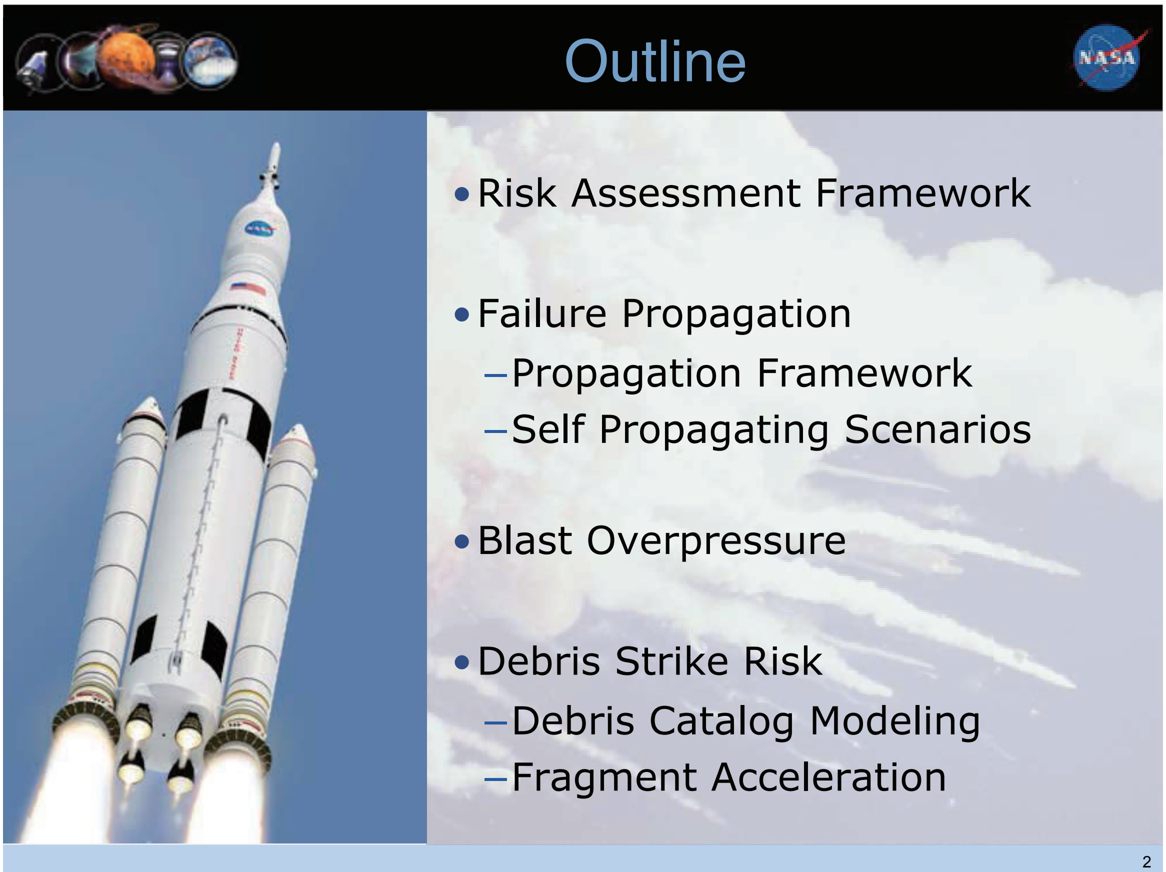


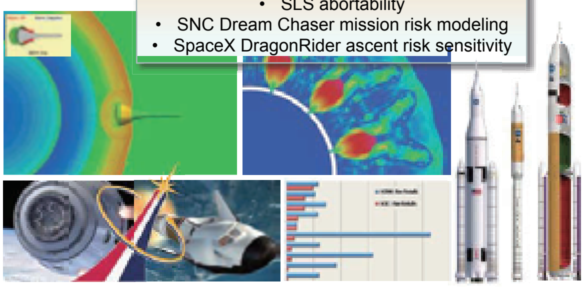
This document is provided by JAXA.

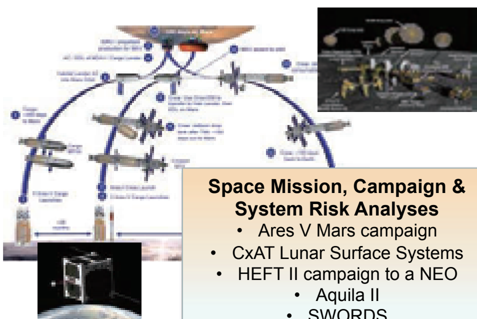
Engineering Risk Assessment (ERA) Team

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

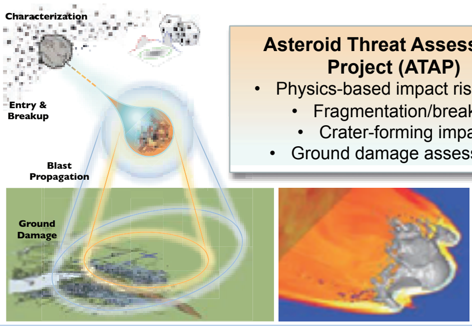
Engineering Risk Assessment Activity

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

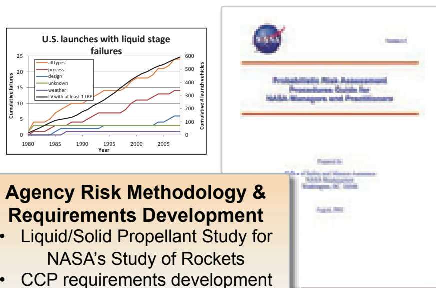




Space Mission, Campaign & System Risk Analyses
- Ares V Mars campaign
- CxAT Lunar Surface Systems
- HEFT II campaign to a NEO
- Aquila II
- SWORDS



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.

This document is provided by JAXA.

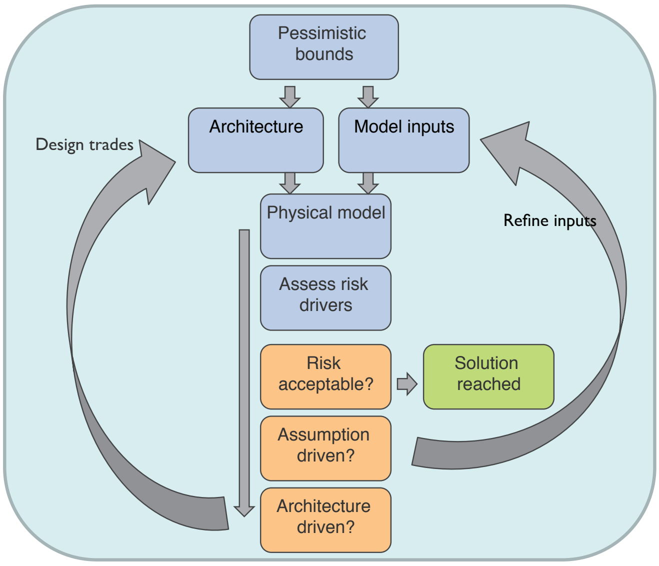
Outline

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

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

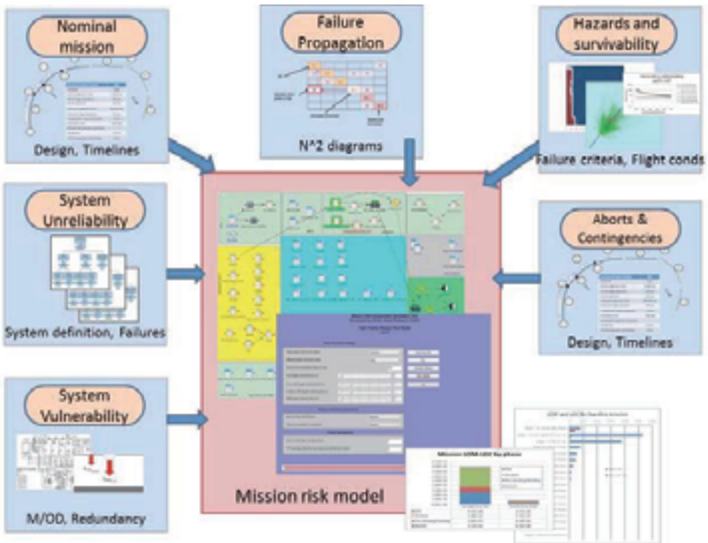


This document is provided by JAXA.

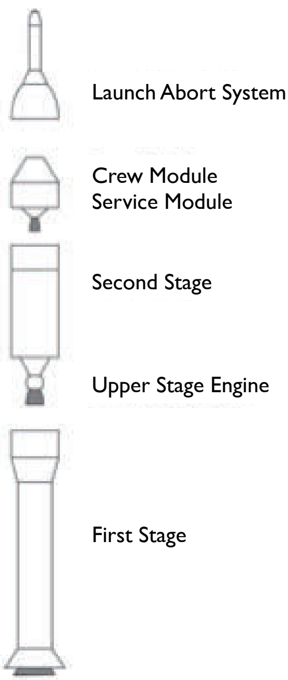
What is ERA?

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

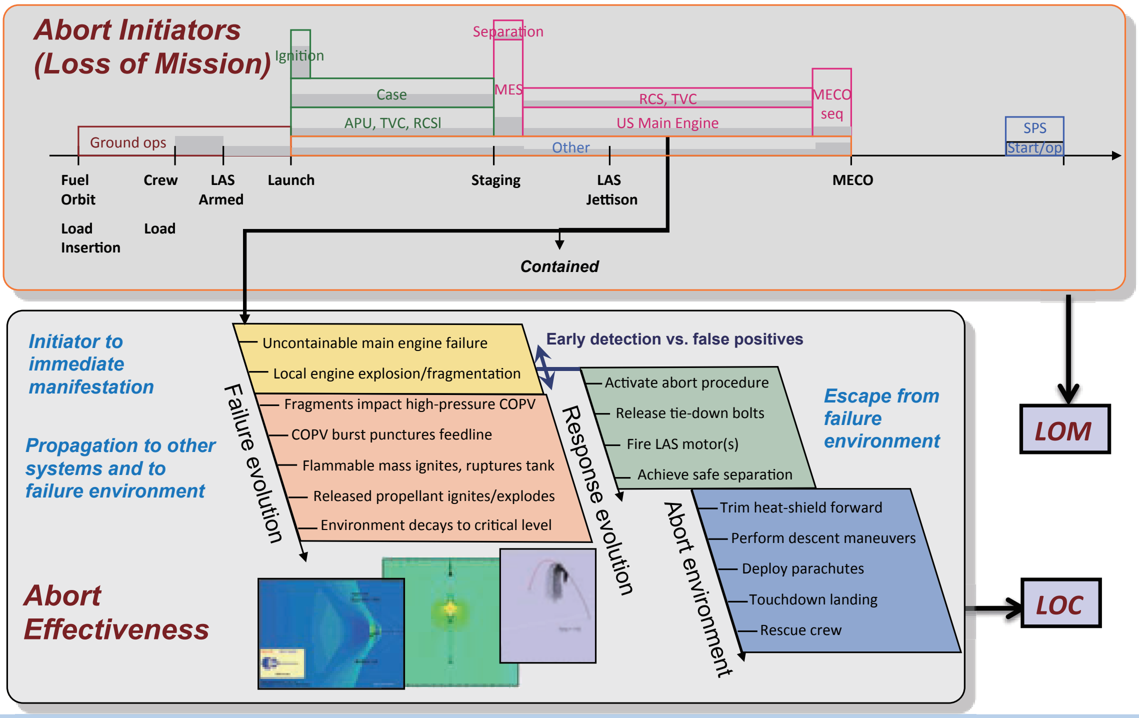


Crewed Launch Mission



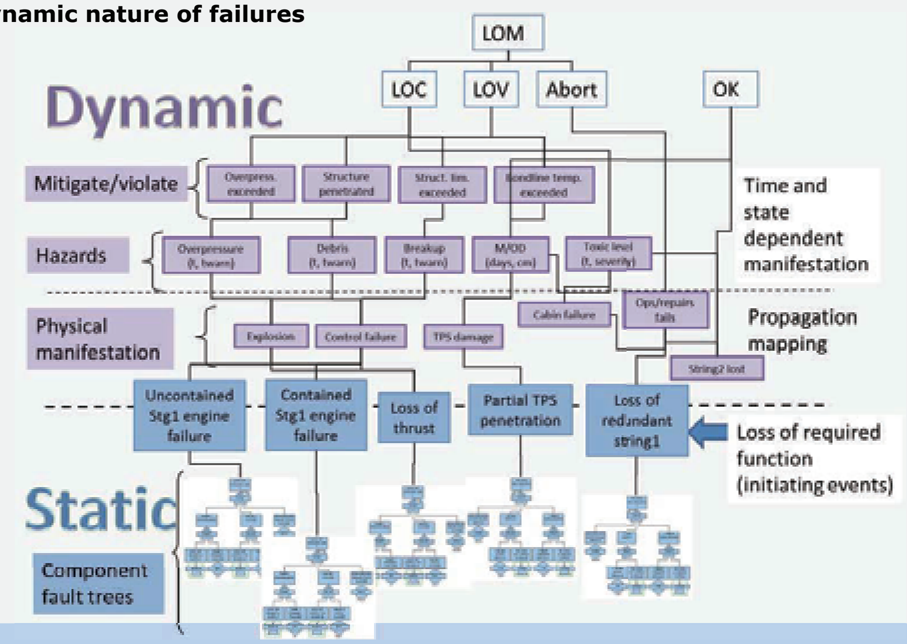
This document is provided by JAXA.

