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Radioisotope Power Systems Launch Safety Process

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Nuclear Power Enables Exploration of the Outer Solar System
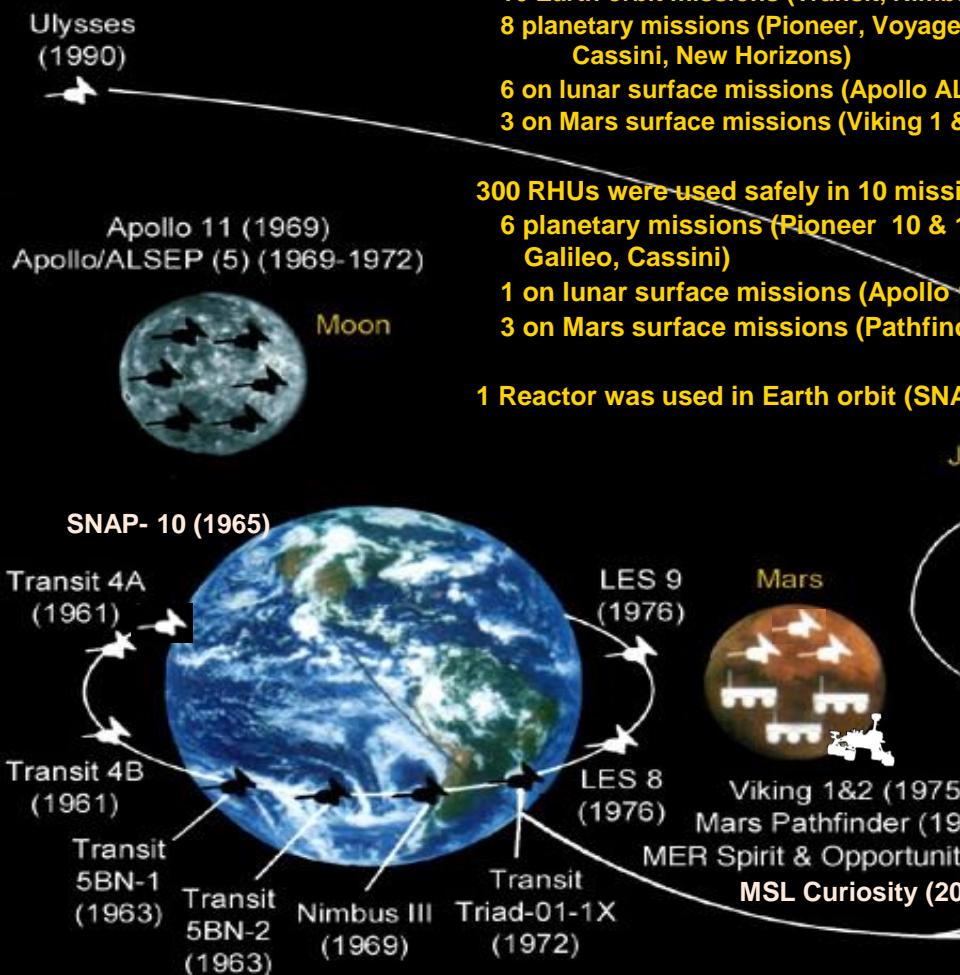
46 RTGs were used safely in 27 missions since 1961
- **10 Earth orbit missions (Transit, Nimbus, LES)**
- **8 planetary missions (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)**
- **6 on lunar surface missions (Apollo ALSEP)**
- **3 on Mars surface missions (Viking 1 & 2, MSL Curiosity)**

300 RHUs were used safely in 10 missions since 1969
- **6 planetary missions (Pioneer 10 & 11, Voyager 1 & 2, Galileo, Cassini)**
- **1 on lunar surface missions (Apollo 11)**
- **3 on Mars surface missions (Pathfinder, MER A & B)**

1 Reactor was used in Earth orbit (SNAP-10)

Pluto

New Horizons (2006)

Voyager 2 (1977)

Neptune

Uranus

Ulysses (1990)

Saturn

Voyager 1 (1977)

Cassini (1997)

Apollo 11 (1969)
Apollo/ALSEP (5) (1969-1972)

Moon

Pioneer 11 (1973)

SNAP- 10 (1965)

Jupiter

Galileo (1989)

Transit 4A (1961)

LES 9 (1976)

Mars

Pioneer 10 (1972)

Transit 4B (1961)

LES 8 (1976)

Transit 5BN-1 (1963)

Transit 5BN-2 (1963)

Nimbus III (1969)

Transit Triad-01-1X (1972)

Viking 1&2 (1975)
Mars Pathfinder (1996)
MER Spirit & Opportunity (2004)
MSL Curiosity (2011)

Distances & Planets Are Not to Scale

Curiosity on Mars

Multi-Mission Radioisotope Thermoelectric Generator
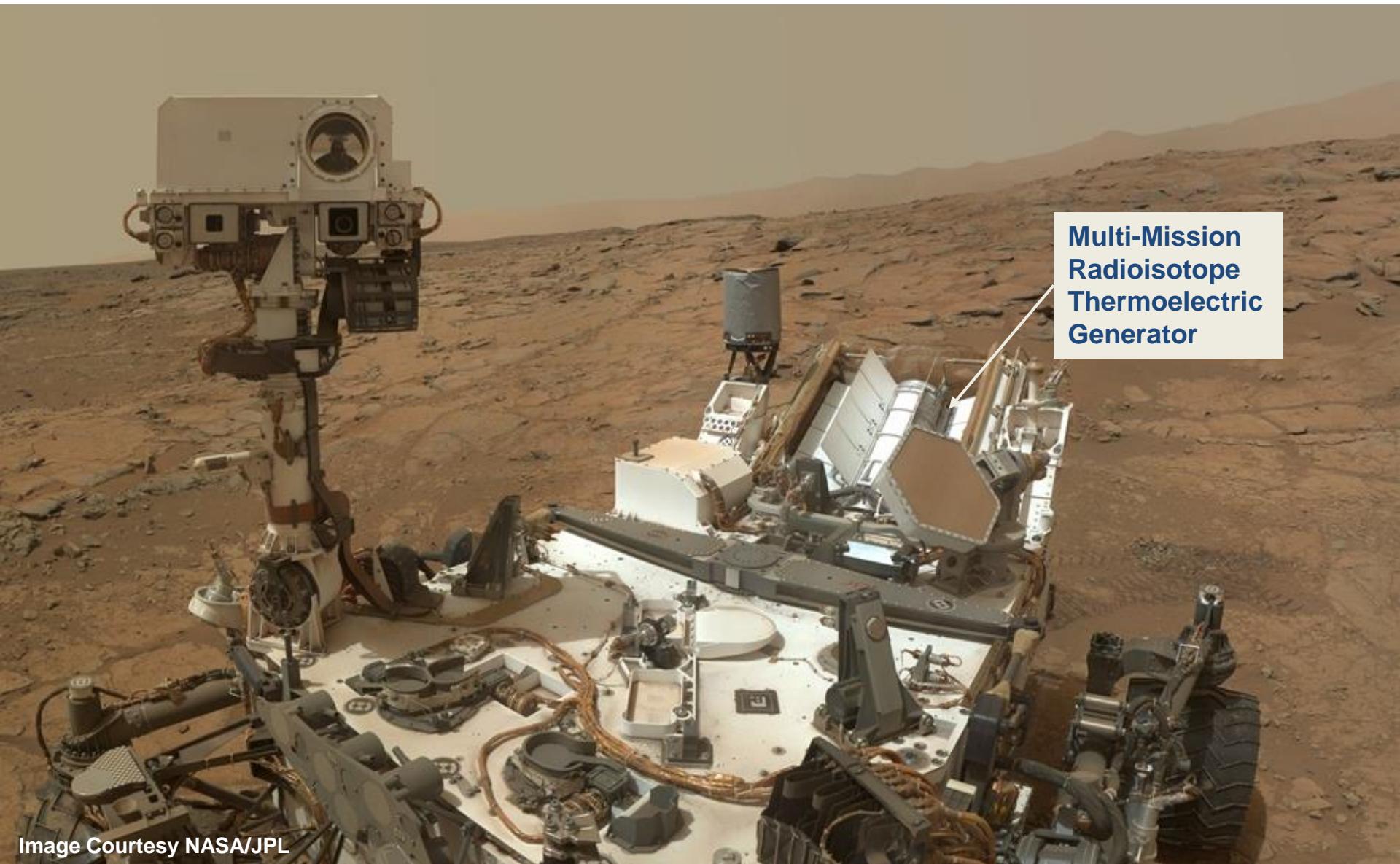
Image Courtesy NASA/JPL

