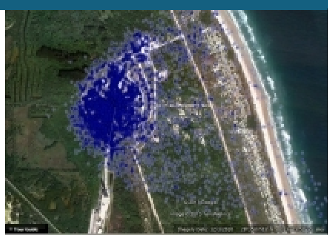
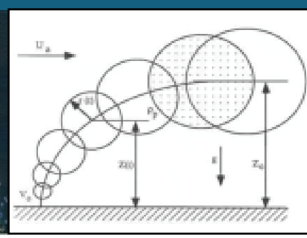
SAND2020-11451C

Sandia National Laboratories

Radioisotope Systems Launch Safety Overview





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Sandia National Laboratories

Nuclear Science Week, Oct 21st 2020

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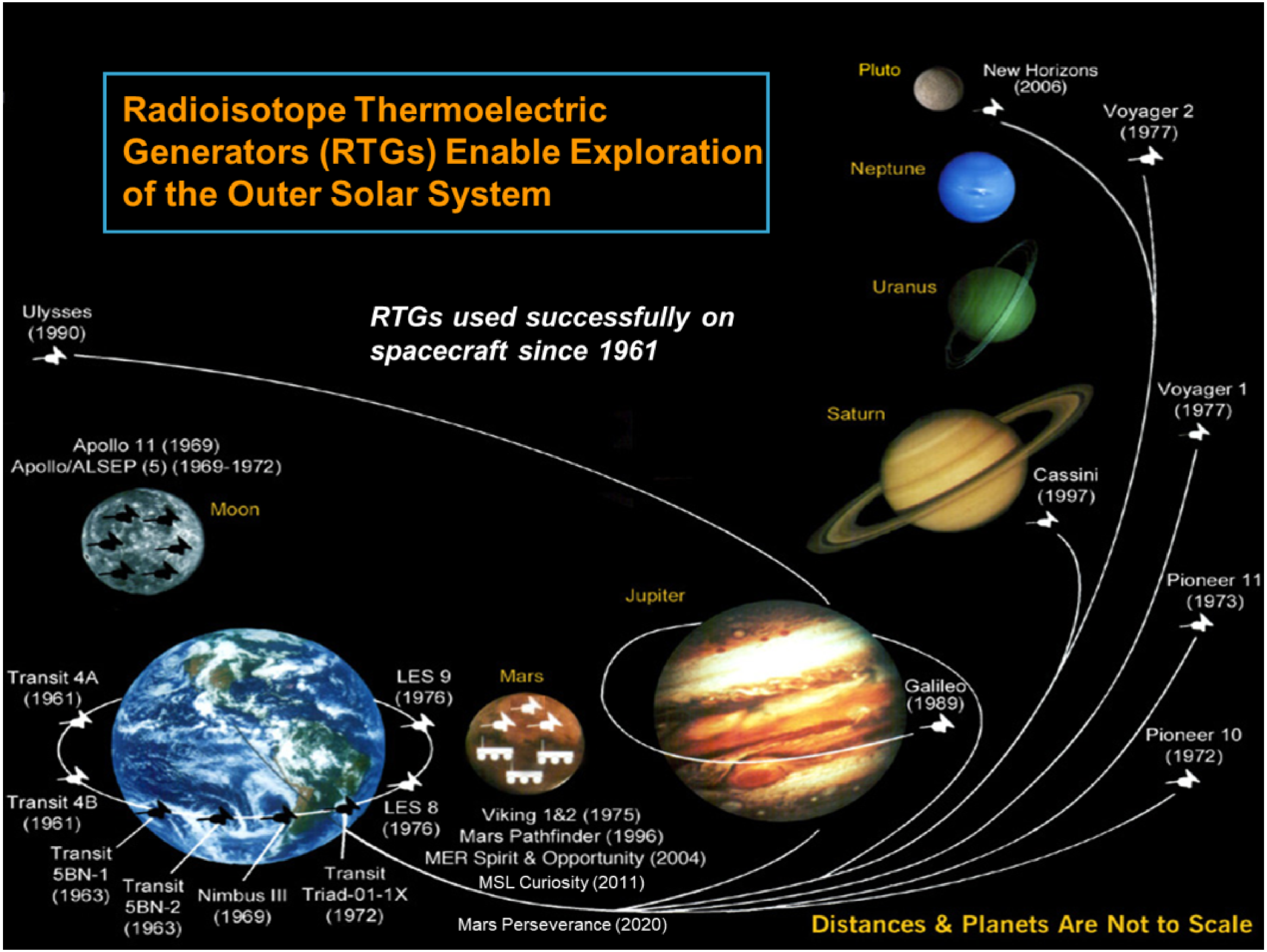

Radioisotope Thermoelectric Generators (RTGs) Enable Exploration of the Outer Solar System
RTGs used successfully on spacecraft since 1961
Pluto
New Horizons (2006)
Voyager 2 (1977)
Neptune
Uranus
Ulysses (1990)
Voyager 1 (1977)
Saturn
Apollo 11 (1969)
Apollo/ALSEP (5) (1969-1972)
Moon
Cassini (1997)
Pioneer 11 (1973)
Jupiter
Transit 4A (1961)
LES 9 (1976)
Mars
Galileo (1989)
Pioneer 10 (1972)
Transit 4B (1961)
LES 8 (1976)
Viking 1&2 (1975)
Mars Pathfinder (1996)
MER Spirit & Opportunity (2004)
MSL Curiosity (2011)
Transit 5BN-1 (1963)
Transit 5BN-2 (1963)
Nimbus III (1969)
Transit Triad-01-1X (1972)
Mars Perseverance (2020)
Distances & Planets Are Not to Scale