Integrated Ascent Risk Modeling

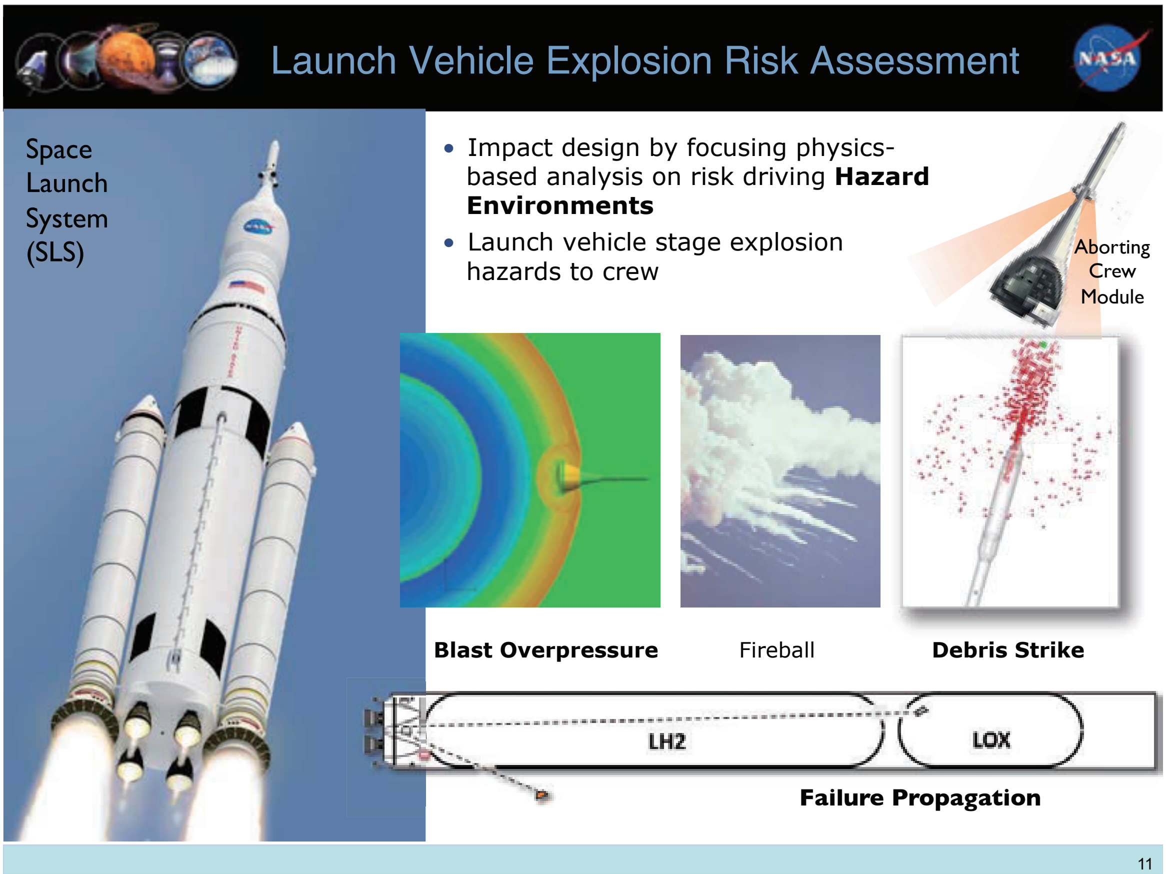


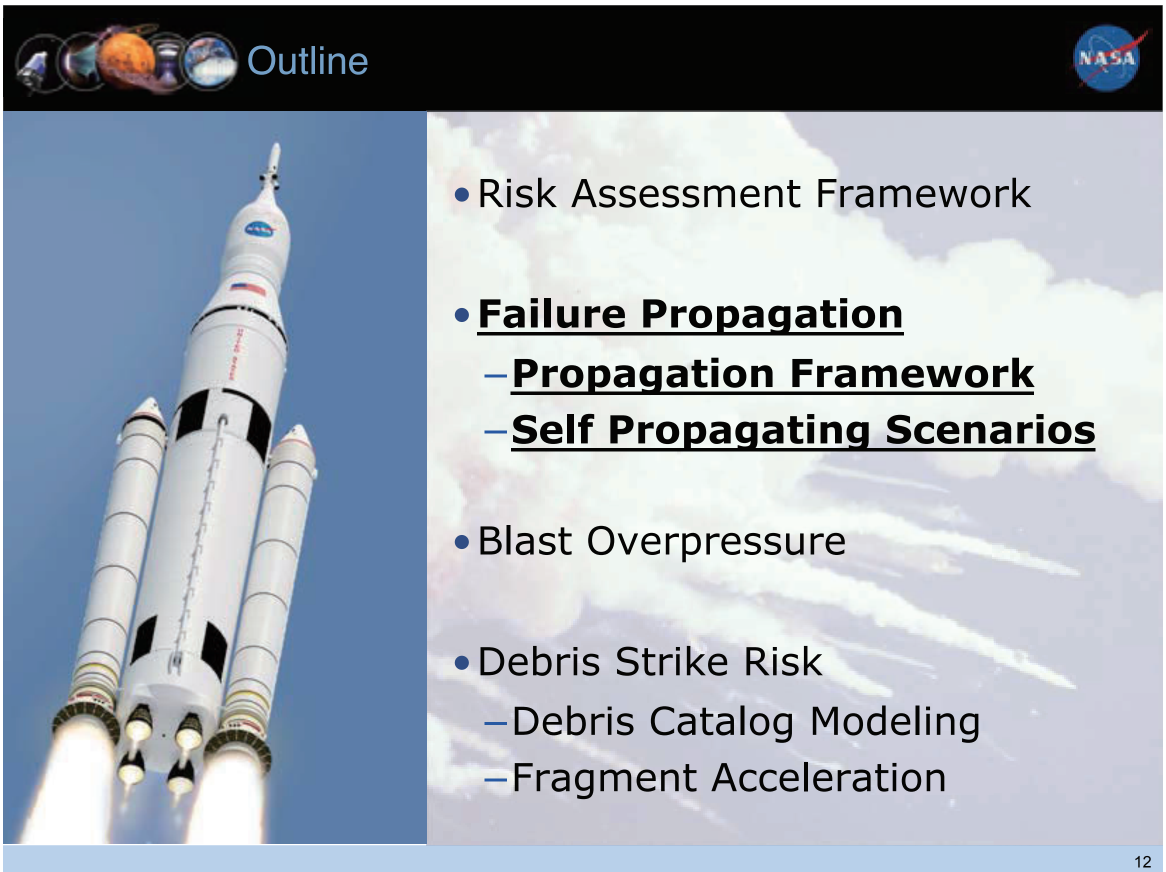
Hybrid Risk Modeling Approach

- Engineering Risk Assessment (ERA) extends traditional Probabilistic Safety/ Risk Assessment (PSA/PRA) approaches to incorporate:
  - **Physics-based analysis of key risk factors**
  - **Dynamic nature of failures**

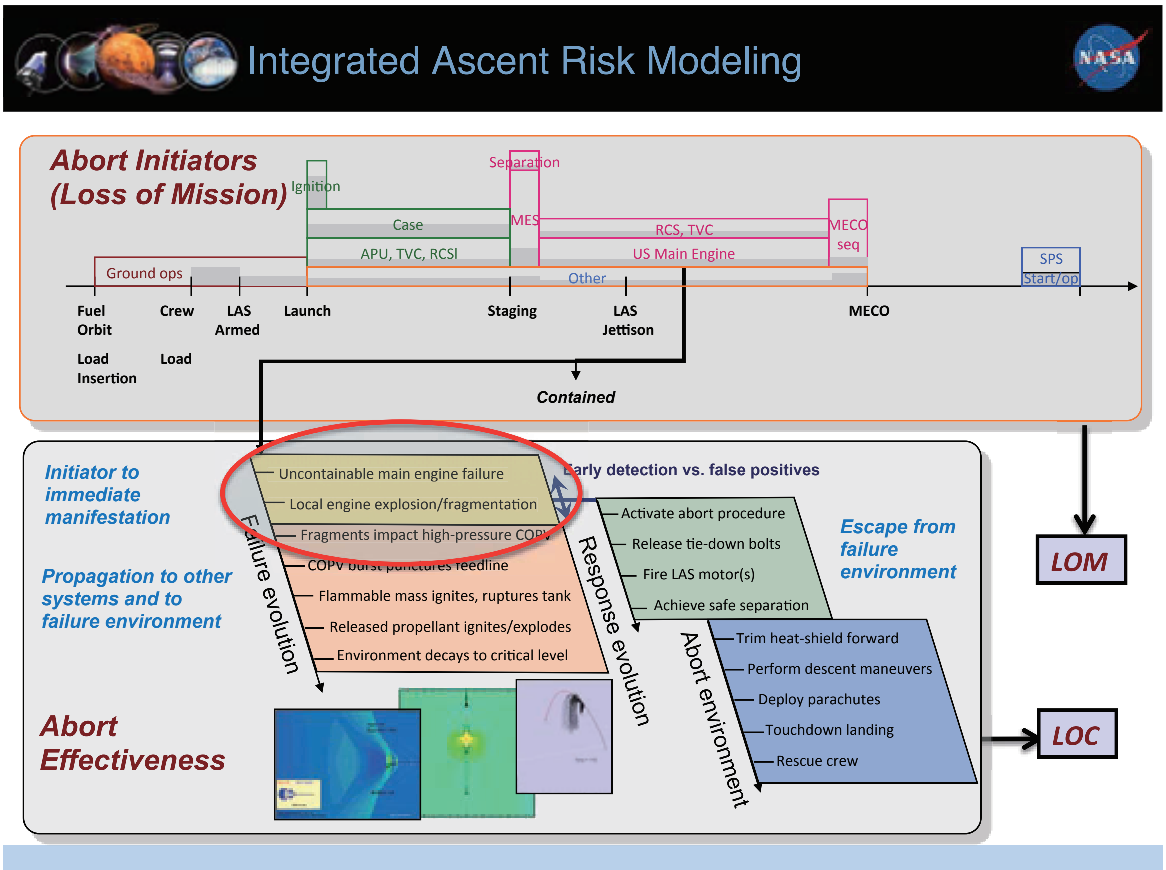


This document is provided by JAXA.