1% of All Launches Fail near the Pad
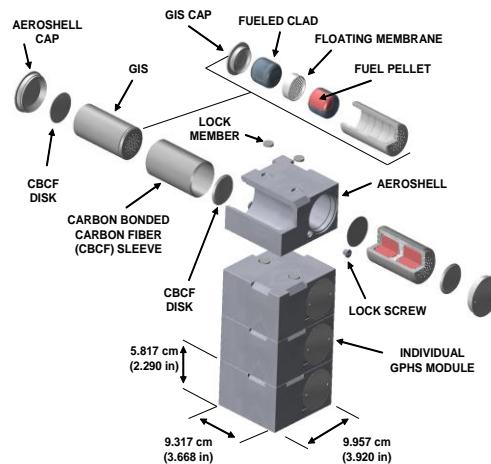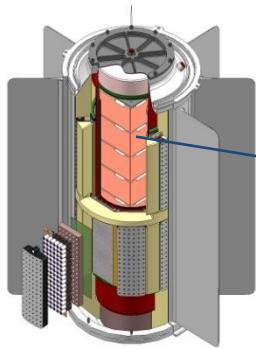
~60,000 Curies of Pu-238 on MSL

Labels on exploded diagram: AEROSHELL CAP, GIS CAP, FUELED CLAD, FLOATING MEMBRANE, FUEL PELLET, GIS, LOCK MEMBER, AEROSHELL, CBCF DISK, CARBON BONDED CARBON FIBER (CBCF) SLEEVE, CBCF DISK, LOCK SCREW, INDIVIDUAL GPHS MODULE, 5.817 cm (2.290 in), 9.317 cm (3.668 in), 9.957 cm (3.920 in)

Titan 34D-April 19, 1986

Delta 241-Jan 27, 1997

Antares-Oct 28, 2014

Courtesy NASA WFF

NEPA Requires EIS for the Mission

MISSION & LAUNCH VEHICLE DATA (NASA)

ACCIDENT DESCRIPTIONS (NASA)

SYSTEM DESIGN & TEST DATA (DOE)

Sandia writes the Nuclear Risk Assessment for DOE for the Environmental Impact Statement

Nuclear Risk Assessment (DOE)

Environmental Impact Statement (NASA)