Curiosity on Mars

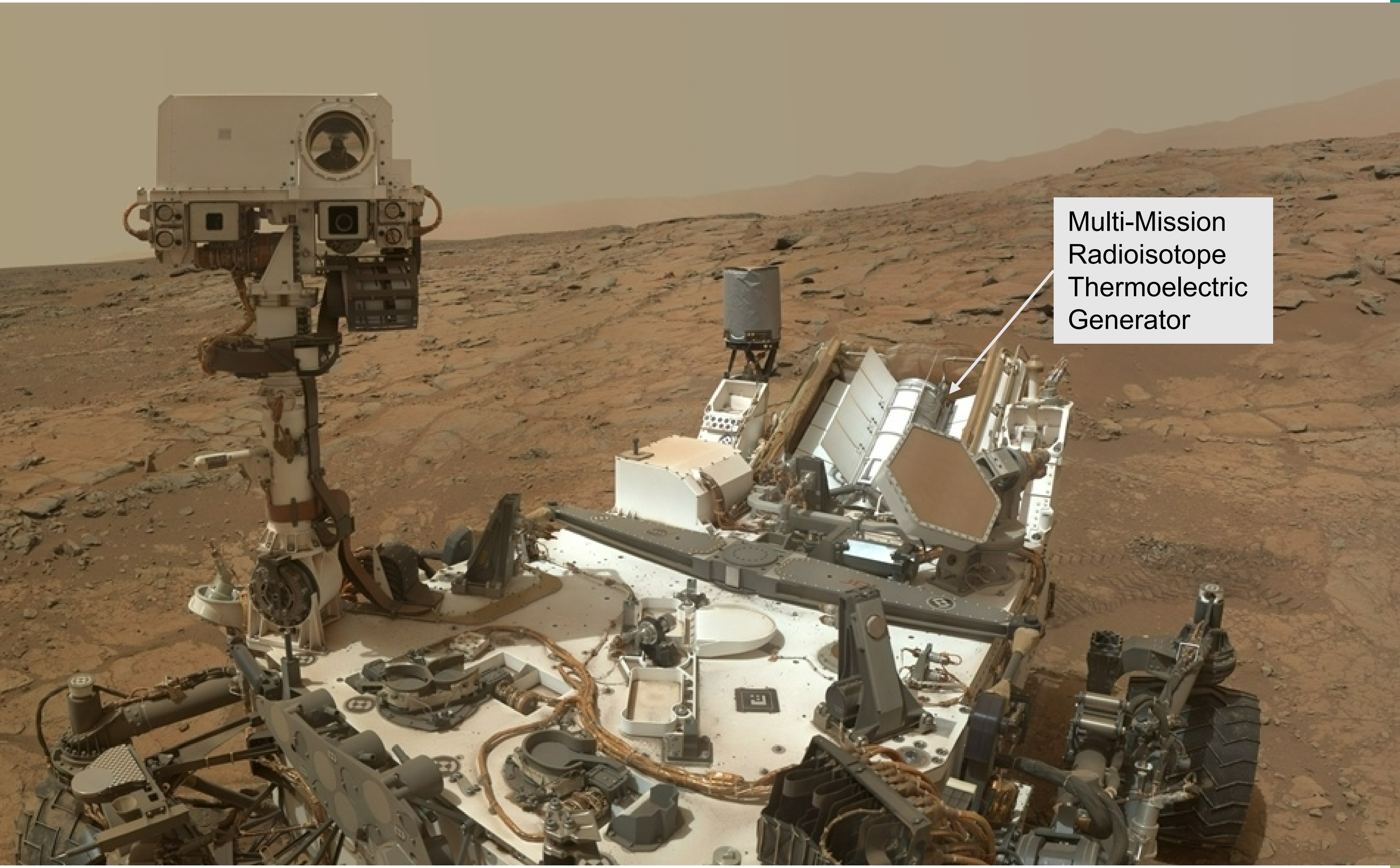