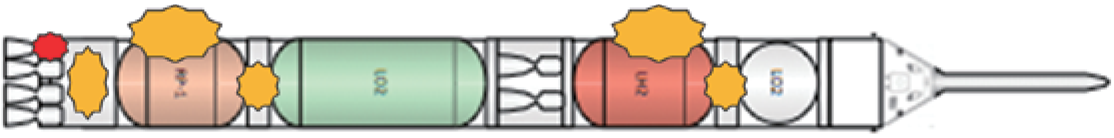


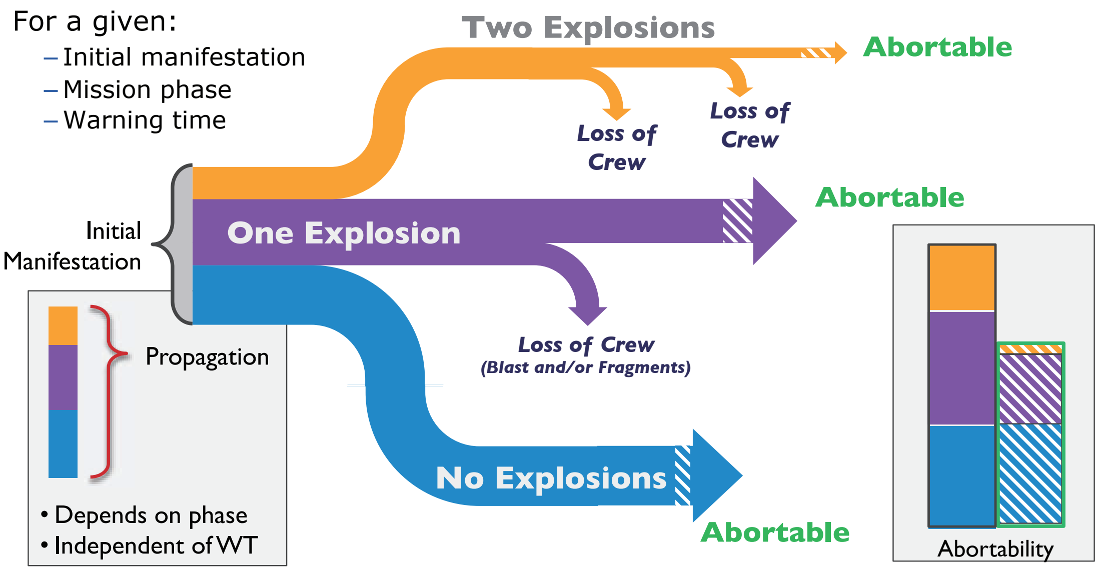
This document is provided by JAXA.



This document is provided by JAXA.

Abortability Flow-Chart: Simple Example





15

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

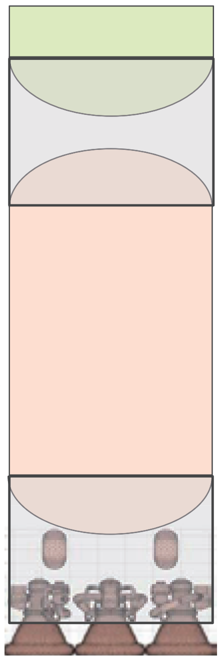
Initiators

Intermediate Environments

Failure Environments

Event Tree

Stage I TP



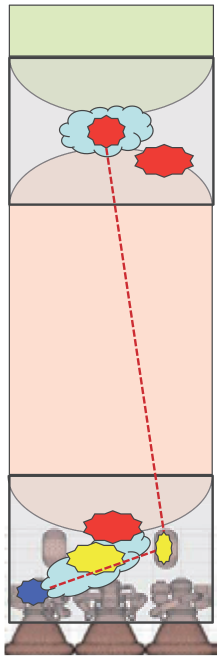
16

This document is provided by JAXA.

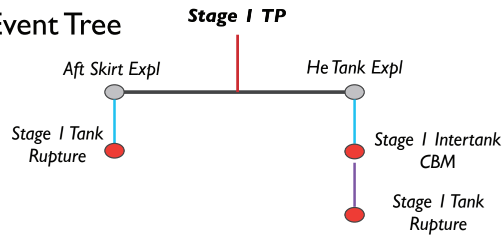
Simple Propagation Matrix Example

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

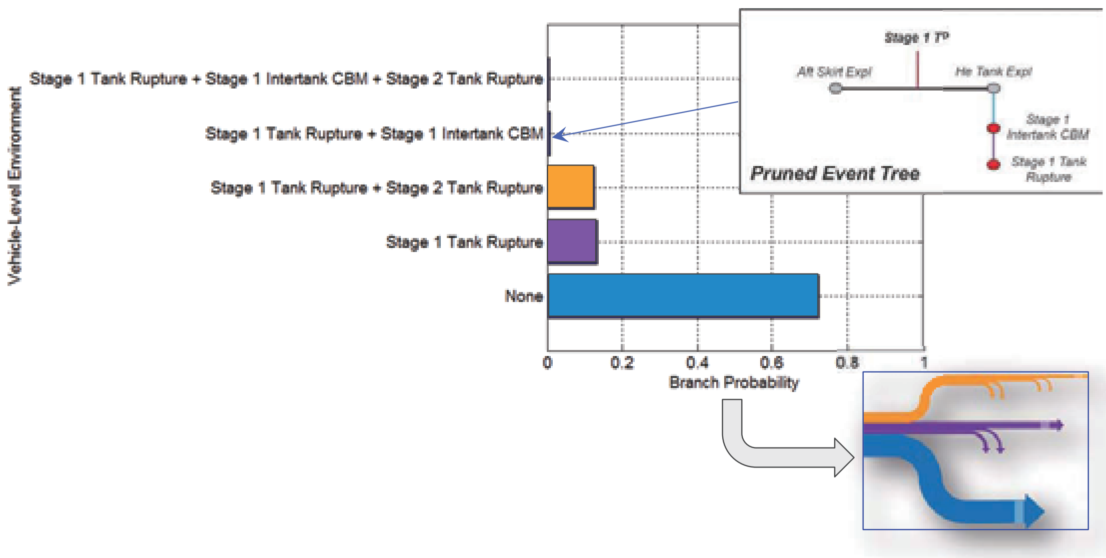


Event Tree



Sample Monte Carlo Results

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



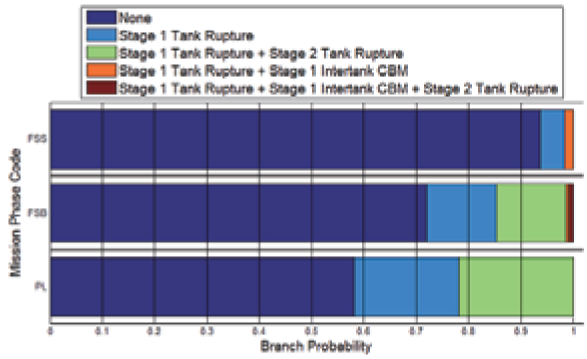
This document is provided by JAXA.

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			
[illegible]	PL	FSB	FSS	[illegible]	[illegible]	[illegible]	Source	Target	Scaling
[illegible]	[illegible]	[illegible]	[illegible]	0/-	0/-	0/-	Stage 1 Turbopump	Stage 1 MCC Expl	0.01/0.01
[illegible]	[illegible]	40/50/15	40/50/15	0/-	0/-	0/-	Stage 1 Turbopump	Aft Skirt Expl	0.1/0.1
[illegible]	[illegible]	[illegible]	[illegible]	0/-	0/-	0/-	Stage 1 Turbopump	HE Tank Explosion	0.1/0.1
[illegible]	[illegible]	[illegible]	[illegible]	0/-	0/-	0/-	Stage 1 MCC Expl	Aft Skirt Expl	0.1/0.1
[illegible]	5/0/0	5/0/0	5/0/0	0/-	0/-	0/-	Stage 1 MCC Expl	HE Tank Explosion	0.01/0.01
[illegible]	100/15/0	15/5/0	0/-	0/-	0/-	0/-	Stage 1 MCC Expl	Stage 1 Tank Rupture	0.01/0.01
[illegible]	0/-	0/-	0/-	0/-	0/-	0/-	Stage 1 MCC Expl	Stage 1 Intertank CBM	0.1/0.1



Mapping: Dependence on Phase

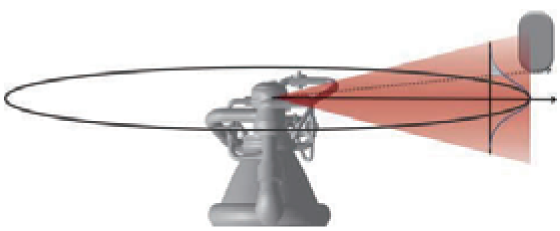
Stage I Shutdown/Separation

Stage I Boost

Pre-Launch

Transition Analysis Thought Process

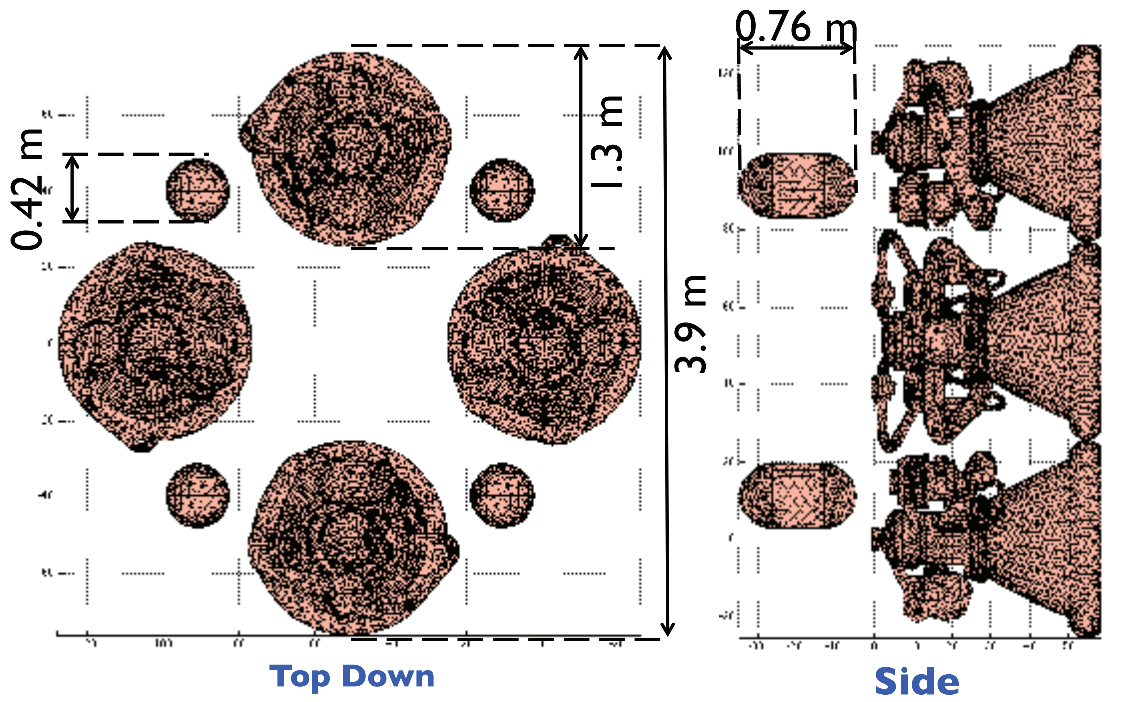
- Energy Transfer Mode(s)
  - Overpressure
  - Kinetic Energy (Fragments)
  - Shock & Vibration
  - Environment (pressure, temperature)
  - Etc.
- Source Severity
  - Energy type: ***[KE]***
  - Magnitude: ***[Velocity and density]***
  - Uncertainties: ***[Velocity and density]***
- Target Vulnerability
  - 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

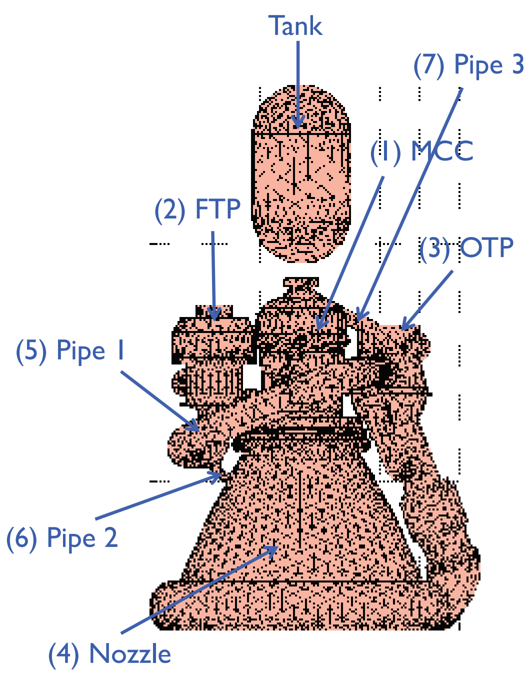
This document is provided by JAXA.

