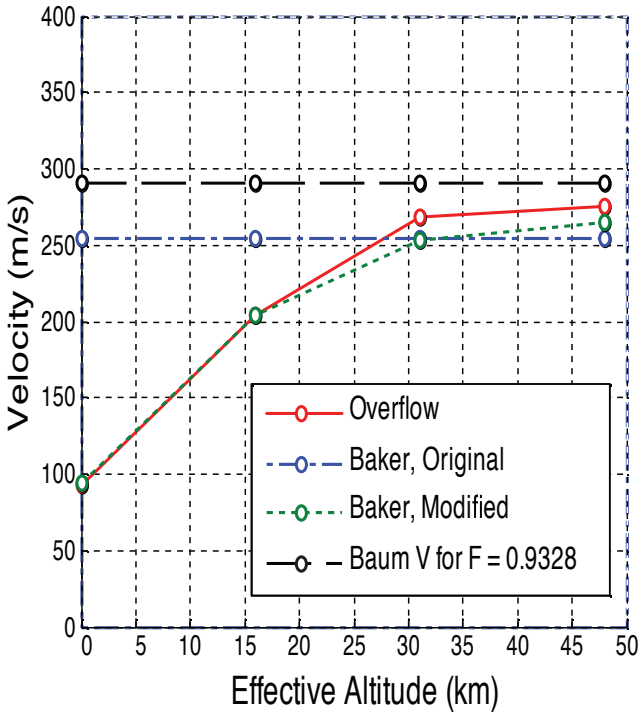
Original Baker | Modified Baker | OVERFLOW CFD

STS External Tank: External Pressure Senstivity

T_{00}=293K, Δp=22 psi, γ_{00}=1.4 (Air), R_{gas00} = 287 J/kg K
External Pressure, p_∞ = 0.001, 0.01, 0.1, and 1 atm