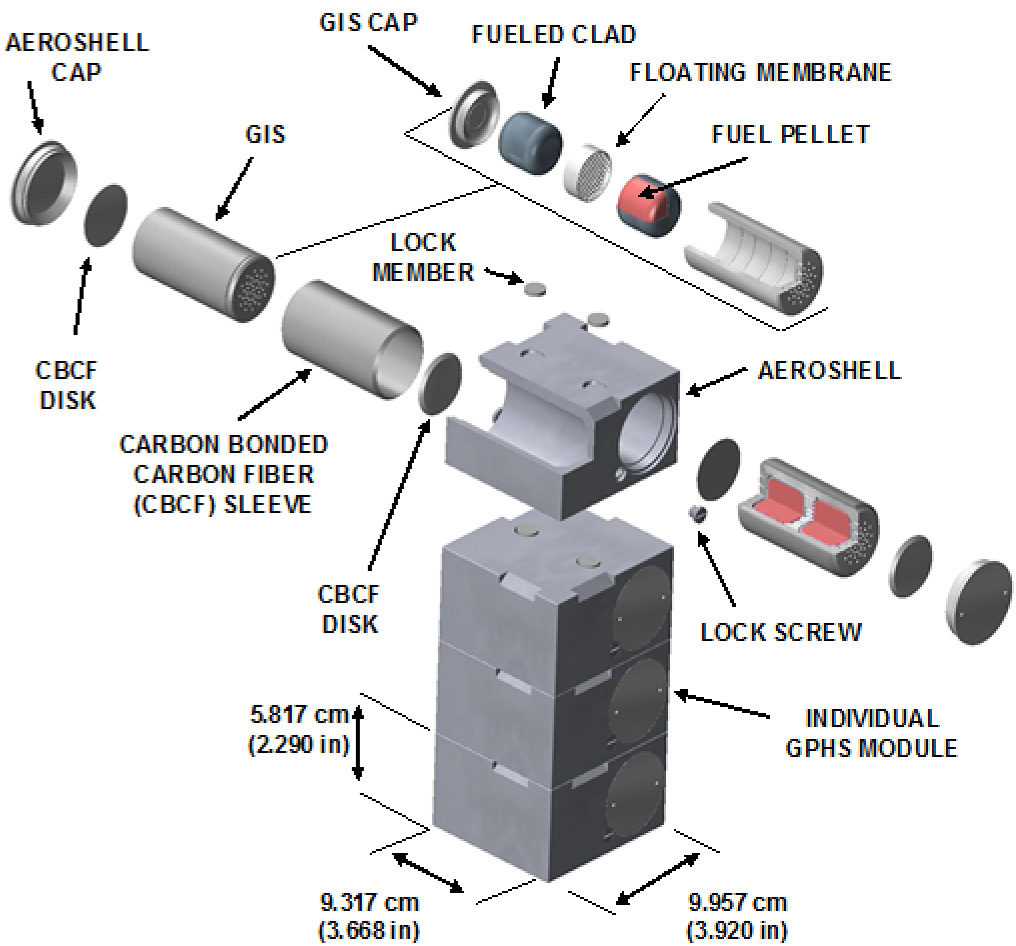
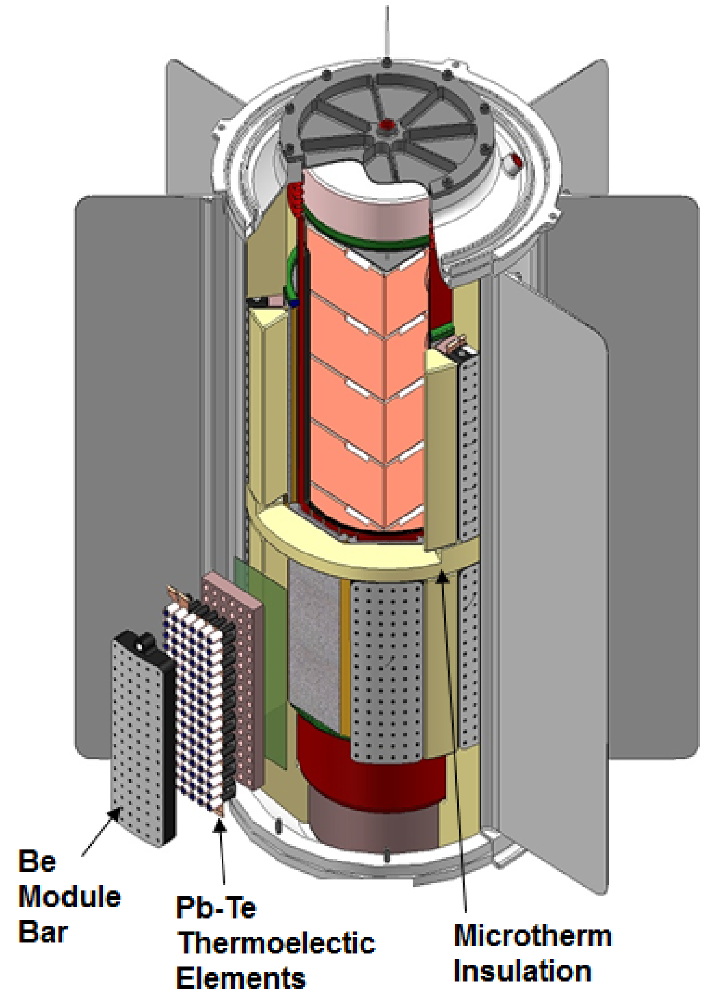