Self Propagating Failure Scenarios



Test Case: 4 Engines + Tanks

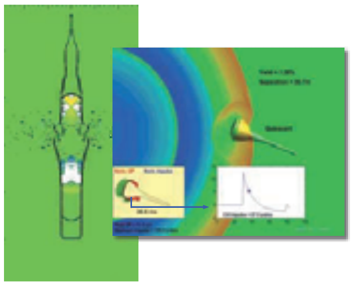
- Simple engine model for generic launch vehicle platform (derived from J2X)
- 32 components: 7 per engine and 4 tanks
  - Main combustion chamber (MCC)
  - 2 turbopumps: fuel (FTP) and oxidizer (OTP)
  - 3 pipes (fuel, oxidizer, hot gas)
  - Nozzle
- Between ~1k–6k triangles per component
- 3 different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

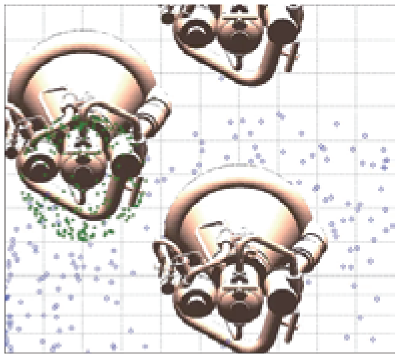


This document is provided by JAXA.

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

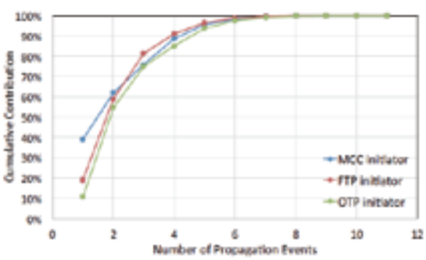
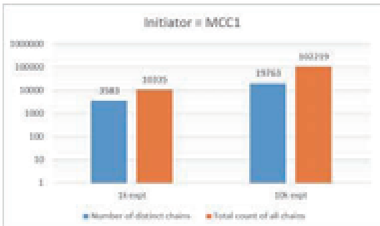
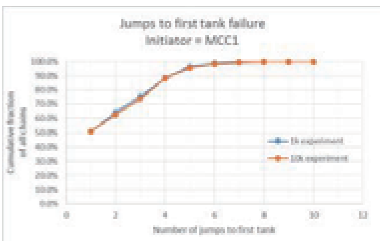


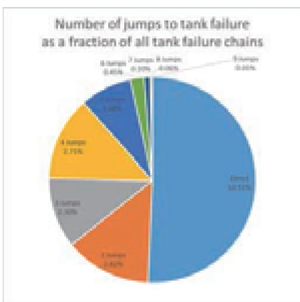
Figure 9 – Contribution of Propagation Events for First Tank Burst

Non-truncated MCC chains, 10k realizations





Average of 10 different failure propagation chains per realization.



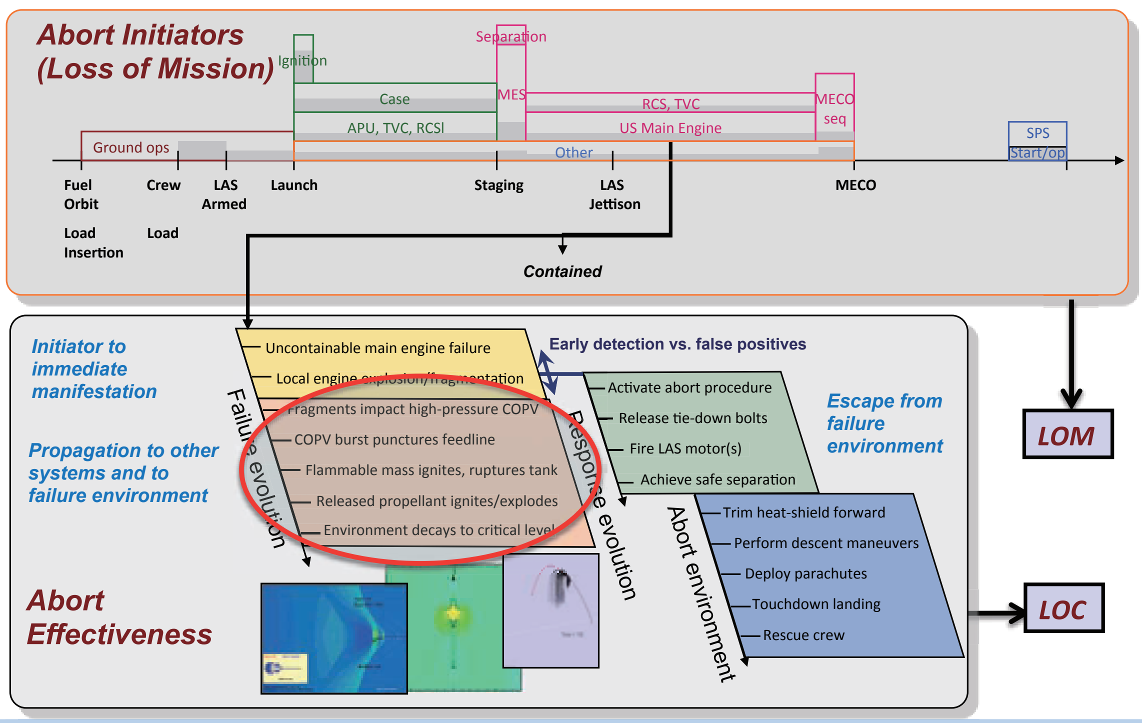
This document is provided by JAXA.

Outline

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

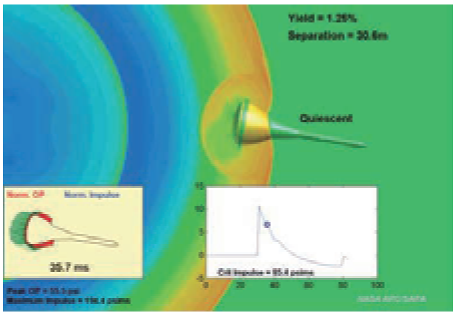
25

Integrated Ascent Risk Modeling

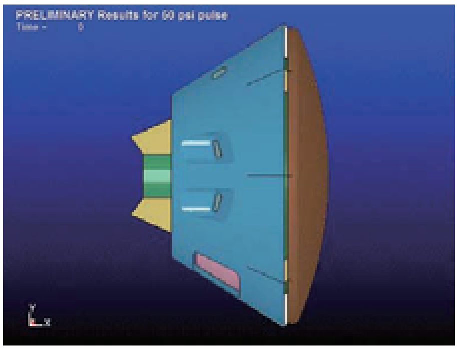


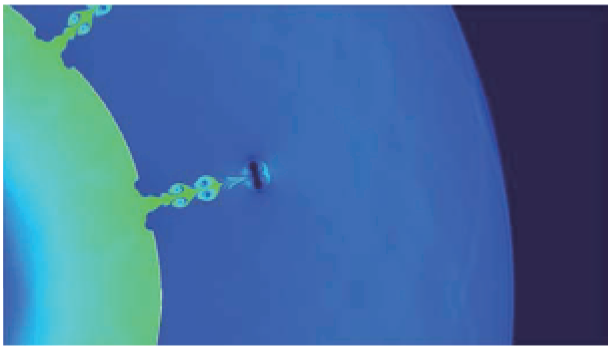
This document is provided by JAXA.

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





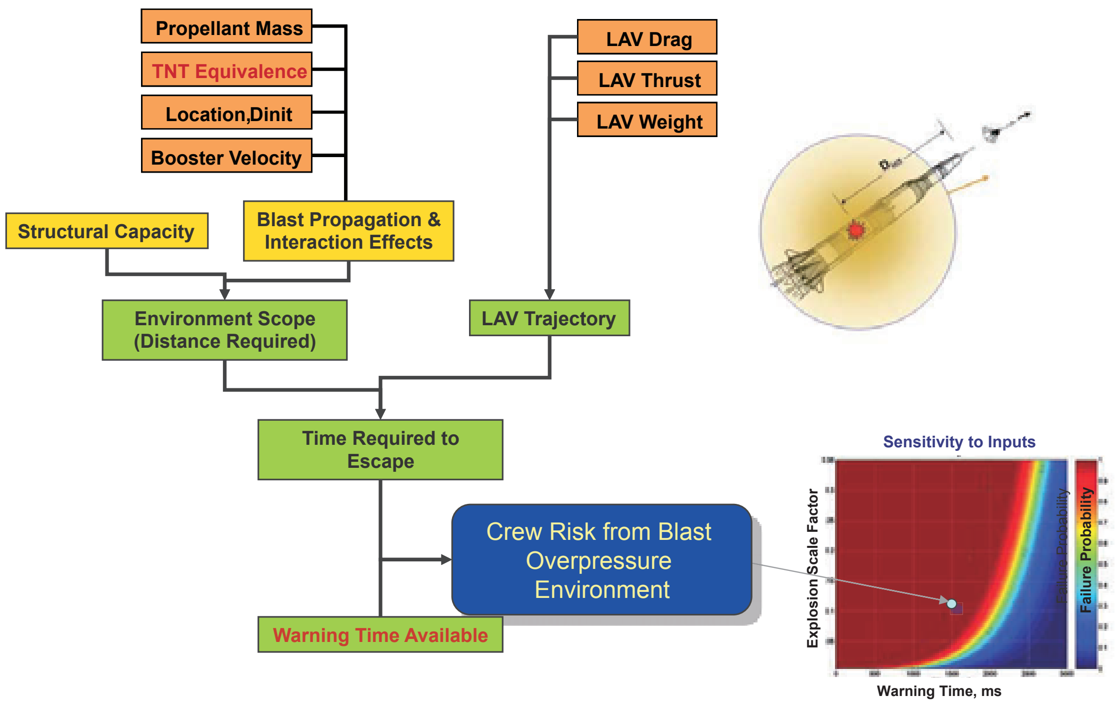
This document is provided by JAXA.

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



This document is provided by JAXA.

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

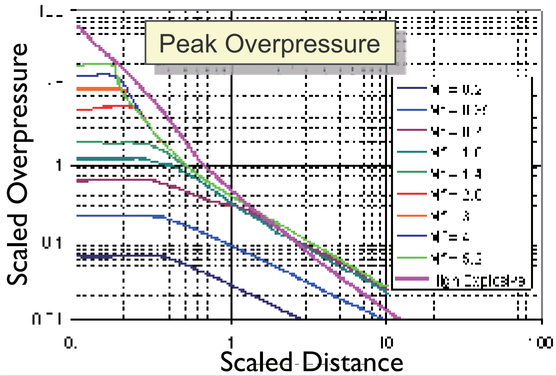
TNT Equivalency/Sachs Scaling:

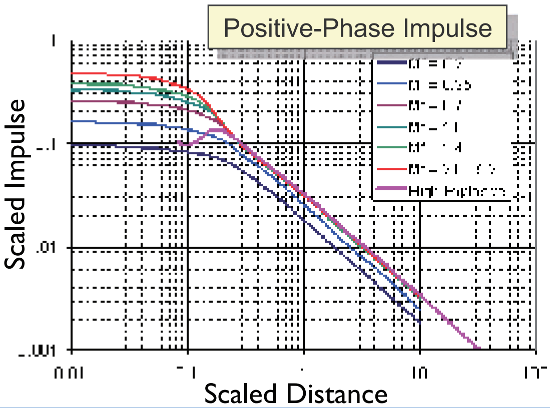
Overpressure: $OP = (p_{max} - p_\infty)/p_\infty$