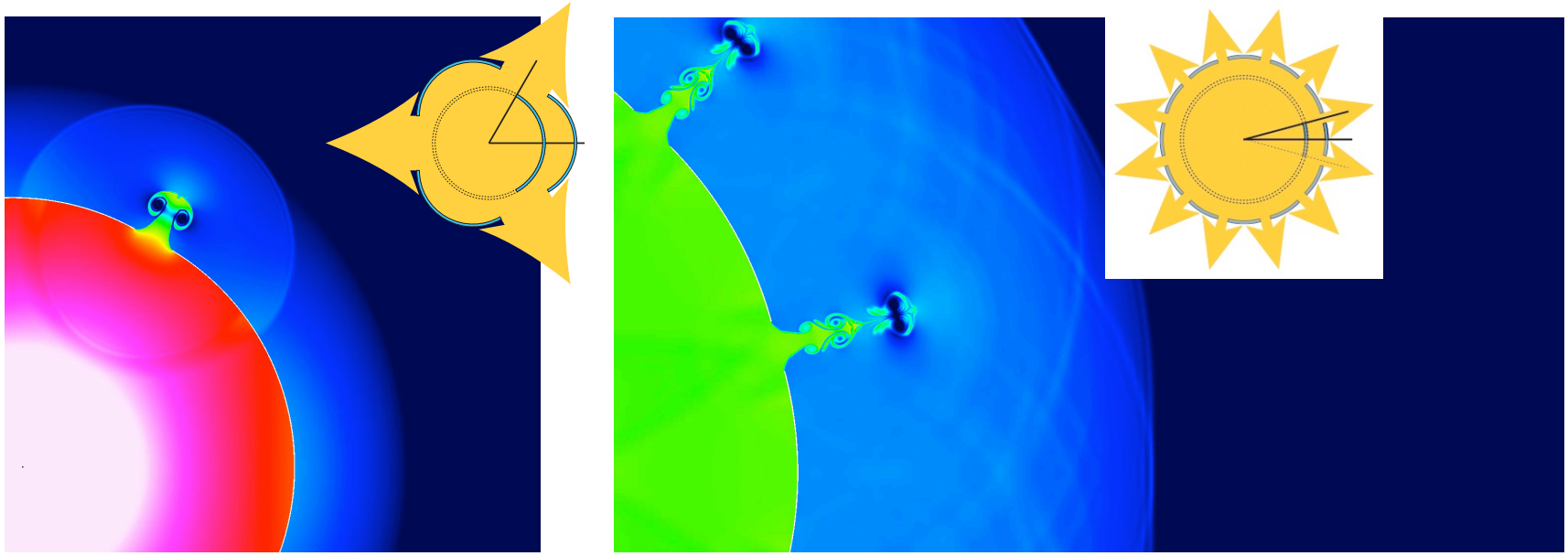


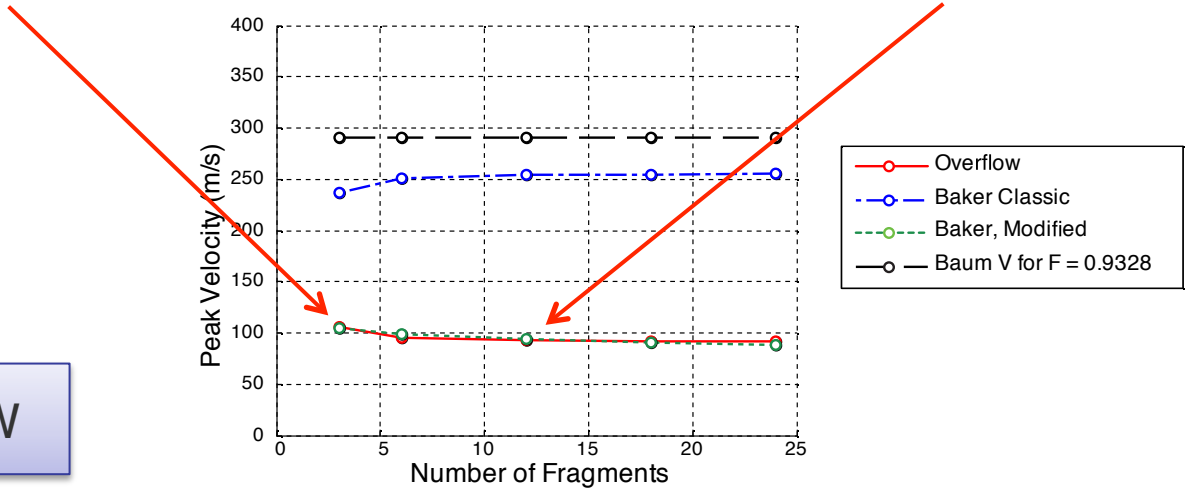
1 atm 0.1 atm 0.01 atm 0.001 atm

Original Baker | Modified Baker | OVERFLOW CFD

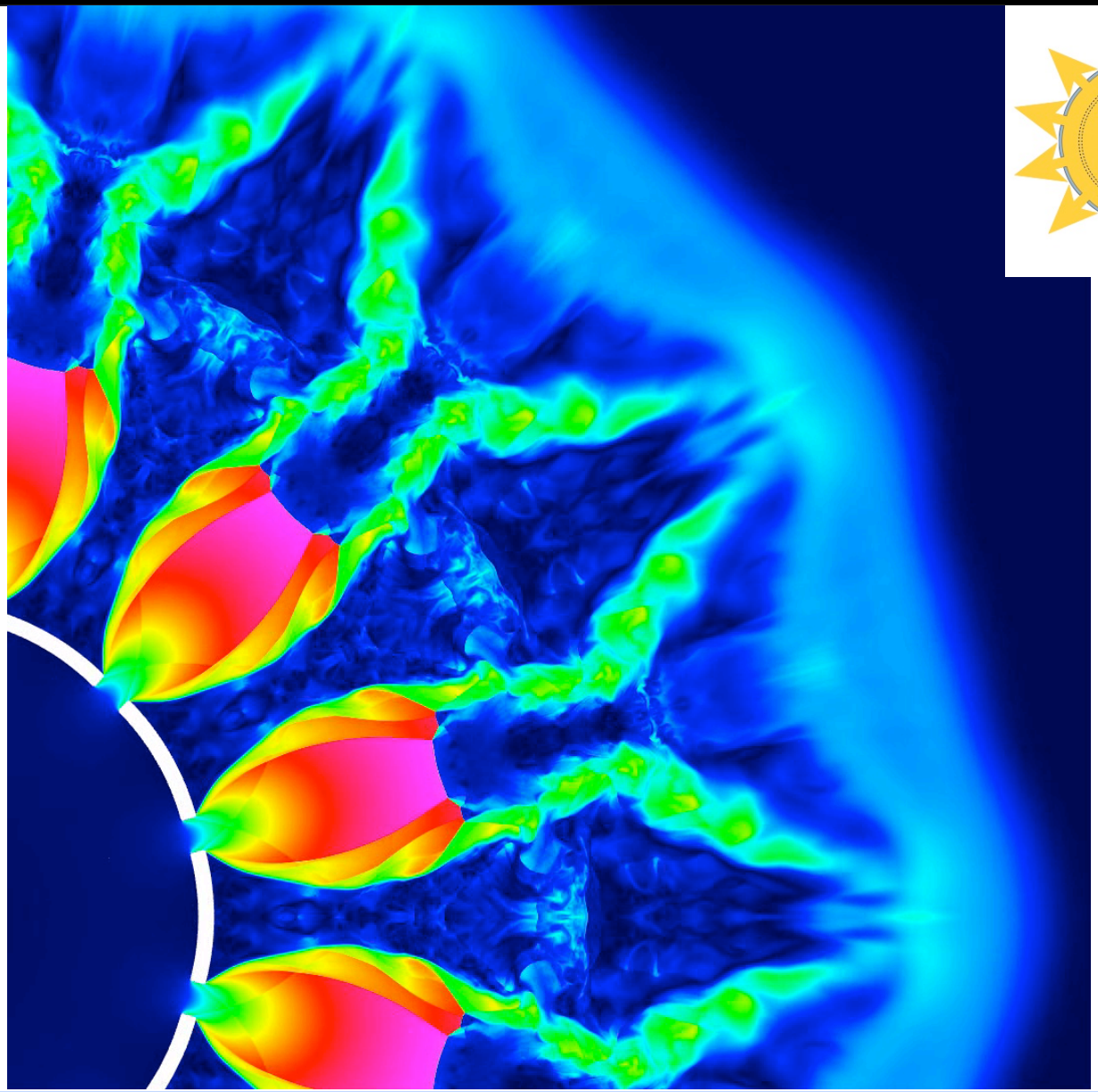
STS External Tank: Fragment Count *N*

N = 3 fragments $\log(\rho/\rho_\infty)$ *N*=12 fragments p_∞ = 1 atm





OVERFLOW



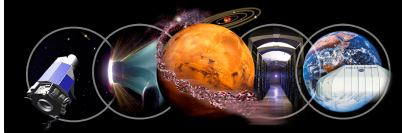
SSME MCC:

P_{00} = 3000 psi

Mach contours

p_∞ = 14.7 psi (1 atm)

OVERFLOW CFD



Fragment Acceleration Summary

- Tank Burst Simulations
  - Developed CFD-based capability to predict fragment velocity and understand flow field
- Engineering Modeling
  - Better understand limitations of Baker tank burst velocity model
  - Improved Baker Model account for external atmospheric effects and fragment size/curvature
  - Improvements greatest for low altitude tank (low pressure ratio)
- Future Work:
  - Extend Modified Velocity Model
    - To other burst geometries: sphere and tank domes
    - Include effects of cryogenics
  - Apply velocity model results to
    - Debris strike risk assessments
    - Failure propagation analysis
  - Develop fracture sizing models

Engineering Risk Assessment



- Risk Assessment Framework
- Failure Propagation
  - Propagation Framework
  - Self Propagating Scenarios
- Blast Overpressure
- Debris Strike Risk
  - Debris Catalog Modeling
  - Fragment Acceleration