Image Courtesy NASA/JPL

Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)





Safety is built from the inside out and from the outside in. Analysis must quantify this for decision makers.

Launches Can Fail

Atlas Fallback-1965

Titan 34D-Apr 18, 1986

Antares-Oct 28, 2014

Delta 241-Jan 27, 1997

Launch Safety Analysis Approach

Identify **main sources** of risk, to allow for potential **mitigating actions**, to **reduce** the overall mission **risk**

Goal: **Quantitative** estimate of the risk that is **defensible** and **credible**

- Mean probability of an accident
- Mean probability of release of PuO_2
- Mass of PuO_2 released ("source term")
- Health effects (dose, latent cancer fatalities over 50 years)
- Land, crop contamination
- All expressed as mean values, percentile values, and exceedance probability graphs
- Quantify uncertainty

Risk Estimation Methodology

Detailed simulations and Monte Carlo sequence codes used to develop the probabilistic risk analysis

- Potential accidents associated with the launch
  - Probability
  - Environment
- Detailed understanding of the response of power system to insults
  - Explosion Overpressure
  - Fragments
  - Ground Impact
  - Thermal Environment
  - Reentry
- Atmospheric transport and consequences
  - Thermal buoyancy effects from fires
  - Meteorological conditions
  - Population and land usage distribution

Mission Phases

Phase 0 – Prelaunch, $T < t_1$, from installation of the MMRTG to just prior to start of engines at t_1

Phase 1 – Early Launch, $t_1 \leq T < t_x$, start of engines to no potential for land impact in the launch area, t_x

Phase 2 – Late Launch, $t_x \leq T$, end of Phase 1 to the launch vehicle reaching 30,480 m (100,000 ft), above which reentry heating could occur

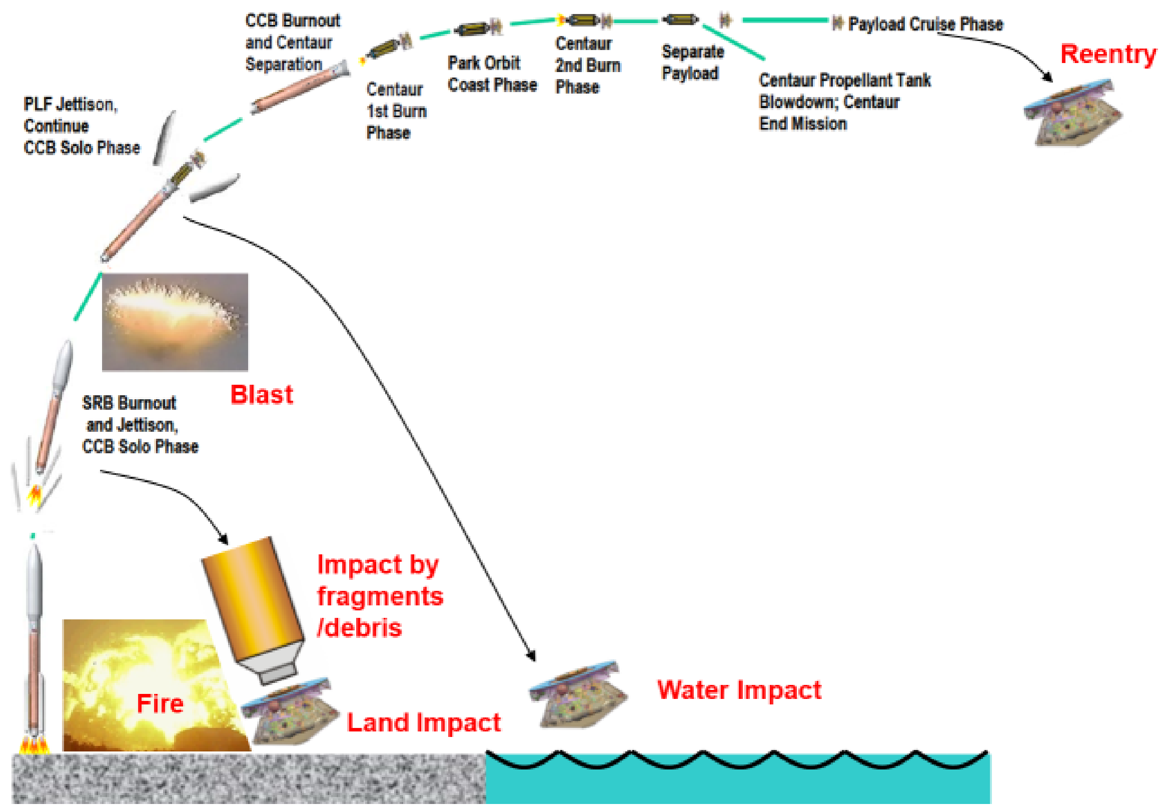
Phase 3 – Suborbital Reentry, end of Phase 2 to just prior to orbit