Distance: $\lambda = x/\alpha$

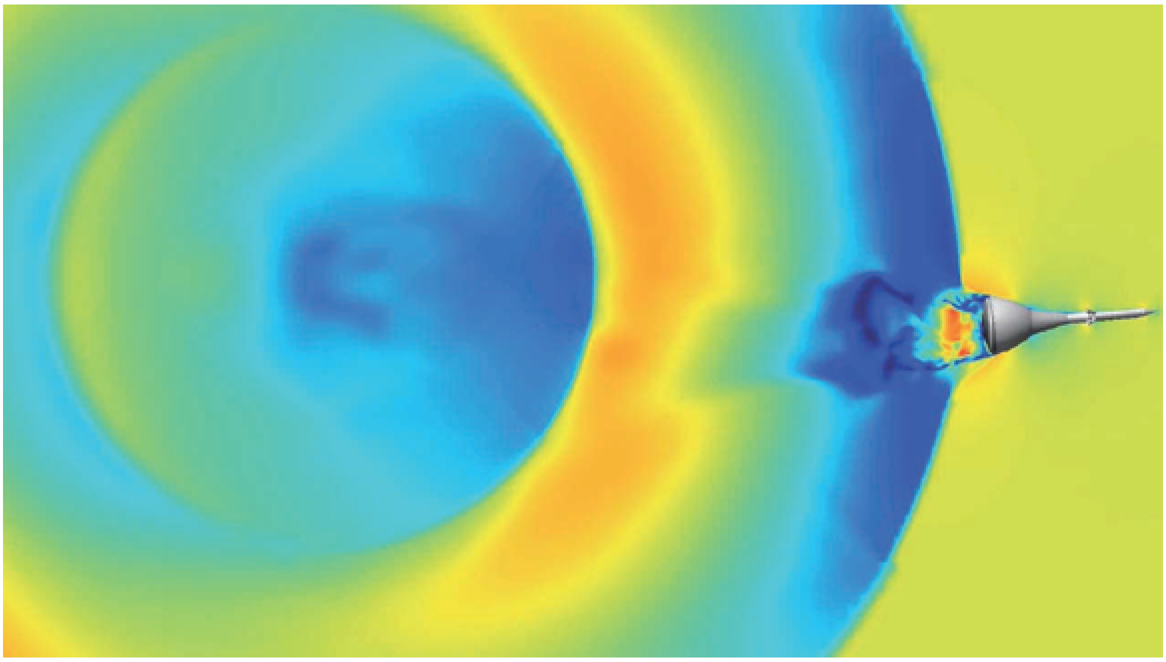
$\alpha = (E_{prop}/p_\infty)^{1/3}$

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





Blast Propagation Model

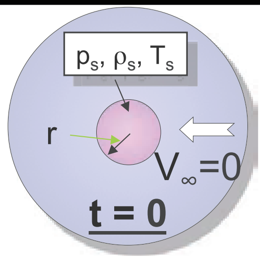


This document is provided by JAXA.

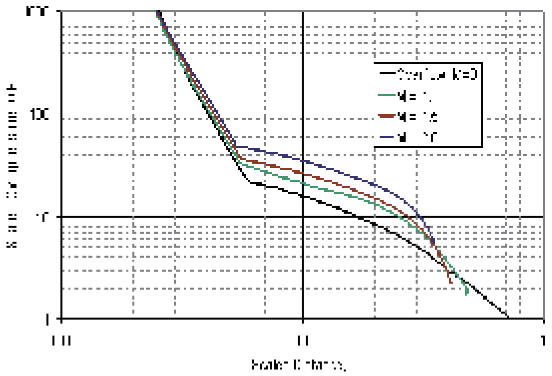
Headwinds: Navier-Stokes Simulations

Perfect gas simulations at selected conditions along ascent trajectory

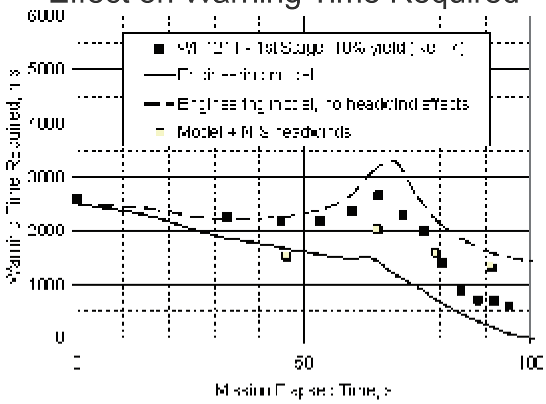
- Increase initial shock strength
- Increase penetration
- Sensitive to initial conditions



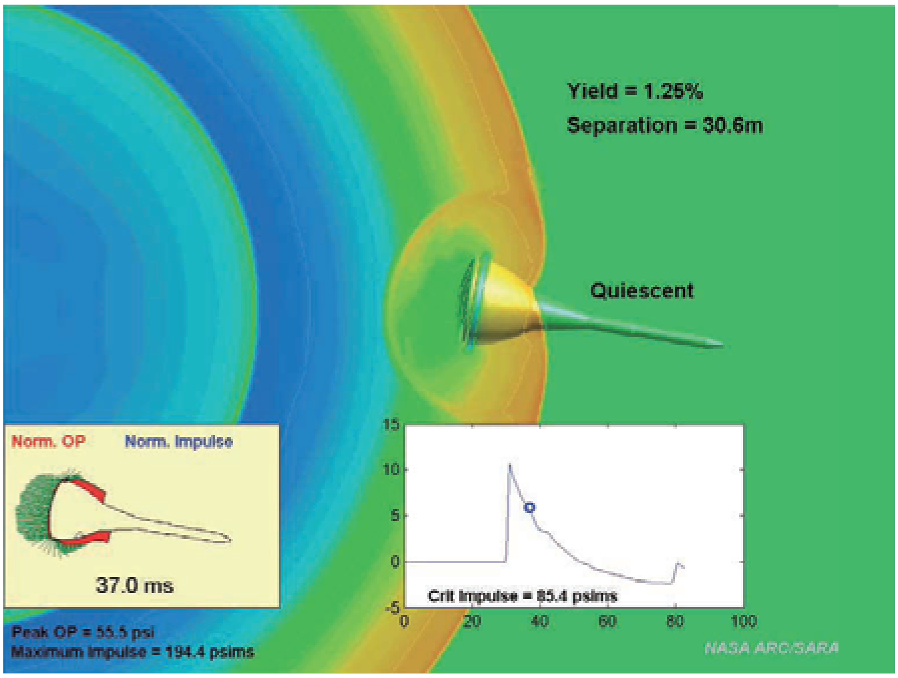
Overpressure Characteristics



Effect on Warning Time Required

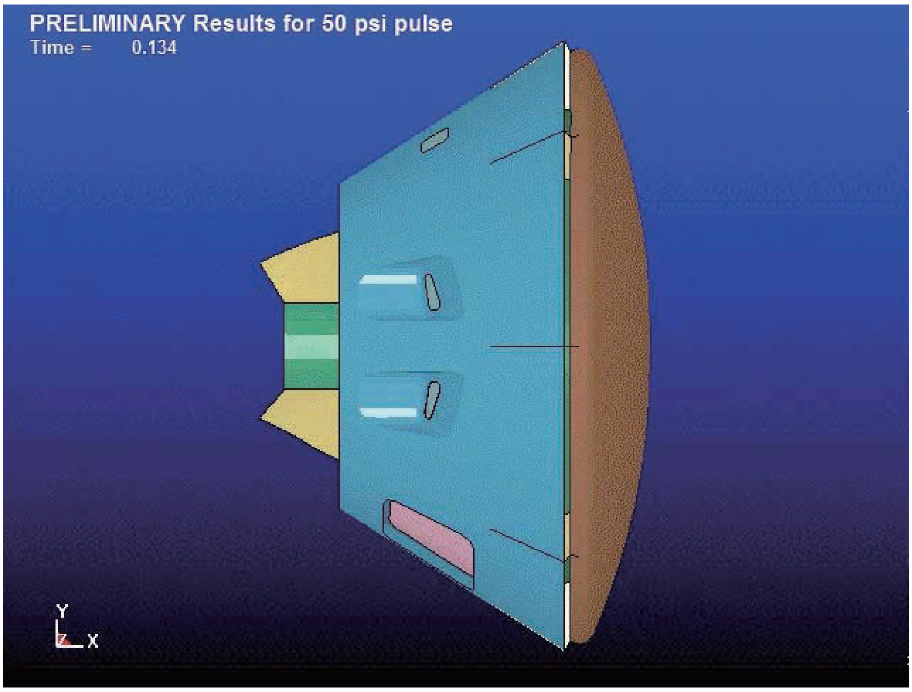


Blast Propagation Model

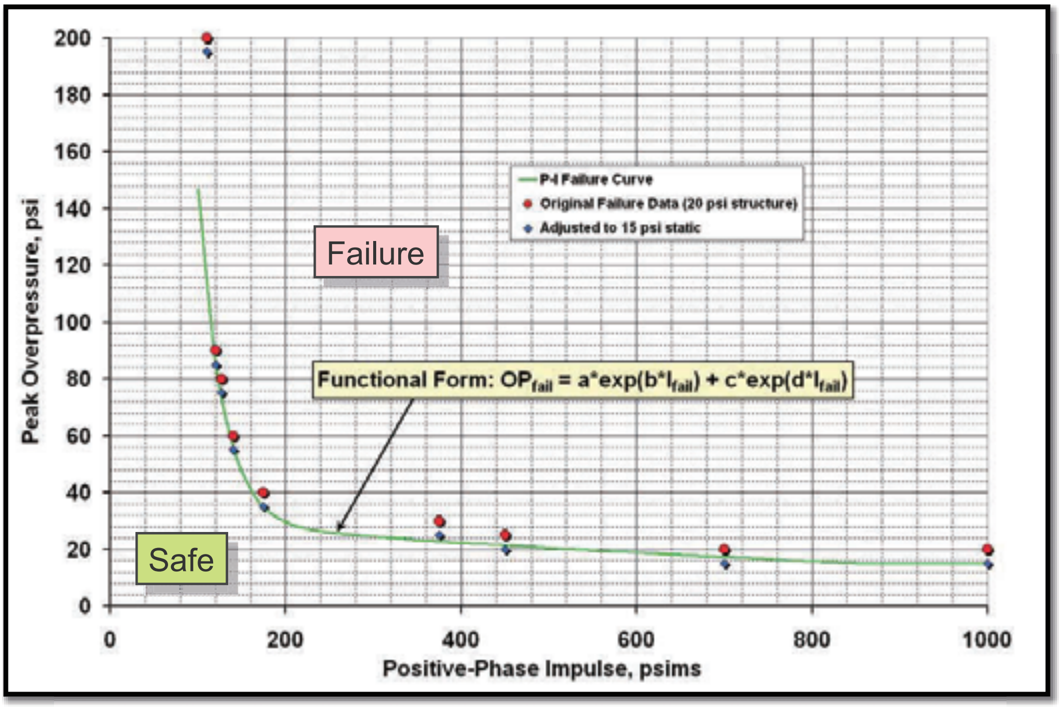


This document is provided by JAXA.

Structural Response Model

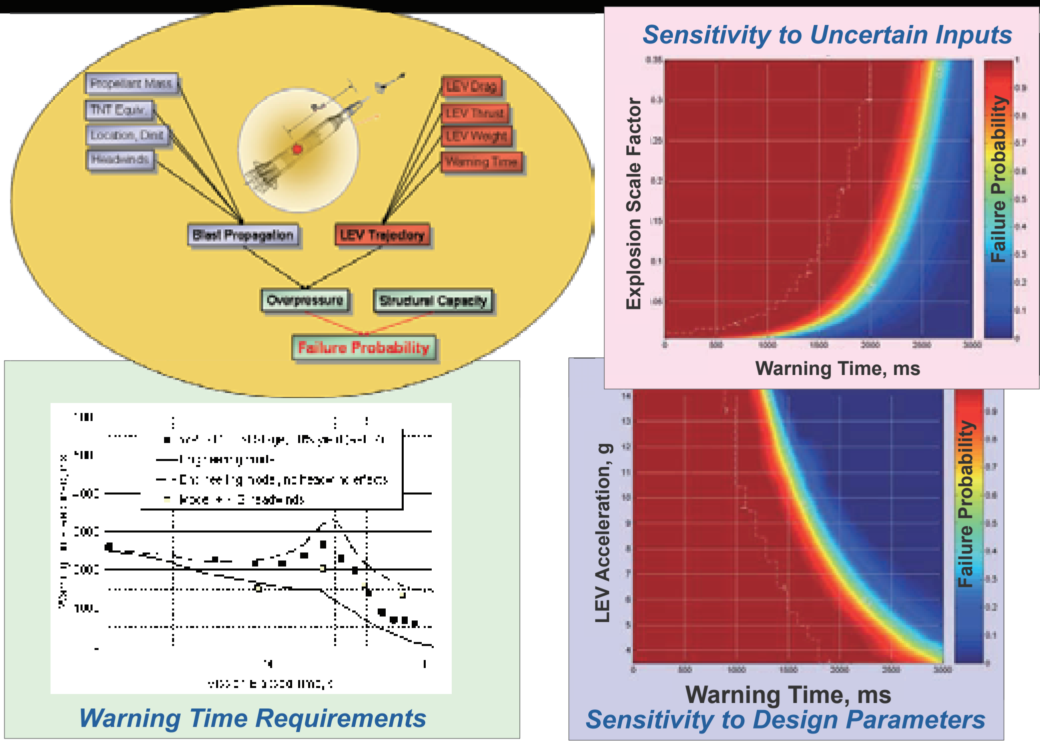


Overpressure-Impulse (P-I) Failure Criteria



This document is provided by JAXA.