NASA Record of Decision
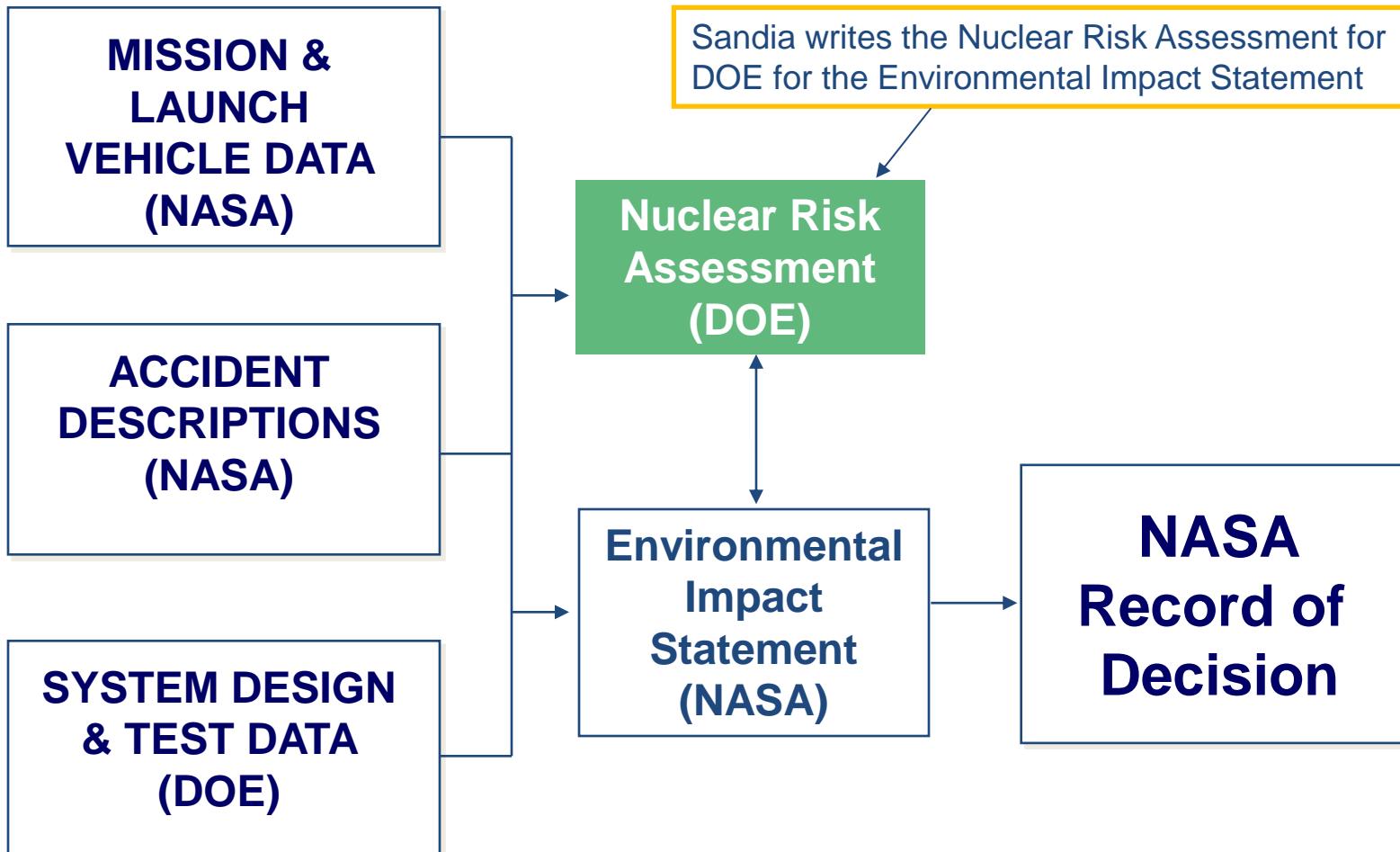
Presidential Directive / NSC-25 Requires Presidential Approval (or Designee) for All Launches with Significant Nuclear Payload
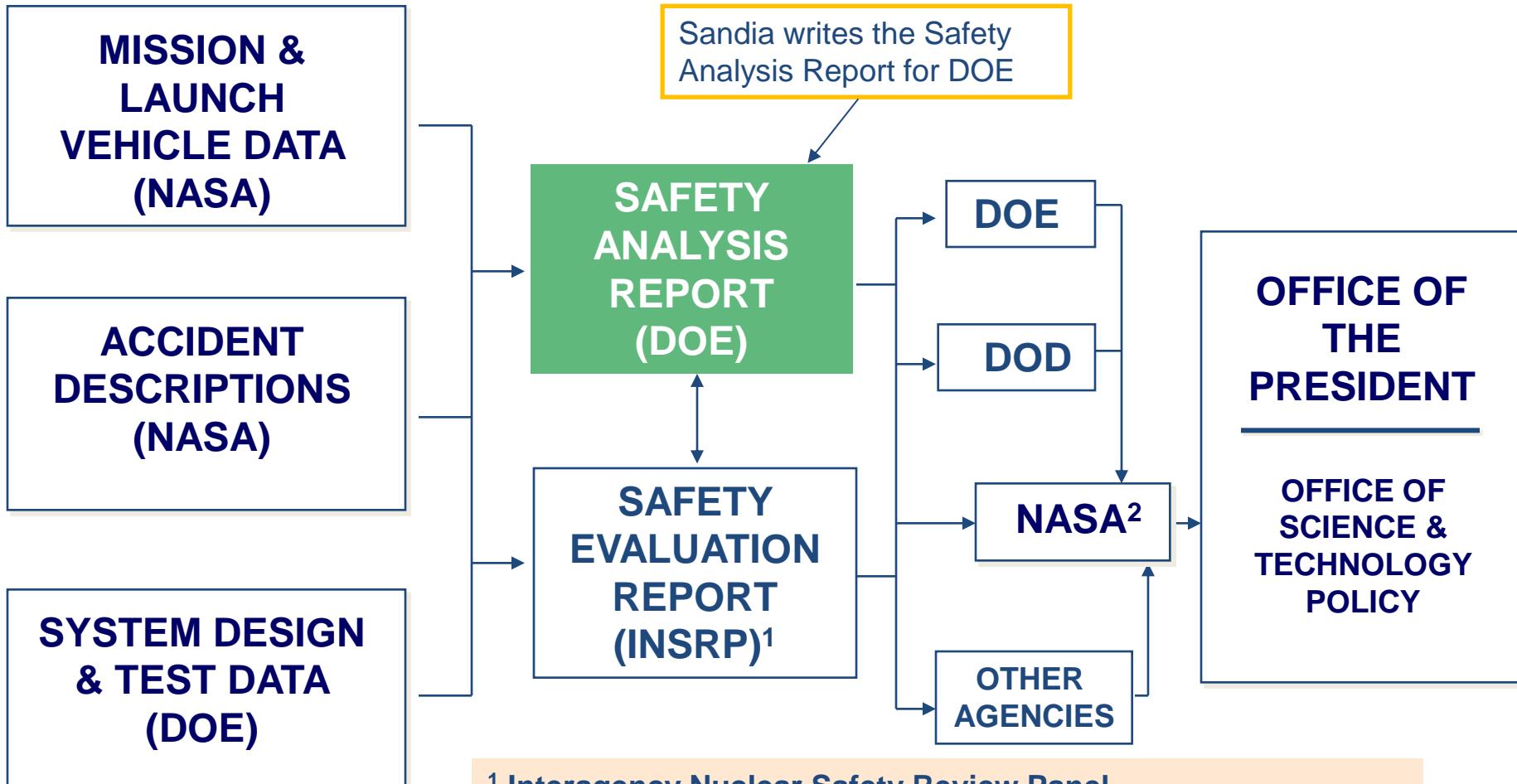
Step-2 GPHS Modules and MMRTG
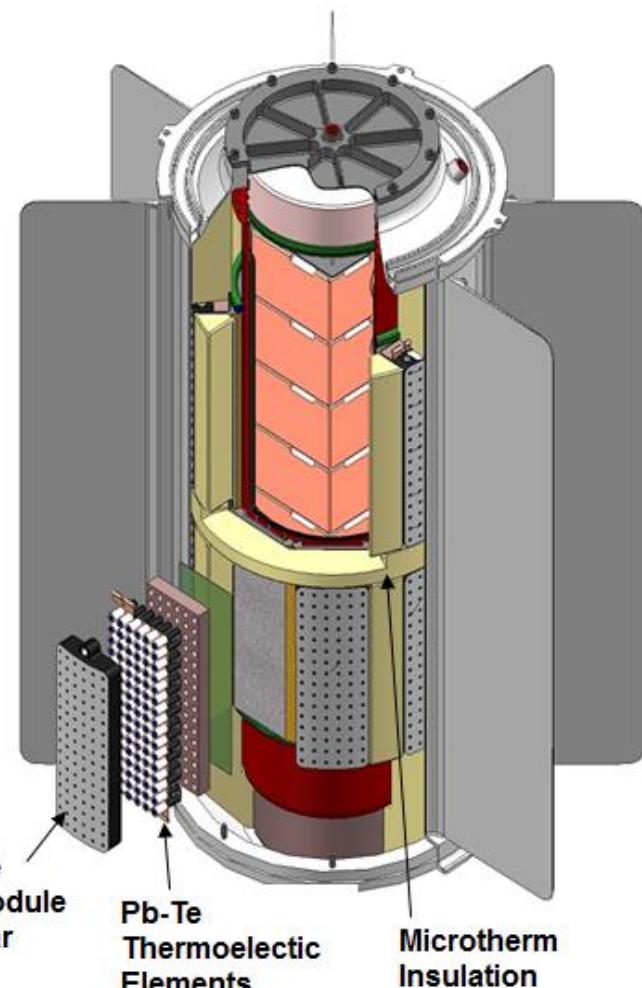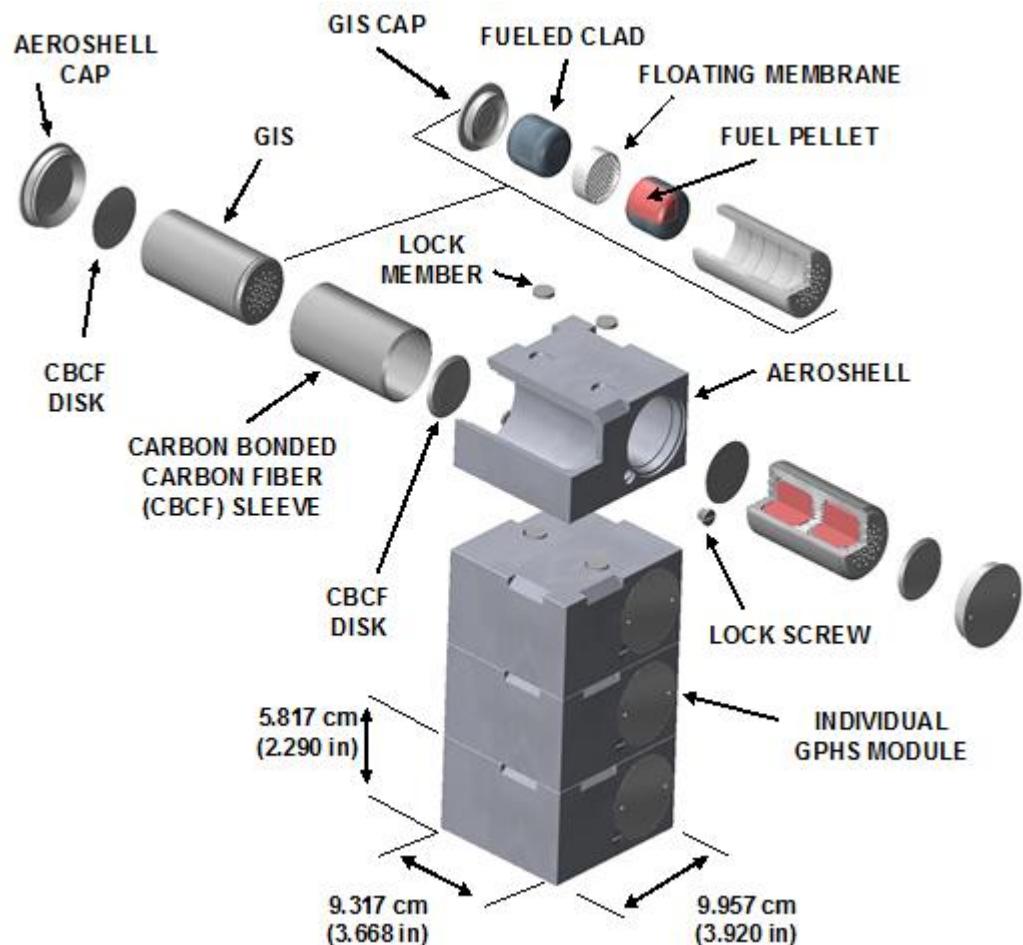
Safety is built from the inside out and from the outside in. Analysis must quantify this for decision makers.