Phase 4 – Orbital Reentry, end of Phase 3 to spacecraft separation

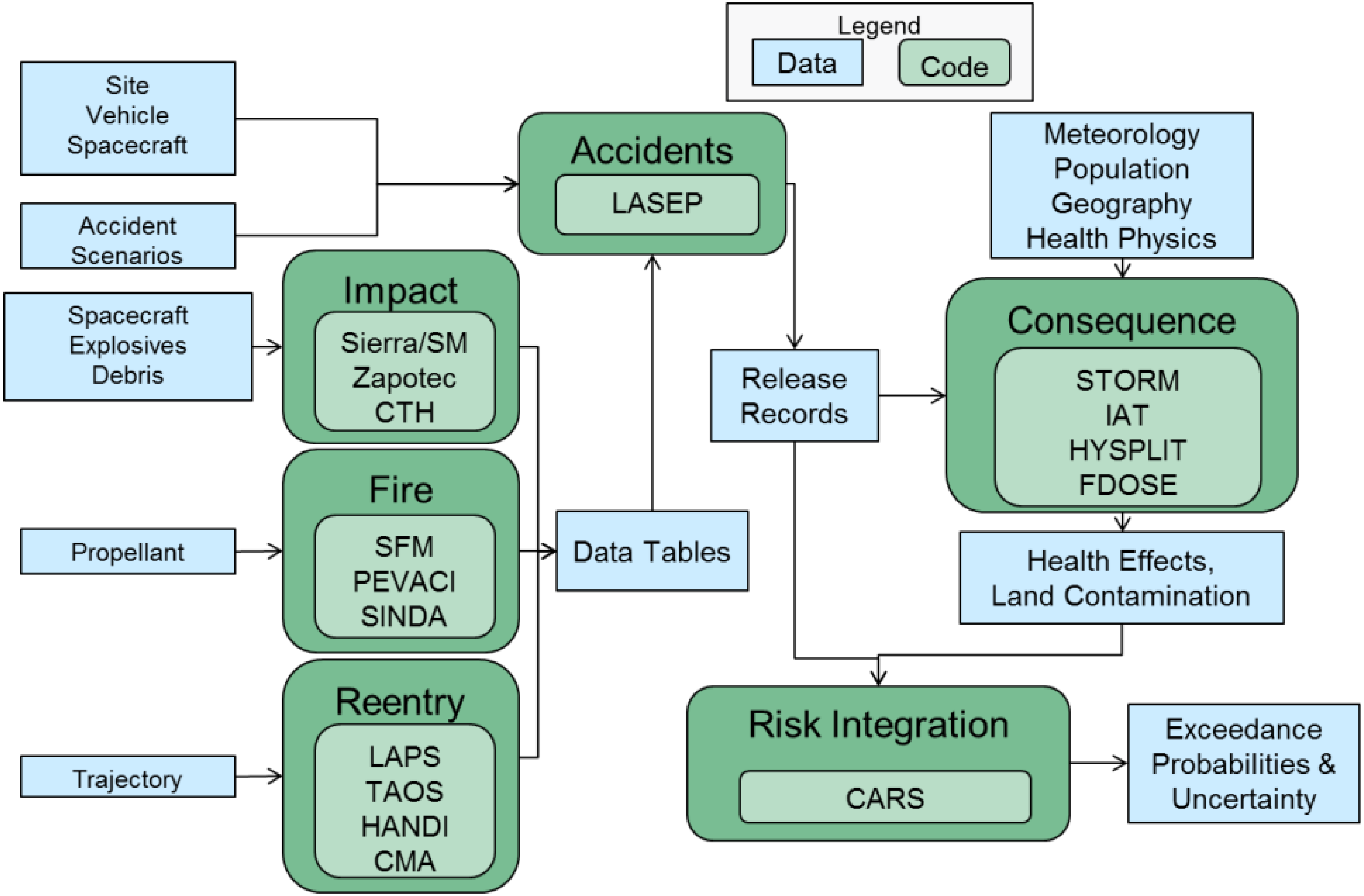
Phase 5 – Long-Term Reentry, end of Phase 4 to no chance of Earth reentry

Representative Accident Scenarios (RASs)

- Divide mission into six phases
- Construct accident scenarios within each phase
- Groups accident environments into RASs
- Combine results from each RASs into phase and overall results, based on the relative probability



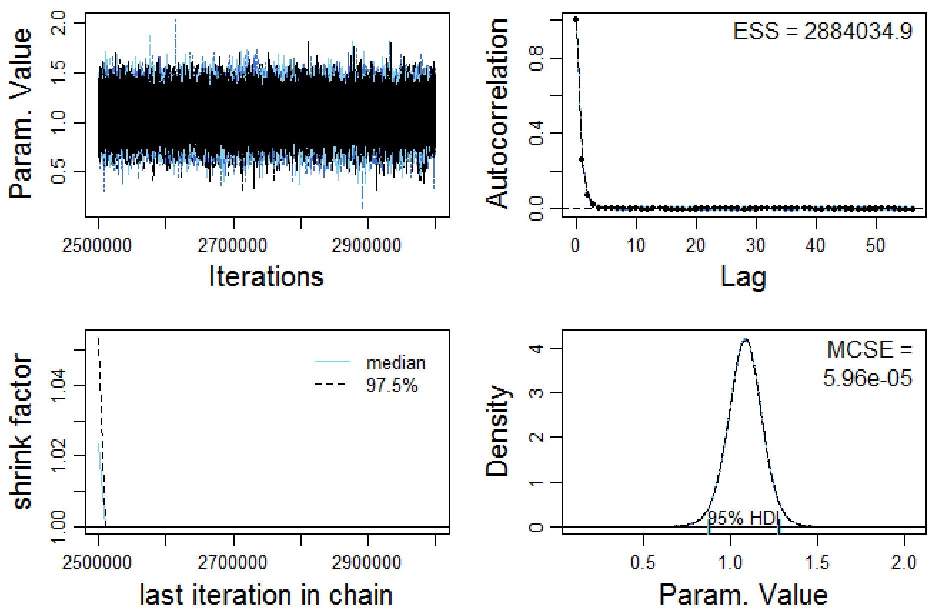
Launch Safety Code Suite



Risk & Uncertainty

Provide a comprehensive risk & uncertainty picture developed to cover the entire analysis process

- Performance of stability and convergence analyses
- Update of unknown probability distributions using Bayesian methods