Blast Overpressure: Applications



Debris Strike Risk

K. Gee, S. Lawrence, "Launch Vehicle Debris Models and Crew Vehicle Ascent Abort Risk, RAMS, January 2013.

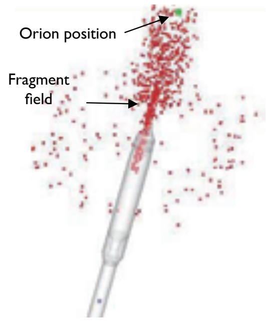
K. Gee, S. Lawrence, "Sensitivity Analysis of Launch Vehicle Debris Risk Model," PSAM10, June 2010.

K. Gee, D. Mathias, "Assessment of Launch Vehicle Debris Risk During Ascent Aborts," RAMS, January 2008.

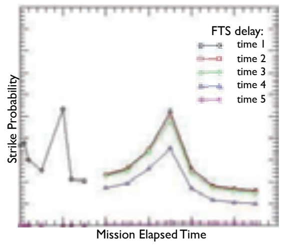
This document is provided by JAXA.

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

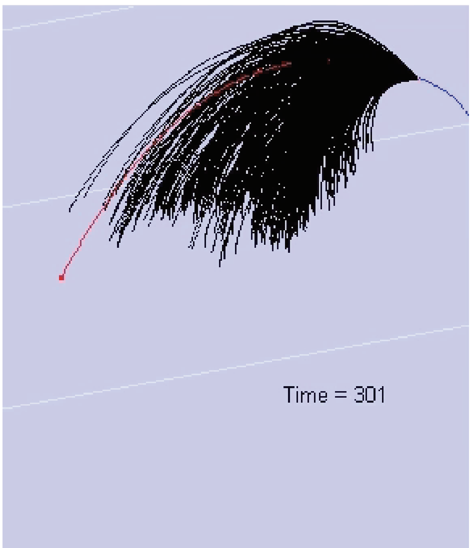


Debris field caused by fragmentation of the Ares I CLV during ascent



Strike probability as a function of MET with penetration criterion

Debris Propagation Model

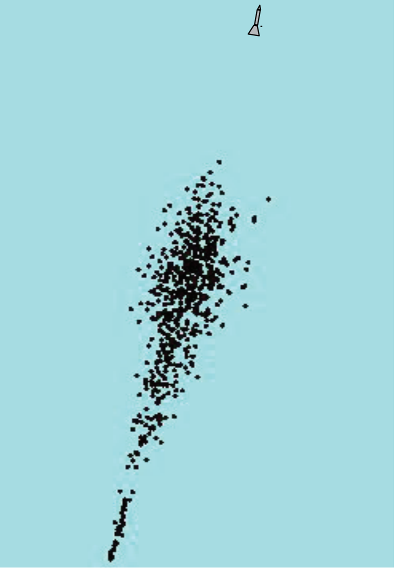


This document is provided by JAXA.

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

This document is provided by JAXA.

Debris Catalog Model

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

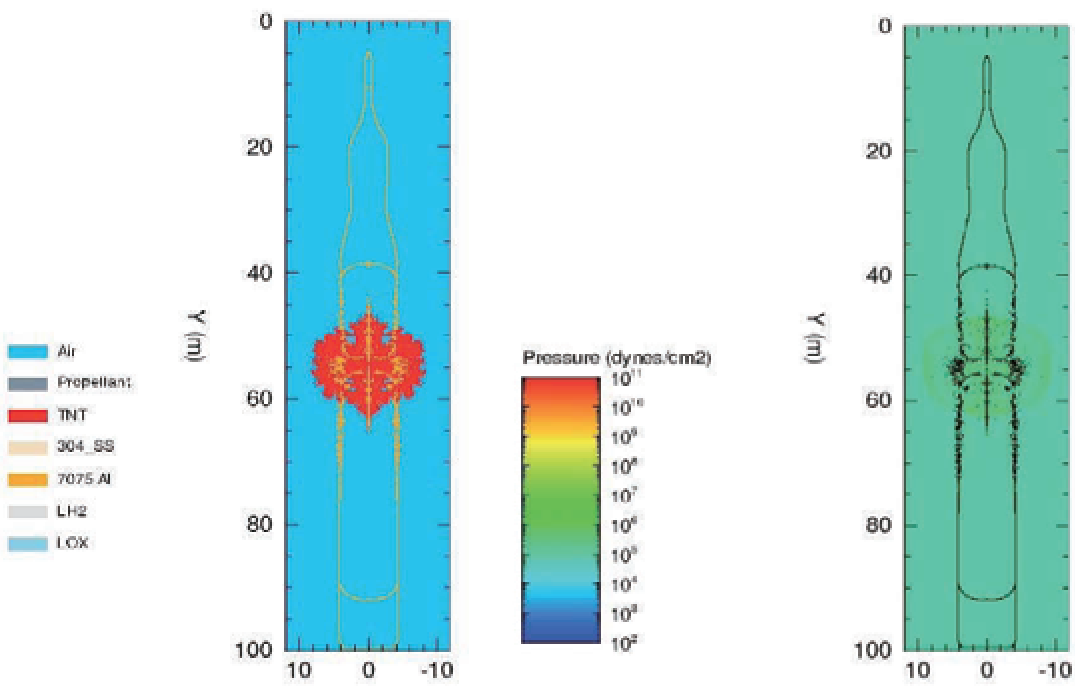
Sternberg 3-part exponential distribution

- 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

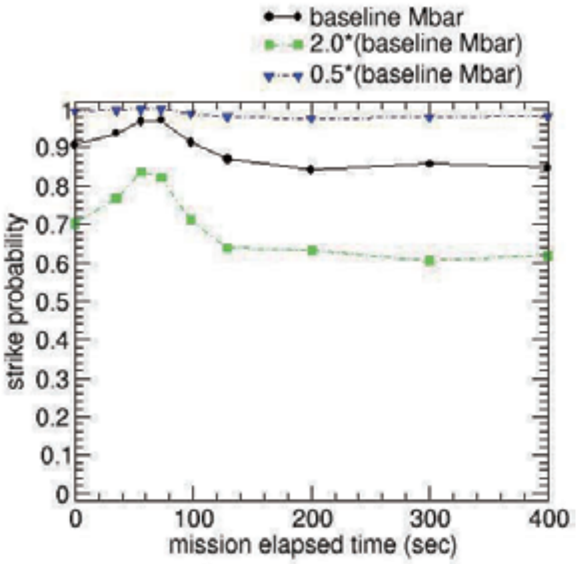
Ken Gee (Ken.Gee-1@nasa.gov)

Vehicle-level Explosion Model II



This document is provided by JAXA.