Launch Safety Analysis Approach

- Goals
  - Quantitative estimate of the risk for use by decision makers
    - Mean probability of release of PuO_2 and consequences (health effects, land contamination and agricultural quarantine)
  - Establish risk drivers to determine steps needed to mitigate risk
- Numerous phenomena need to be modeled
  - Blast and impact
  - Fire and thermal
  - Reentry
  - Accident sequence options
  - Atmospheric transport and consequences
- Leverage multi-disciplinary competencies across laboratory

Launch Safety Code Suite
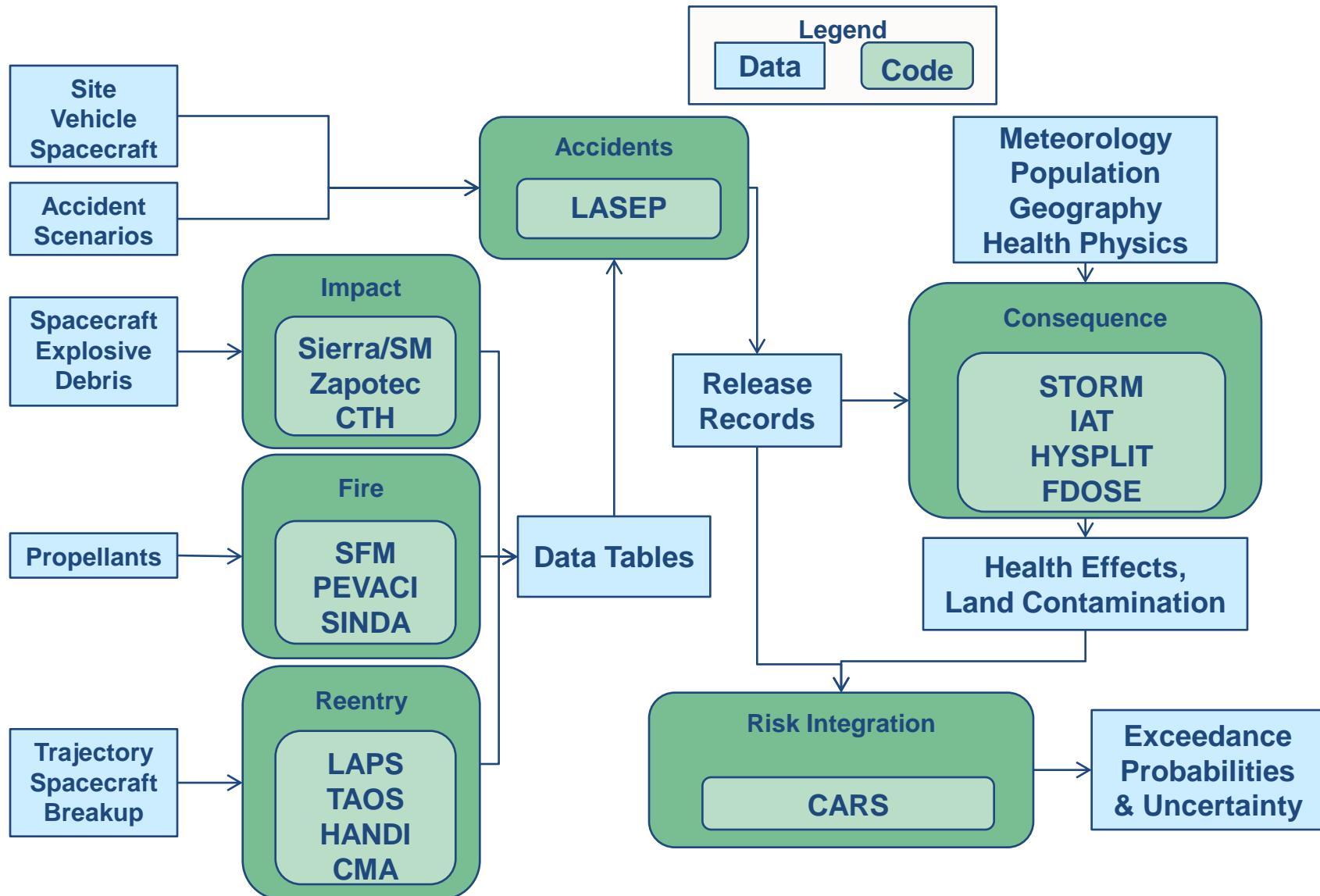
Blast and Impact Modeling