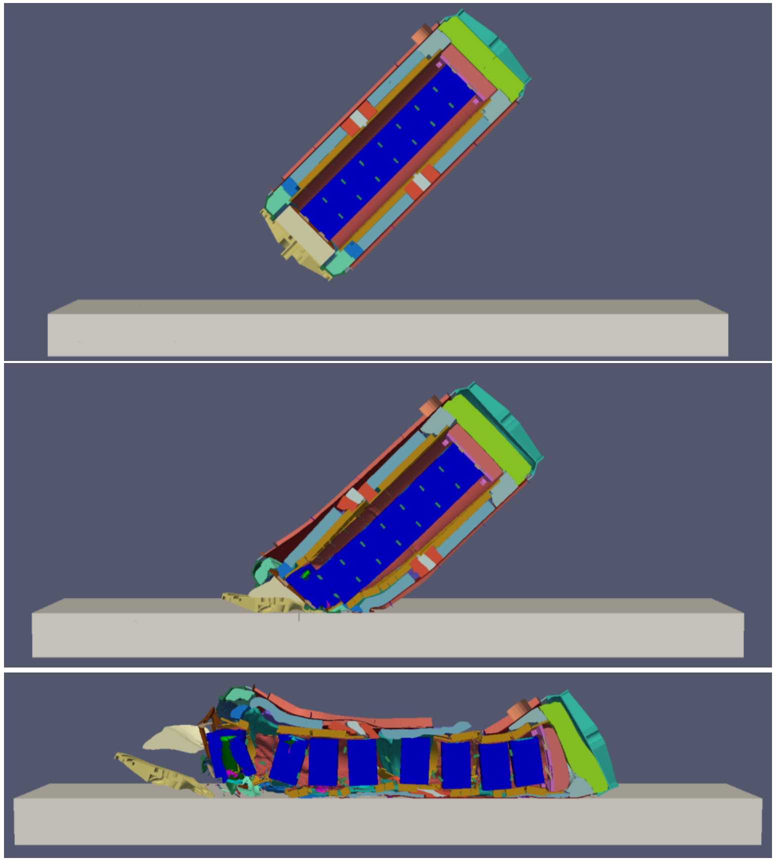
Bayesian Posterior Diagnostics

Blast & Impact

Some blasts and impacts have the potential to breach the multiple layers of protection

Determine range of end states

- Blasts
  - Launch destruct
  - Shockwave from ground impact of propellant tanks
  - Shockwave from ground impact of solid propellant fragments
- Impacts
  - Ground surface
  - Spacecraft and launch vehicle debris/fragments
  - Solid propellant fragments



MMRTG 45° Impact at 100 m/s
(terminal velocity is 60 m/s)
No fuel release

Fire & Thermal

Solid Propellant Burn Test

Liquid propellant fire temperatures exceed PuO_2 vaporization temperatures

Solid propellant fire temperatures exceed iridium clad melt and PuO_2 vaporization temperatures

Determine effect of potential fire environments on the range of PuO_2 vaporized and resulting particle sizes changes due to the vaporization and condensation

Reentry

Atmospheric reentry effects have the potential to breakup

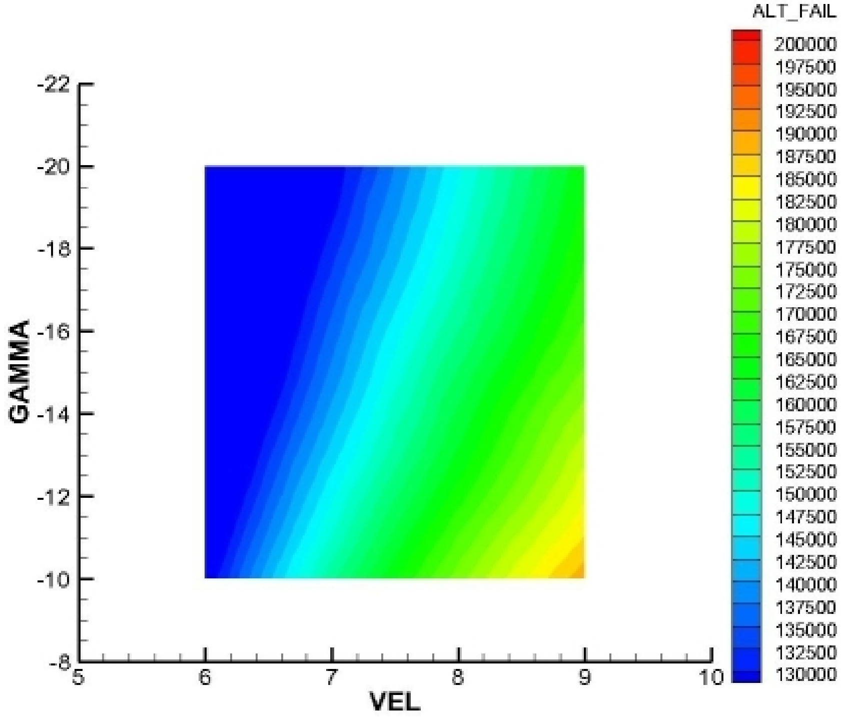
- Launch vehicle
- Space vehicle
- MMRTG