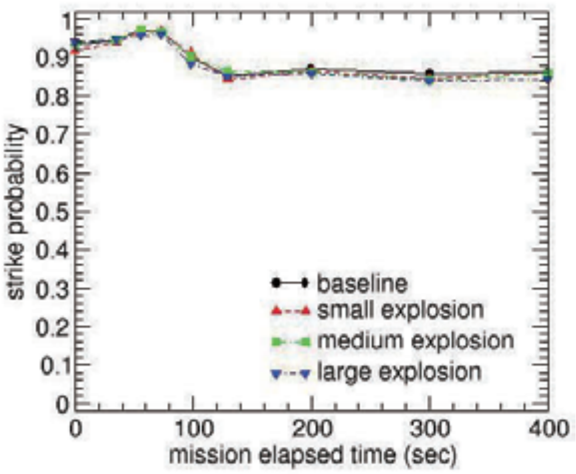
Debris Strike Sensitivity



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

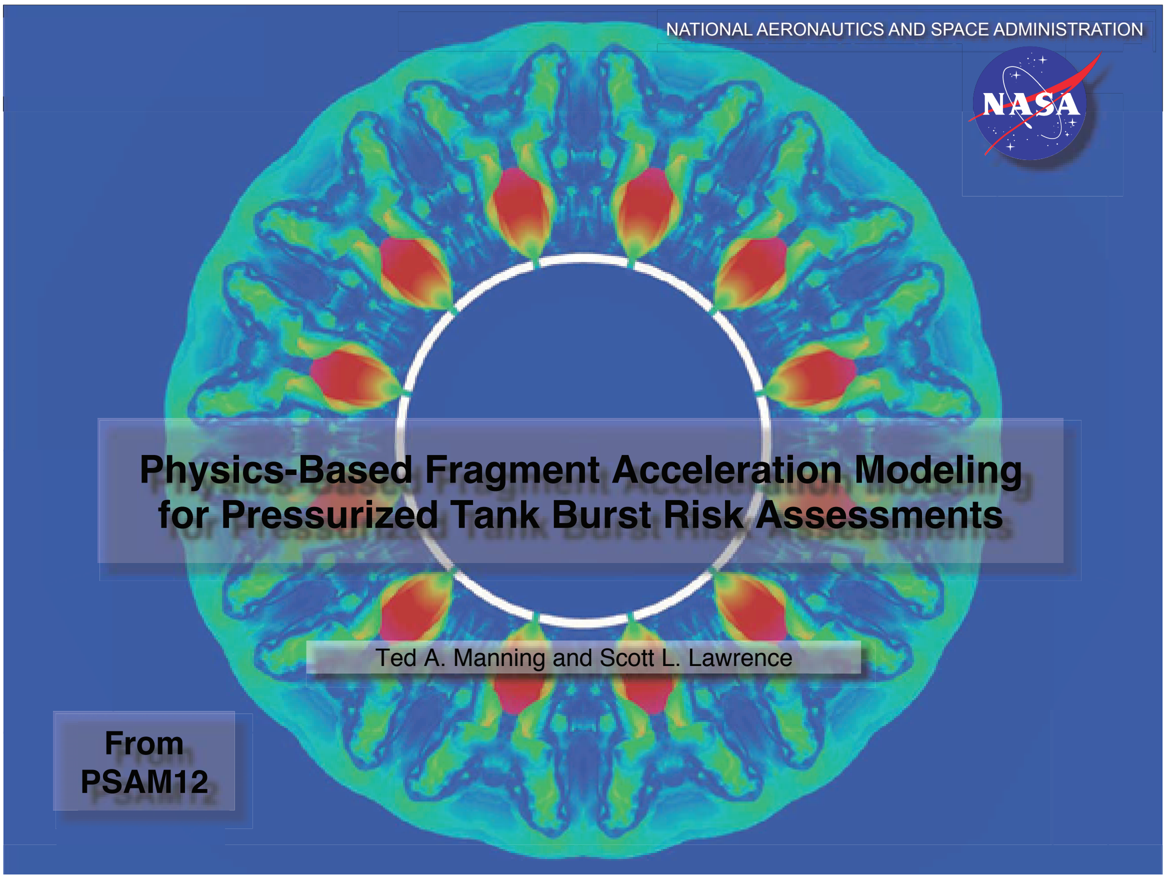
Space Shuttle ET debris model

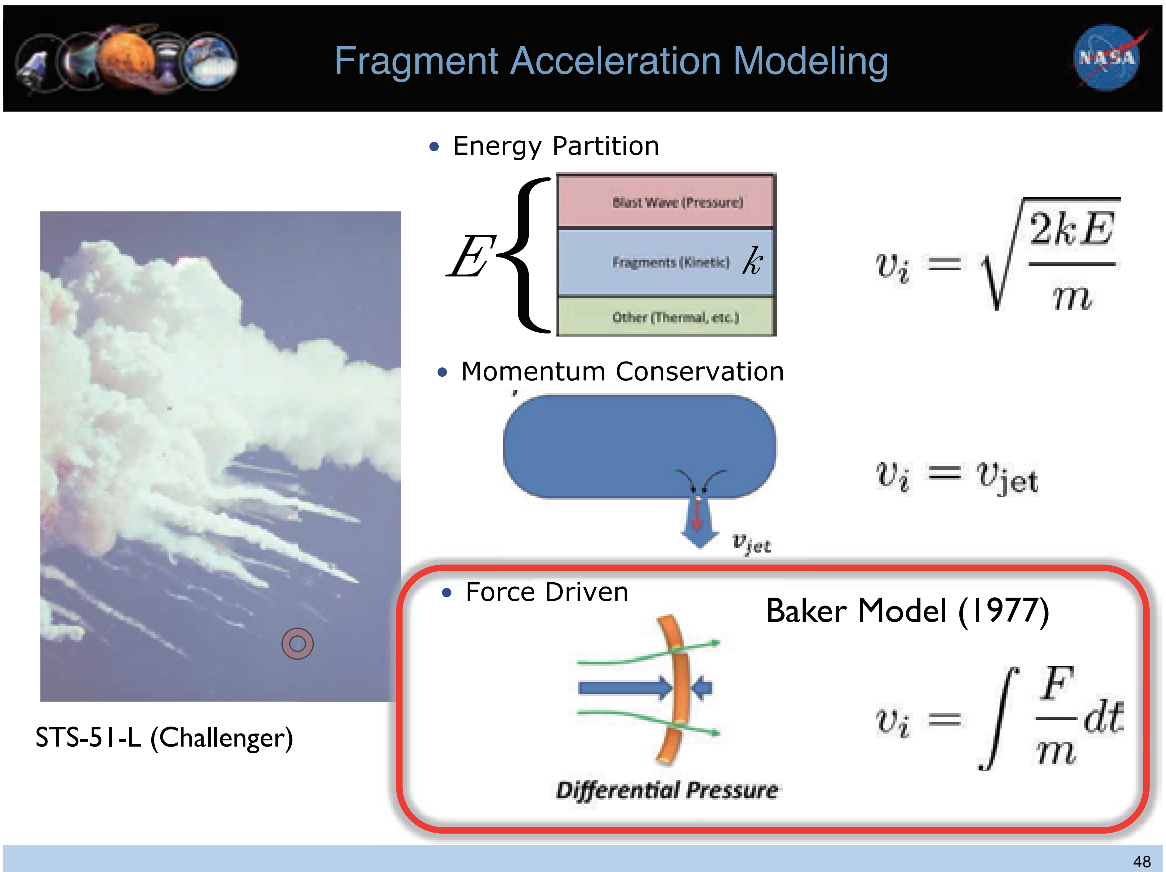
Debris Strike Sensitivity



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

This document is provided by JAXA.





This document is provided by JAXA.

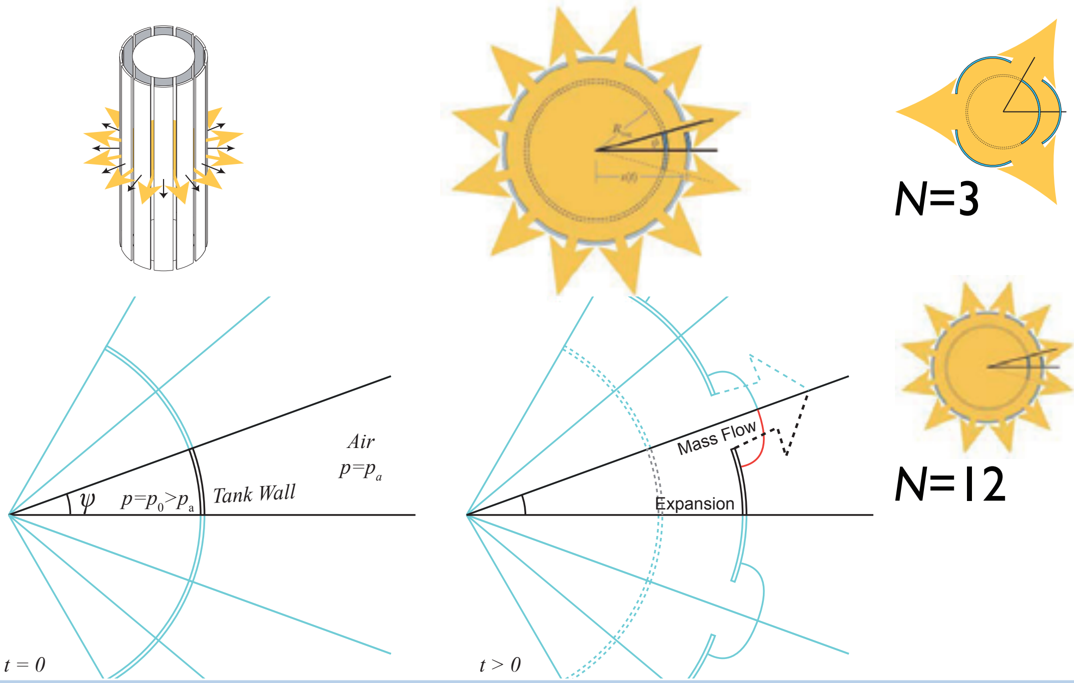
Problem Statement

- 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

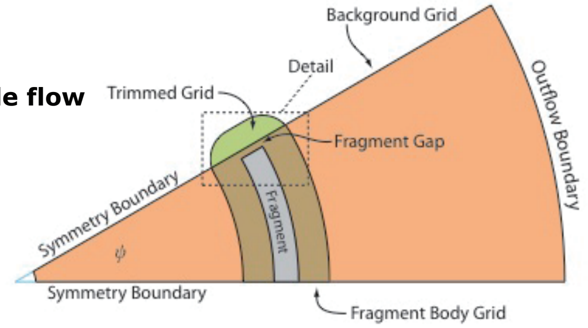
Infinite Cylinder: 2-dimensional expansion of gas, with gap leakage, *N* fragments



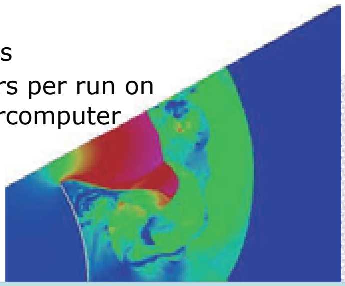
This document is provided by JAXA.

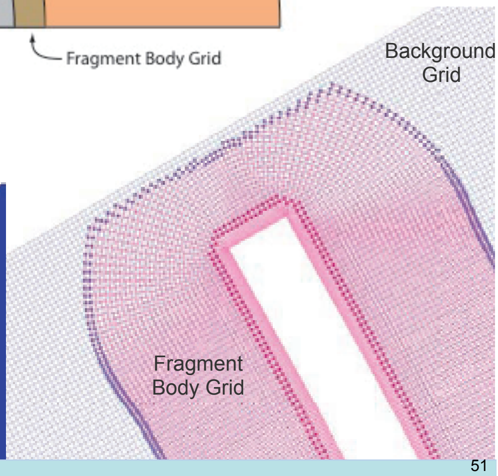
Computational Fluid Dynamics (CFD) Simulations

- 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°

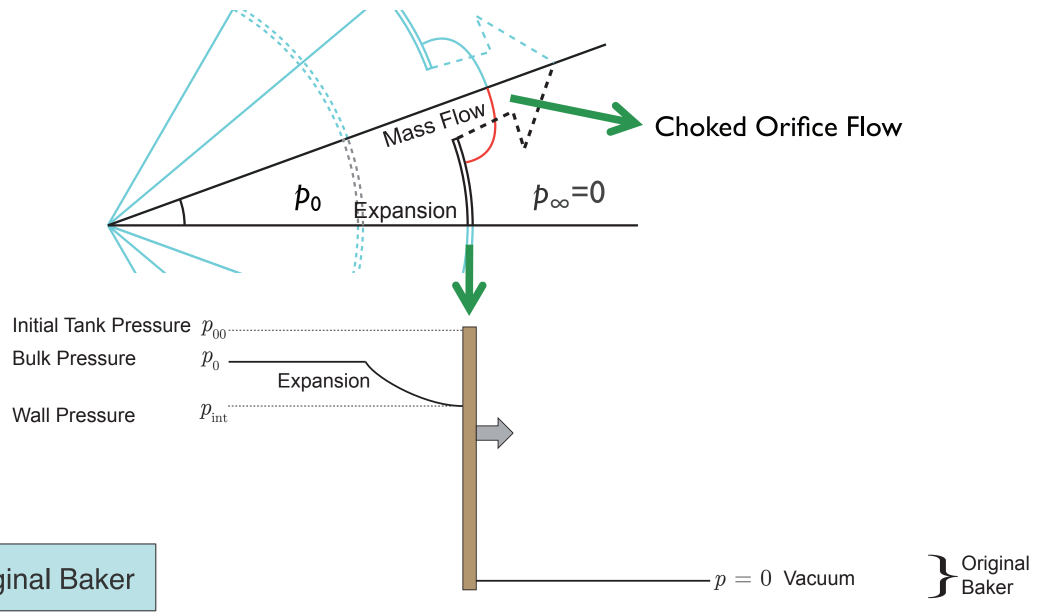




OVERFLOW CFD

Tank Burst Engineering Model (Baker Model)

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

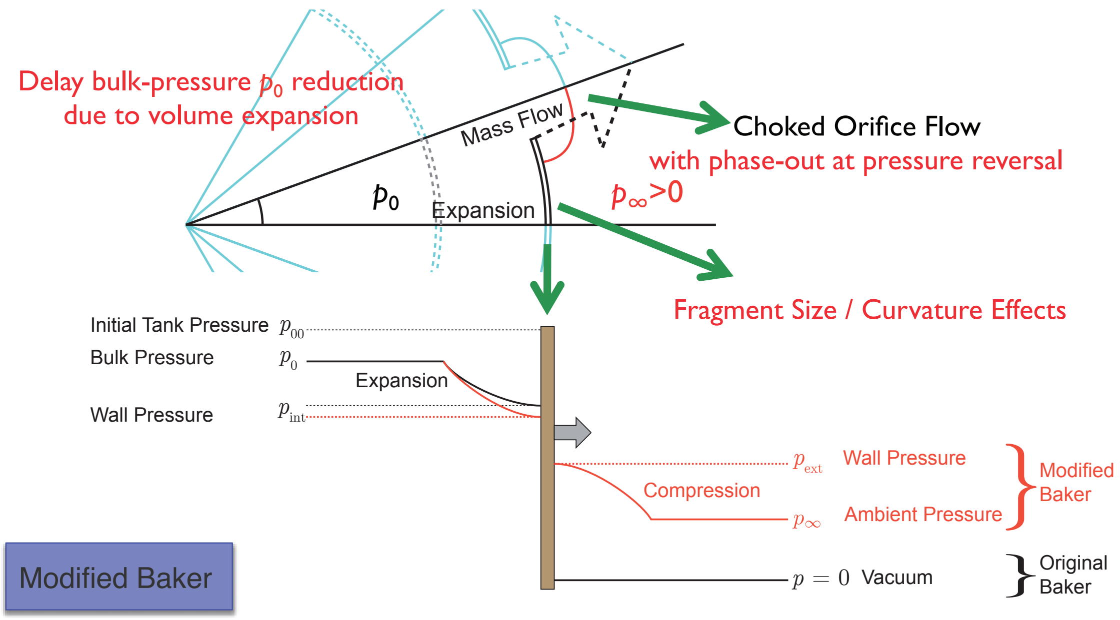


Original Baker

This document is provided by JAXA.