- Blasts from rocket propellant explosions

- Ground impact of MMRTG and debris onto MMRTG

- Impact of solid propellant fragments on MMRTG

- SNL's Sierra/SM used for analyses

- Hundreds of parallel processors, days to weeks of run time for each configuration
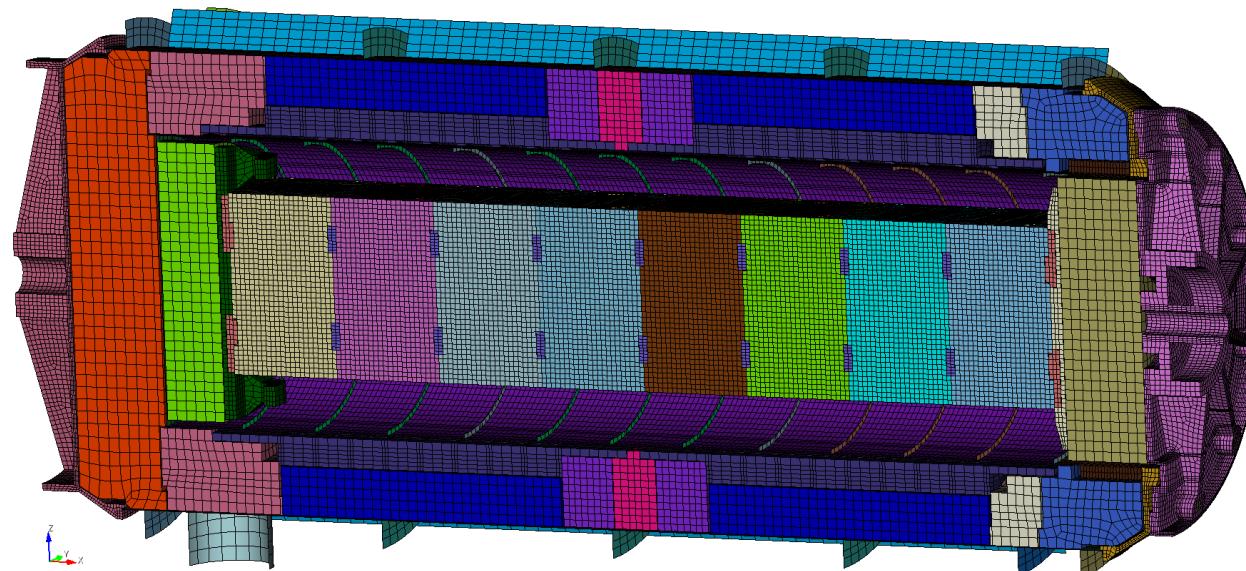
MMRTG 45° Impact at 100 m/s

MMRTG 45° Impact at 100 m/s on a steel target (terminal velocity-60 m/s) No fuel release
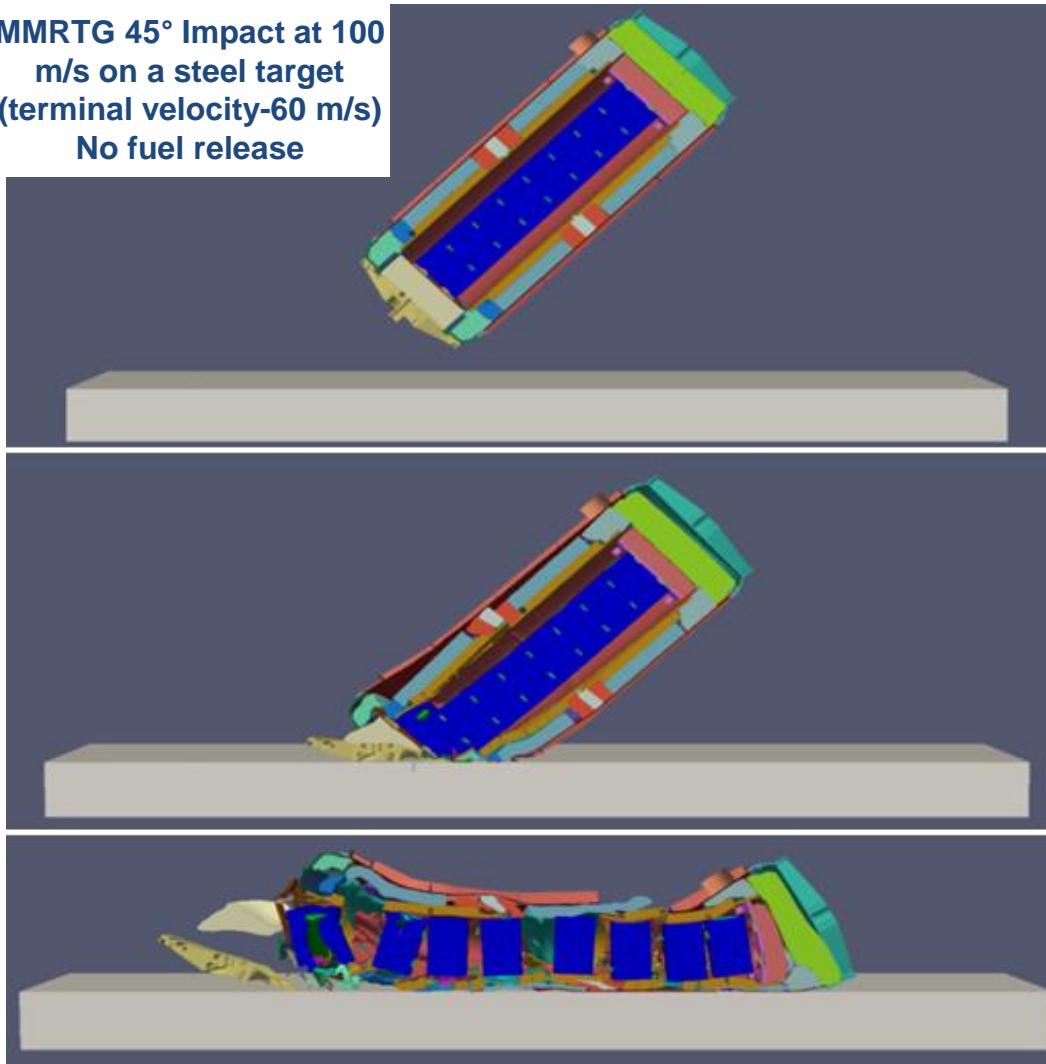
Solid Propellant Burn Modeling

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

- Modeling begins with extensive fire testing and data acquisition

- Uses Sandia's Sierra/Fuego detailed fire model

- Export Fuego's physics module into Fluent for scoping studies

- Feed results into Sandia's PEVACI code for numerous accident simulations

Solid Propellant Burn Test
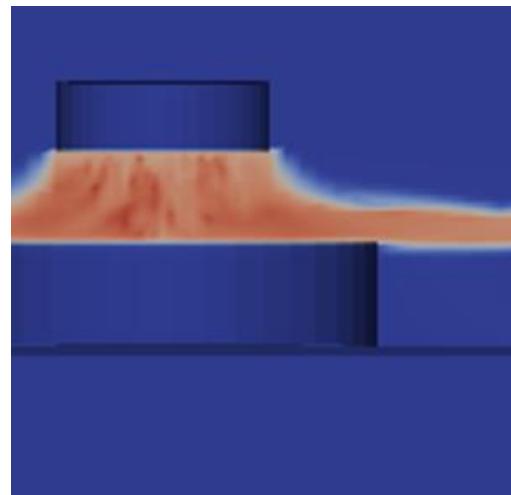
Sierra/Fuego Simulation
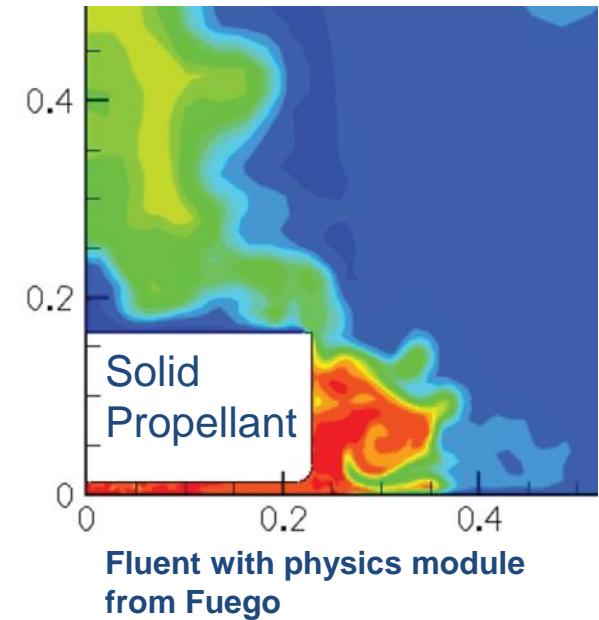
Fluent with physics module from Fuego