Determine range of the reentry environments on the configuration

- Trajectory
- Heating of components
- Ablation

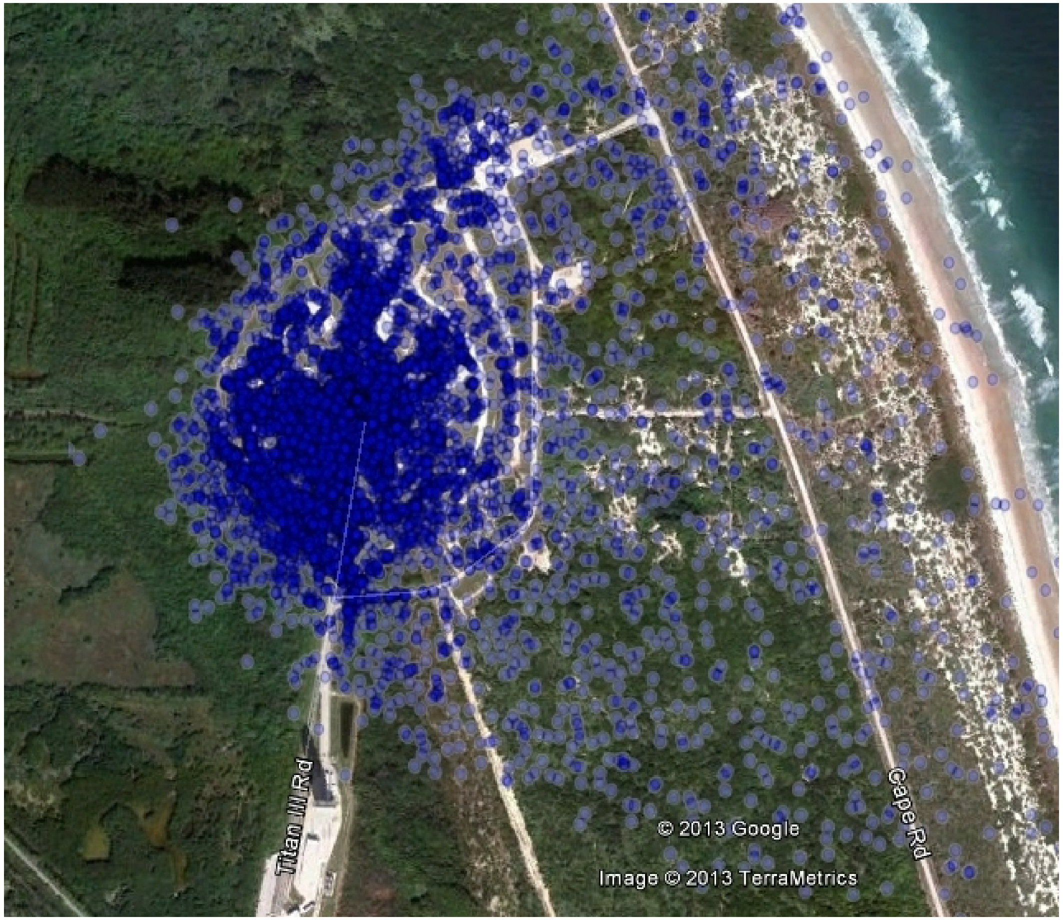
MMRTG Breakup v-gamma Map

(gamma is entry angle)



Release Locations and Amounts

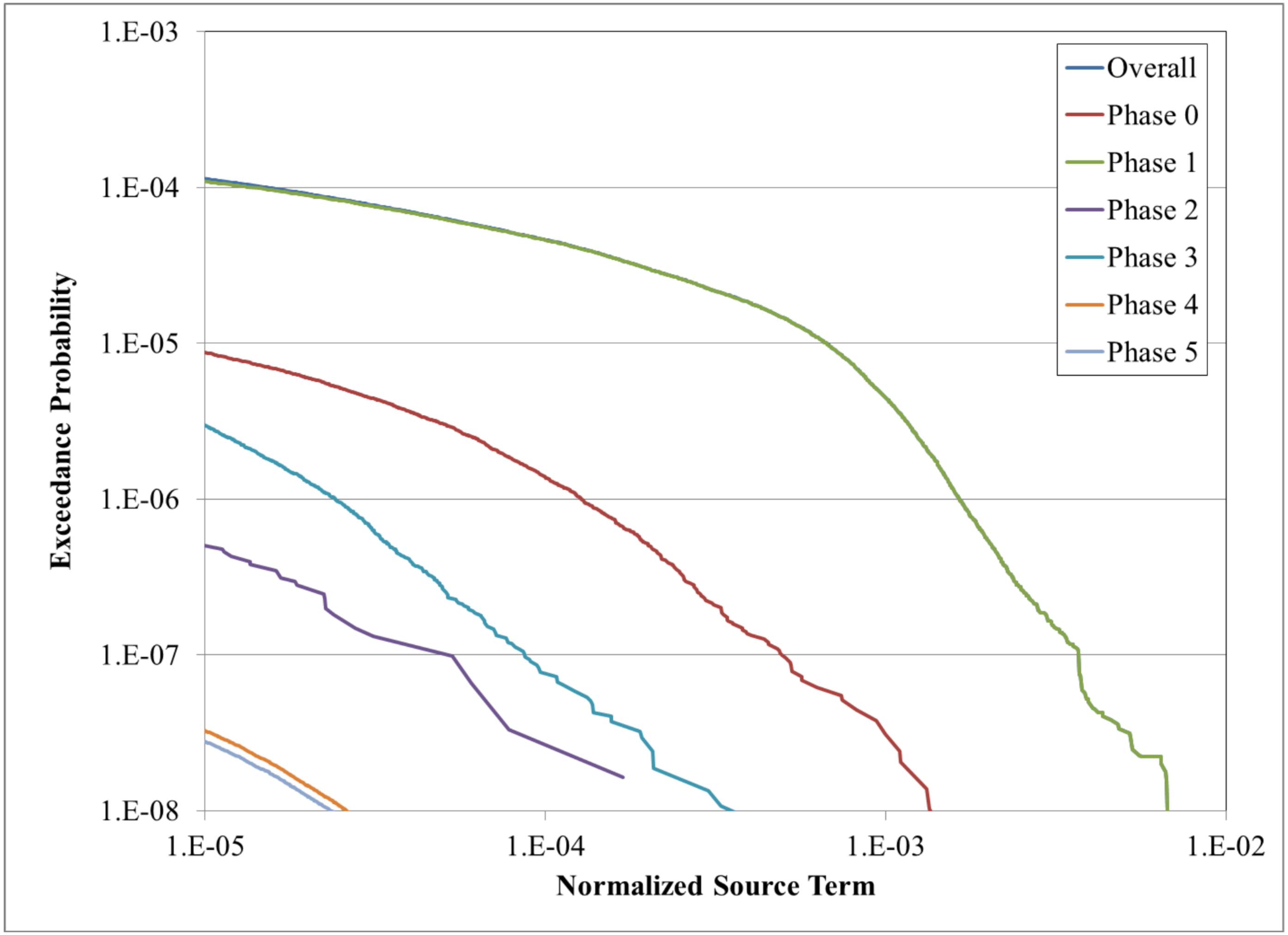
- LASEP (Launch Accident Sequence Evaluation Program) models numerous potential scenarios, randomly choosing time of failure, explosion characteristics, etc.
- Release location and amounts determined mechanistically
- Probability distributions for release are determined