Modifications to Baker Model

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

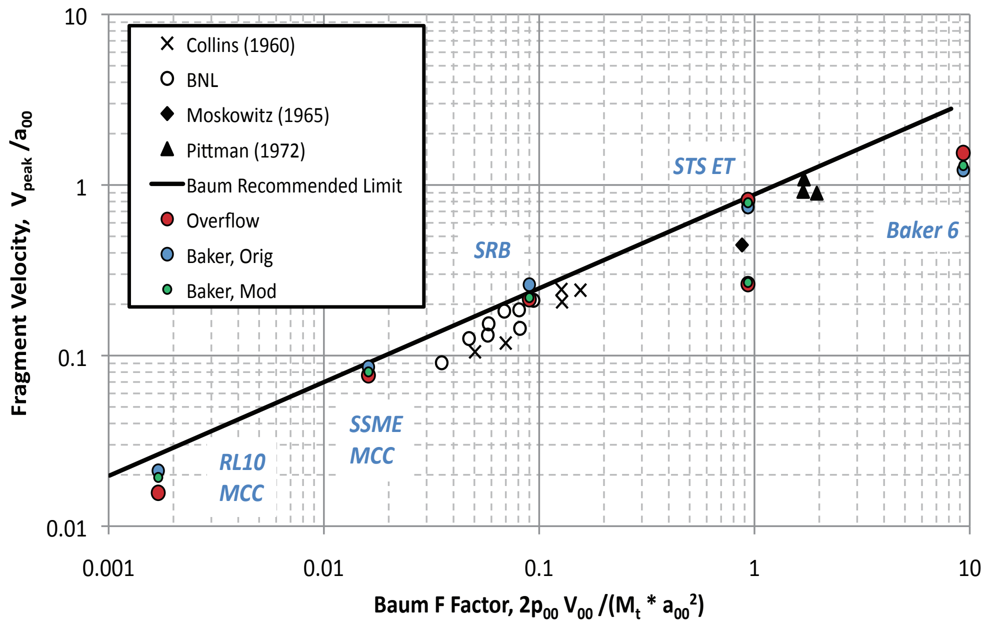


Tank Burst Cases

	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_w (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

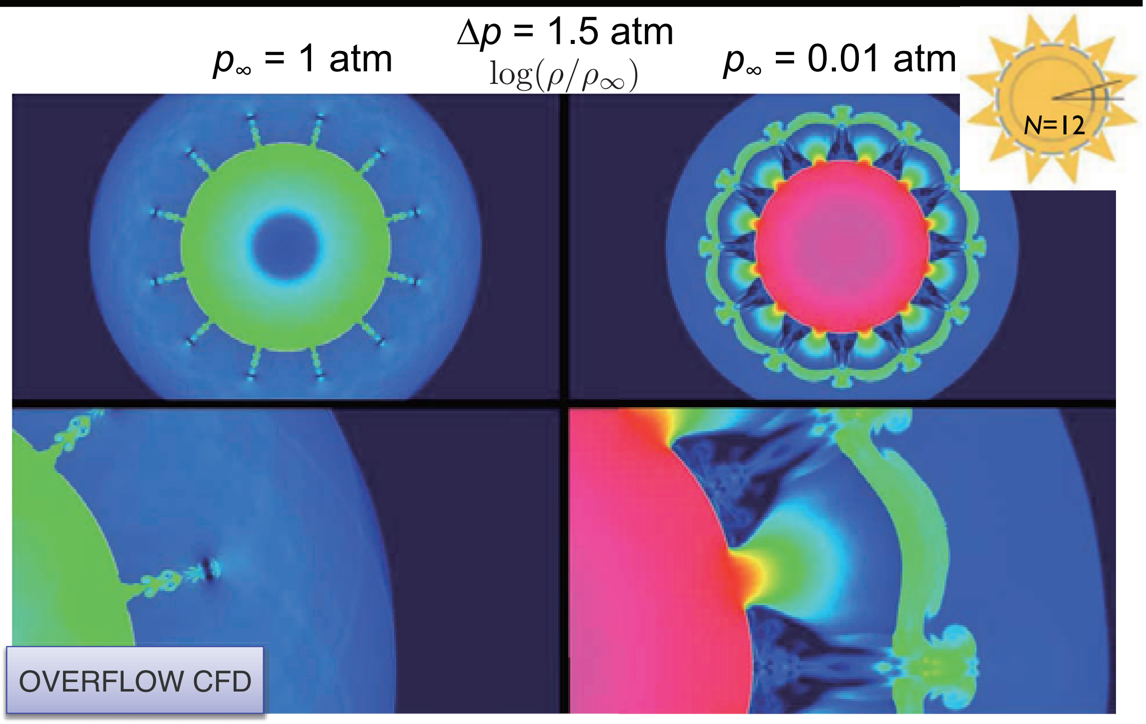
This document is provided by JAXA.

Compared to Baum Velocity Limit



Original Baker | Modified Baker | OVERFLOW CFD

STS External Tank: External Pressure Effect

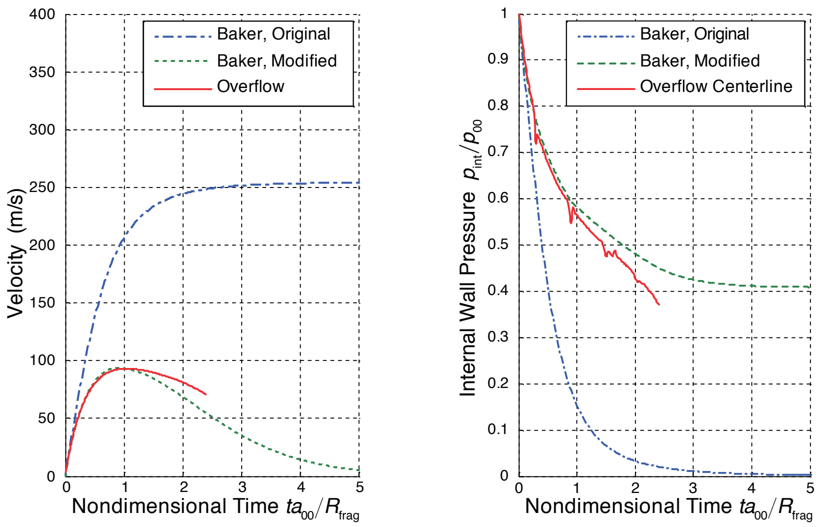


This document is provided by JAXA.

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

N=12



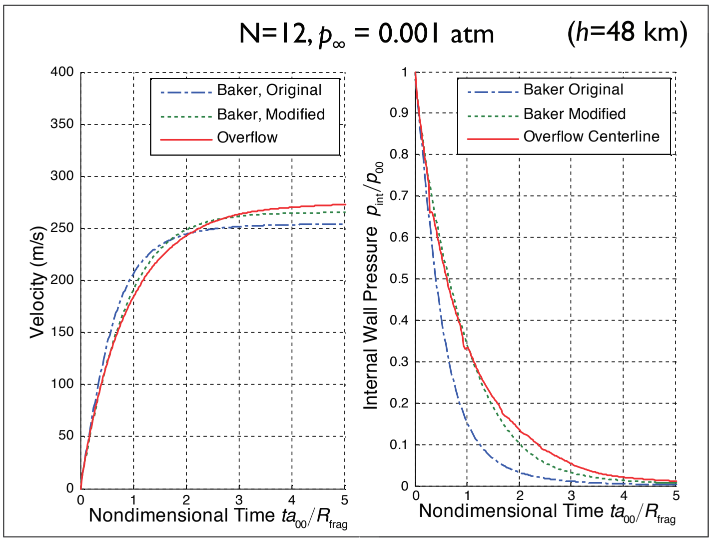
Original Baker | Modified Baker | OVERFLOW CFD

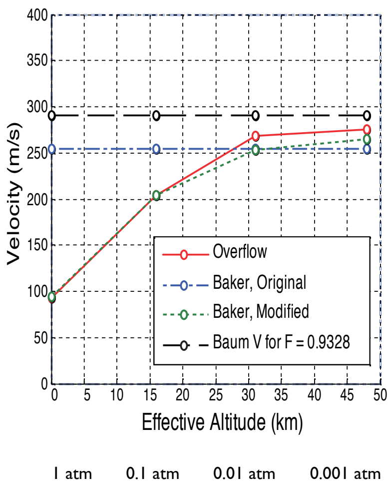
57

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

N=12





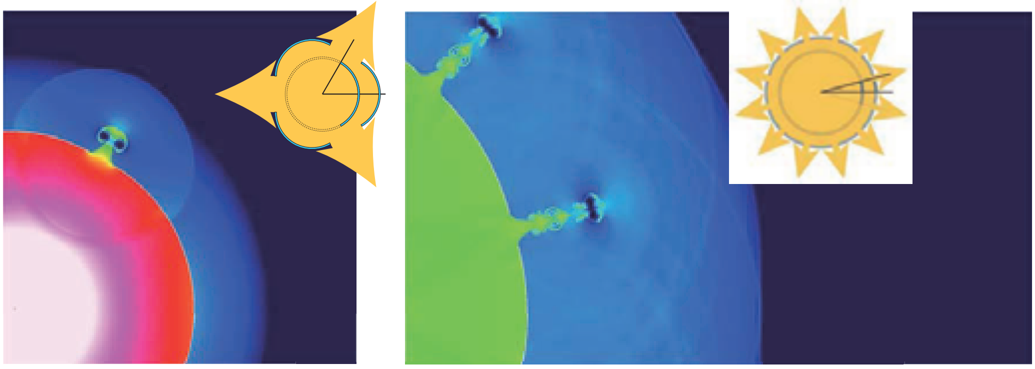
Original Baker | Modified Baker | OVERFLOW CFD

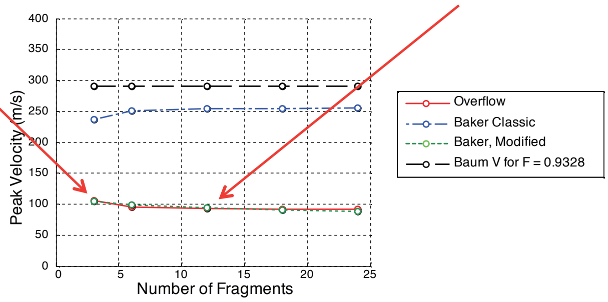
58

This document is provided by JAXA.

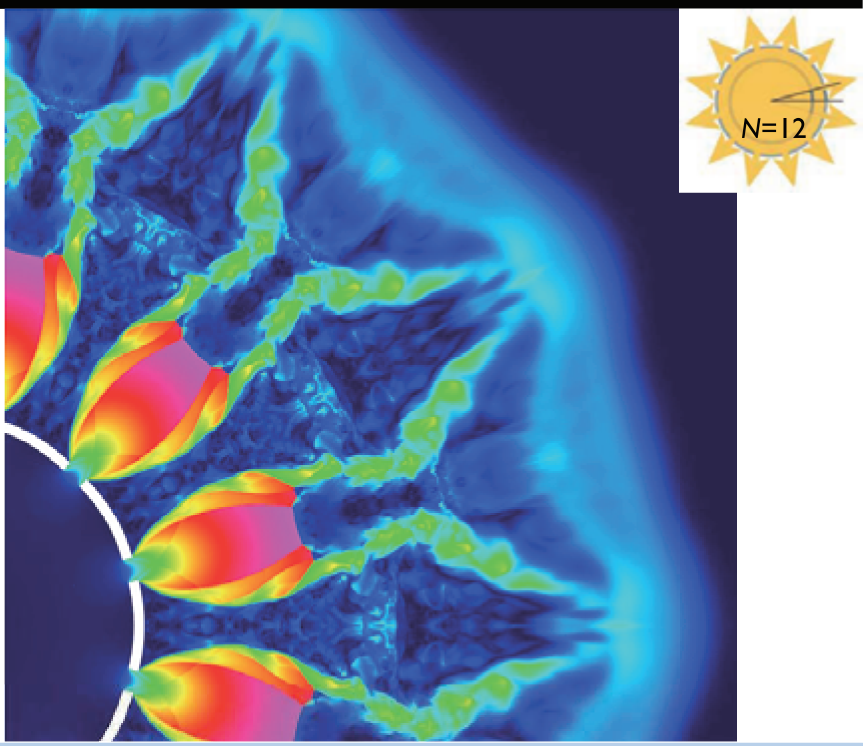
STS External Tank: Fragment Count N

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

This document is provided by JAXA.

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

61

Engineering Risk Assessment

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

62

This document is provided by JAXA.