SNL Reentry Code Suite Description

Reentry Object Definition

↓

Initial Reentry Conditions

↓

Trajectory Definition
(TAOS or user provided)

↓

Non-ablating Cold Wall
Boundary Layer Heating
(BLUNTY, HANDI, or MAGIC)

↓

Ablation & Heat Conduction
(CMA)
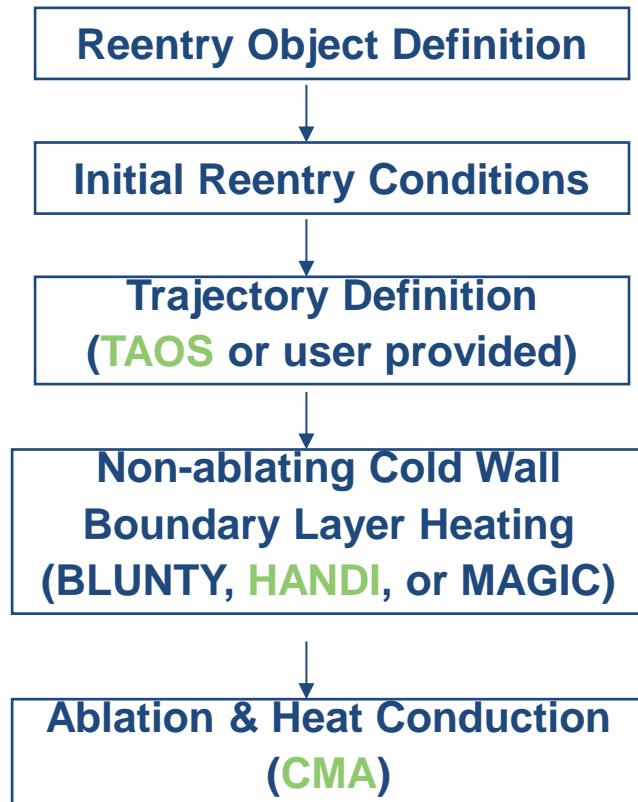
MMRTG Breakup v-gamma Map
(gamma is entry angle)
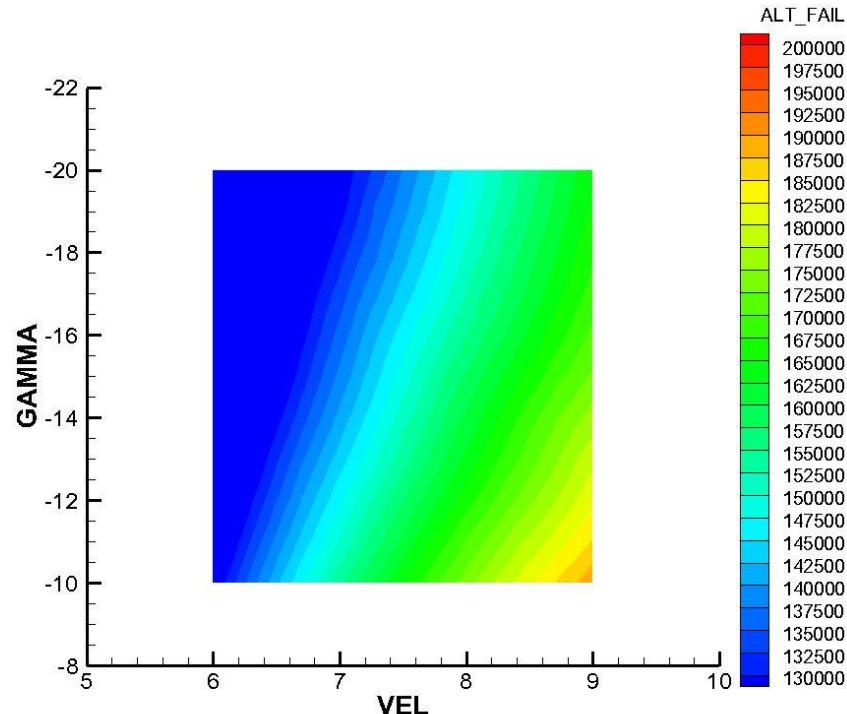
LASEP Stochastically Simulates the Range of Potential Launch Accidents


Launch Accident Sequence Evaluation Program

CCB Burnout and Centaur Separation

PLF Jettison, Continue CCB Solo Phase

Centaur 1st Burn Phase

Park Orbit Coast Phase

Centaur 2nd Burn Phase

Separate Payload

Centaur Propellant Tank Blowdown; Centaur End Mission

Payload Cruise Phase

Reentry

SRB Burnout and Jettison, CCB Solo Phase

Blast

Impact by debris

Fire

Land Impact

Water Impact

Launch Accident Sequence Evaluation Program

- **100,000 lines of Fortran code**
- **Hundreds of subroutines**
- **Extensive QA**
- **Over a million accident scenarios run for FSAR**
- **LASEP Models:**
  – **Rocket trajectory, accident time, liquid propellant explosion and fires, blast effects, fragment impact, component fallback, component ground impact, impact by debris, solid propellant fires, orbital reentry, and other phenomena**

Release Locations and Amounts

- LASEP models numerous potential scenarios, randomly choosing time of failure, explosion characteristics, etc.