Potential release locations from numerous LASEP launch simulations

Example Source Term Results

Source Term Exceedance Graph



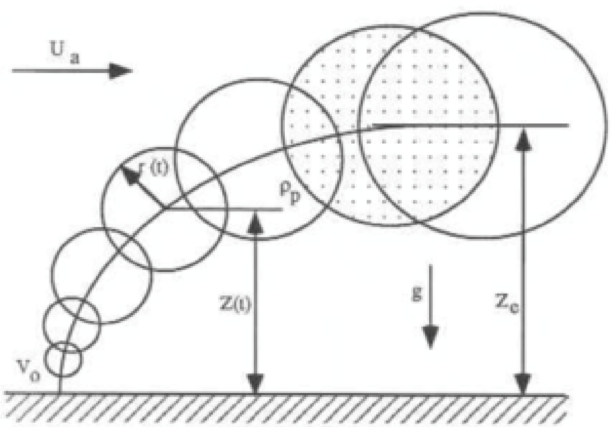
Atmospheric Transport & Consequences

Establish transport and deposition of source terms

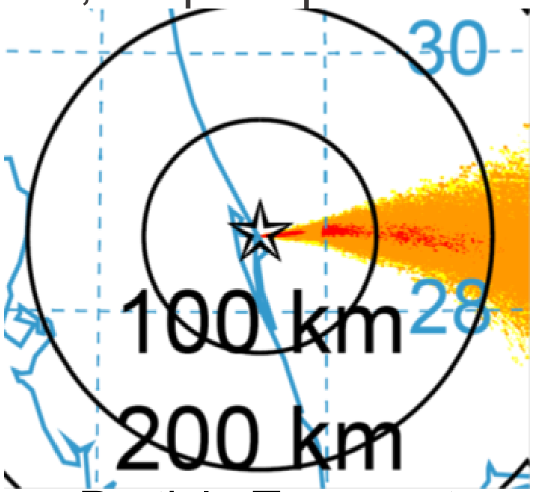
- Puff/plume height (IAT)
- Meteorological effects (HYSPLIT)

Determine potential health effects from release (FDOSE)

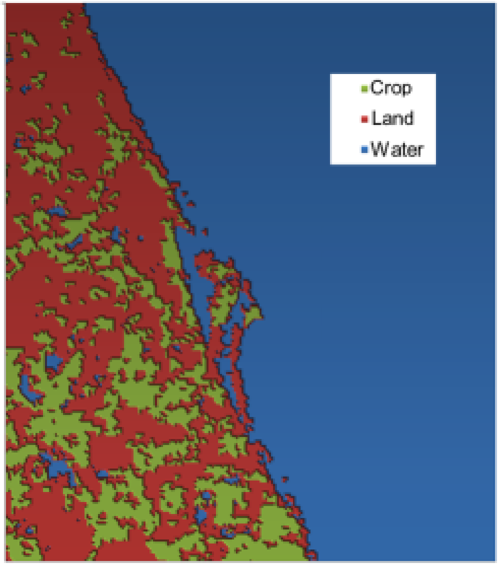
- Inhalation, resuspension, ingestion, cloudshine, and groundshine
- Doses, land contamination, crop sequestration



Fireball Rise Height



Particle Transport



Land Usage

Summary

Safety analyses are required, and enabling, for the use of radioisotope power systems

The response to potential accident scenarios is modeled in a stochastic manner with a Monte Carlo simulation

- Results are combined and weighted by appropriate likelihood values
- Estimated consequences calculated

This information is used to guide power system or spacecraft designs, mission architecture or launch procedures

- Potentially reduce risk
- Inform decision makers