- Release location and amounts determined mechanistically

- Probability distributions for release are determined
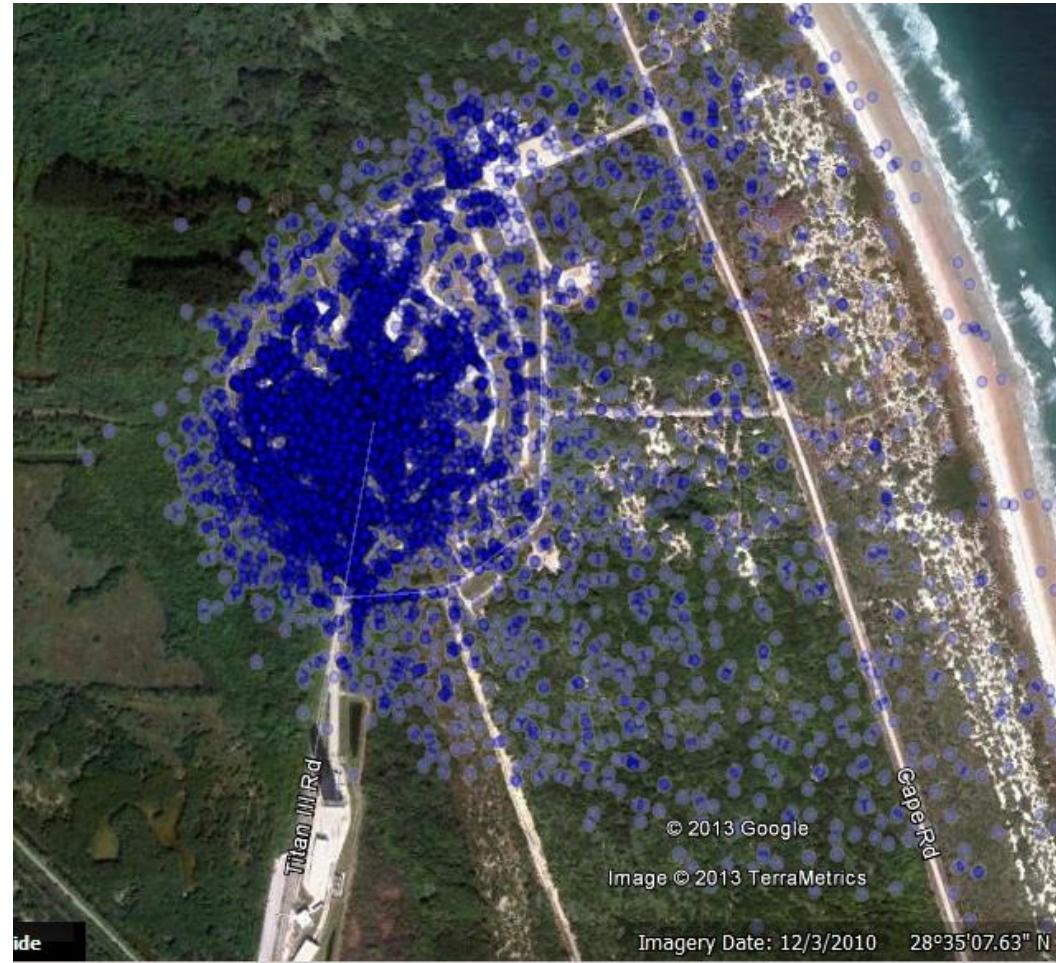
**Potential release locations from numerous LASEP launch simulations, SLC-41**

Example of MSL Release Results

Phase	Mean Accident Probability	Release Probability	Total Probability	Mean Total Release (g)	Mean Effective Release (g)
Prelaunch	0.00003	0.595	0.00002	2.26	0.49
Early Launch	0.008	0.353	0.00278	8.33	1.09
Late Launch	0.006	0.001	0.000007	0.01	0.002
Suborbital	0.014	0.005	0.00007	2.92	0.21
Orbital	0.003	0.110	0.00034	0.12	0.02
Long Term	0.000001	0.173	0.0000002	0.15	0.03
Total Mission	**0.031**	**0.104**	**0.00321**	**7.30**	**0.96**

96.9% 2.8% 0.3%

- Successful Launch (Earth escape)
- Launch Accident with No Release
- Launch Accident with Some Release

D. J. Clayton, et al, NETS-2012, paper 3009
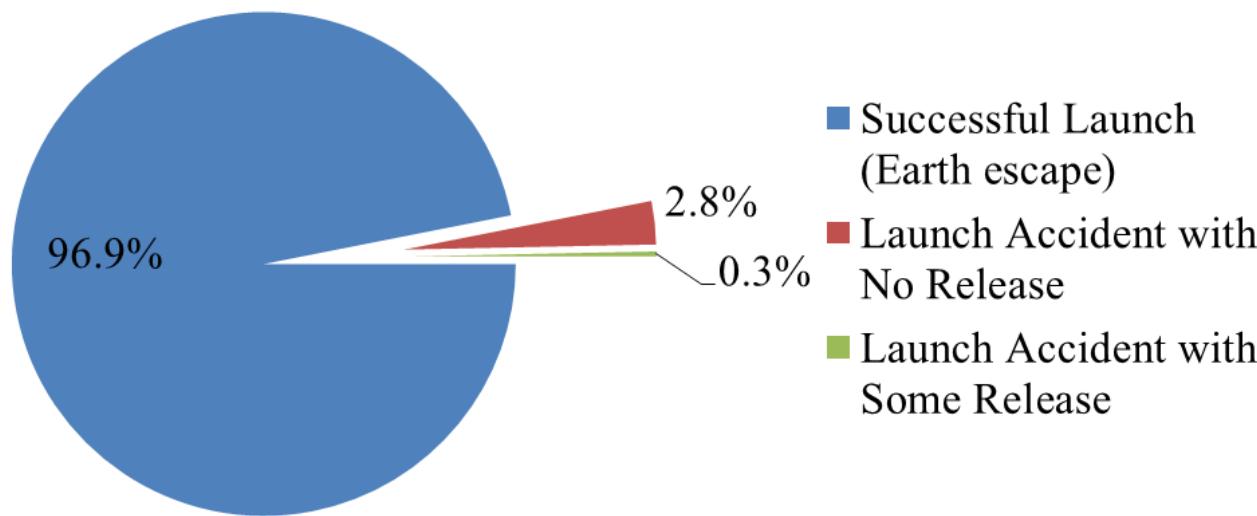
Consequence Modeling

- Sandia Transport Of Radionuclides Model (STORM)

- IAT code employed to determine fireball rise height

- Uses NOAA's HYSPLIT code, leveraging NOAA's extensive investment and readily accessing NOAA's weather database

- FDOSE code calculates health effects from inhalation, resuspension, ingestion, cloudshine, and groundshine

Fireball Rise Height   **Particle Transport**   **Deposition**
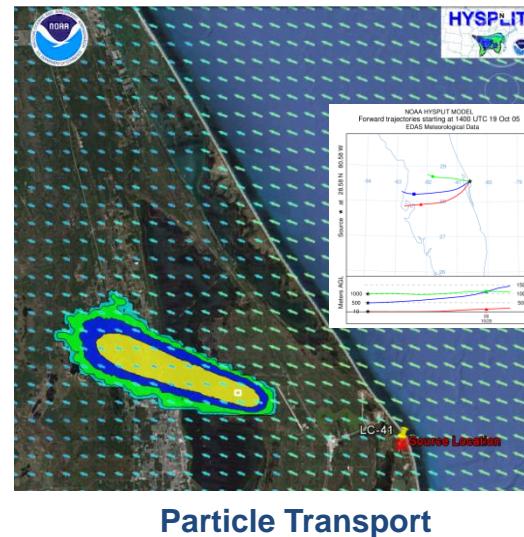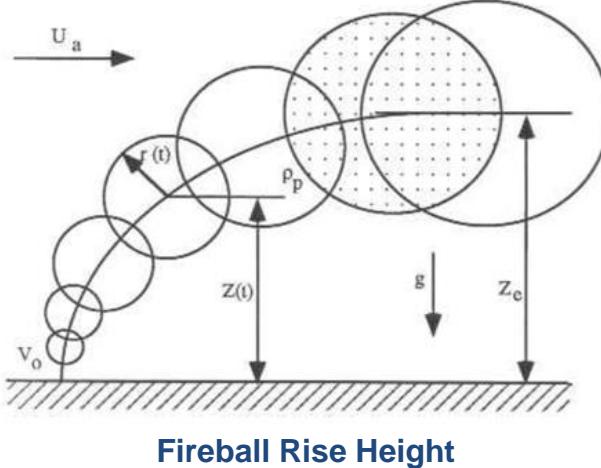
FDOSE (Fortran DOSE Program)

- FDOSE calculates health effects from inhalation, cloud shine, ground shine, and ingestion

- Reads a HYSPLIT deposition and air concentration grid file

- Contains the GLC-2000 land-use database

- Ingestion factors implemented using COMIDA-2 (NRC supported code)
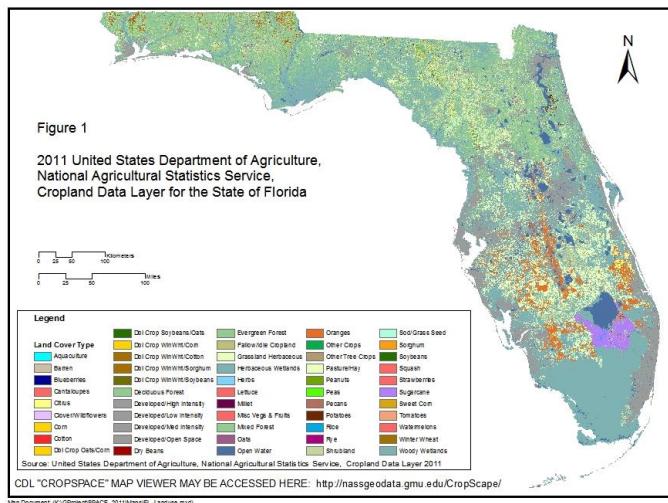
USDA Florida Crop Use Data
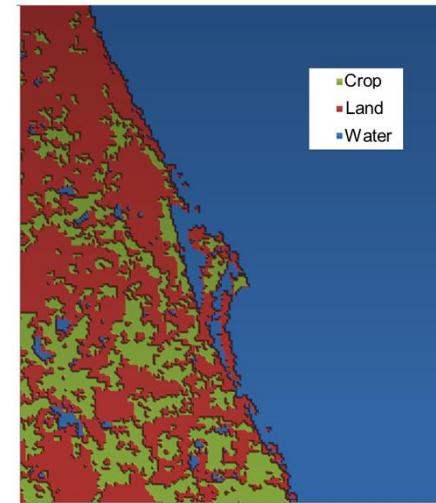
GLC-2000 Land Usage

Example of MSL Consequences

- Produced by previous consequence suite
- Result of over 30,000 simulations with randomly selected source term and weather conditions

Mission Phase No.	Mission Phase Description	Proba-bility of Release	Health Effects[a] without de Minimis	Risk[b] without de Minimis	Land Area[a] Exceeding 0.2 μCi/m^2 (km^2)
0	Prelaunch	1.79E-05	1.38E-01	2.46E-06	2.43E-01
1	Early-Launch	2.78E-03	3.45E-01	9.59E-04	1.63E+00
2	Late-Launch	6.78E-06	1.14E-04	7.71E-10	3.69E-04
3	Suborbital	6.65E-05	5.78E-03	3.84E-07	8.83E-01
4	Orbital	3.36E-04	7.51E-04	2.52E-07	5.13E-02
5	Long Term	2.03E-07	1.75E-03	3.55E-10	6.93E-02
Total Mission		3.21E-03	3.00E-01	9.62E-04	1.44E+00

a. Values are the means conditional on a release occurring.
b. Risk is the expectation value of health effects. It is calculated as the product of the probability of release and the mean number of health effects given a release.

N. E. Bixler, et al, NETS-2013, paper 6793

Code Suite Quality Assurance

- Quality Assurance maintained throughout development, following DOE Order 414.1D, NE-75 PQAR, RPSLS QAPP

- Regular internal assessments and DOE audits

- Electronic SVN repository
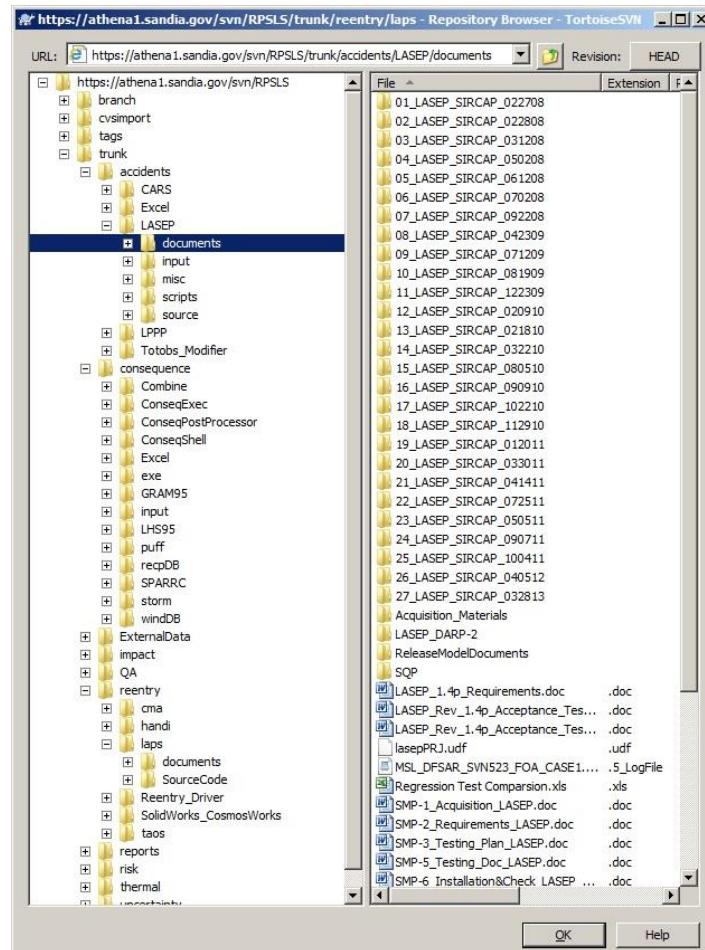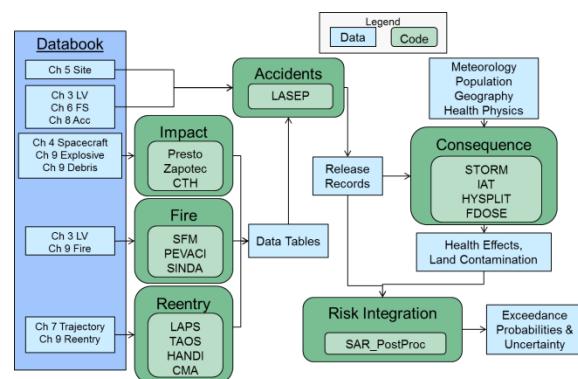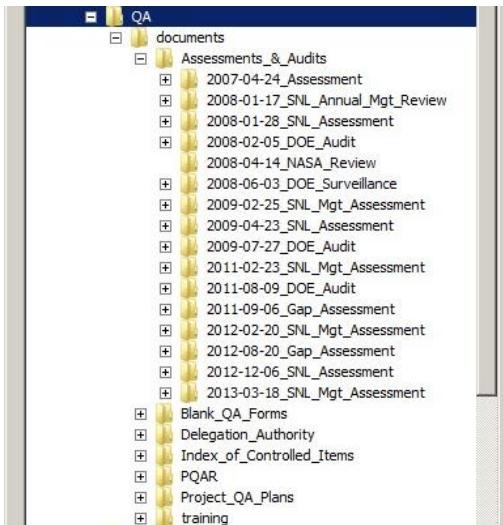
Summary

- Deliver risk analyses for the mission EIS and the Presidential-mandated launch safety review processes

- Draw on multi-disciplinary teams and expertise to handle the diverse phenomena

- Support DOE to enable exploration of the solar system

Pluto - July 14, 2015
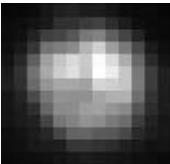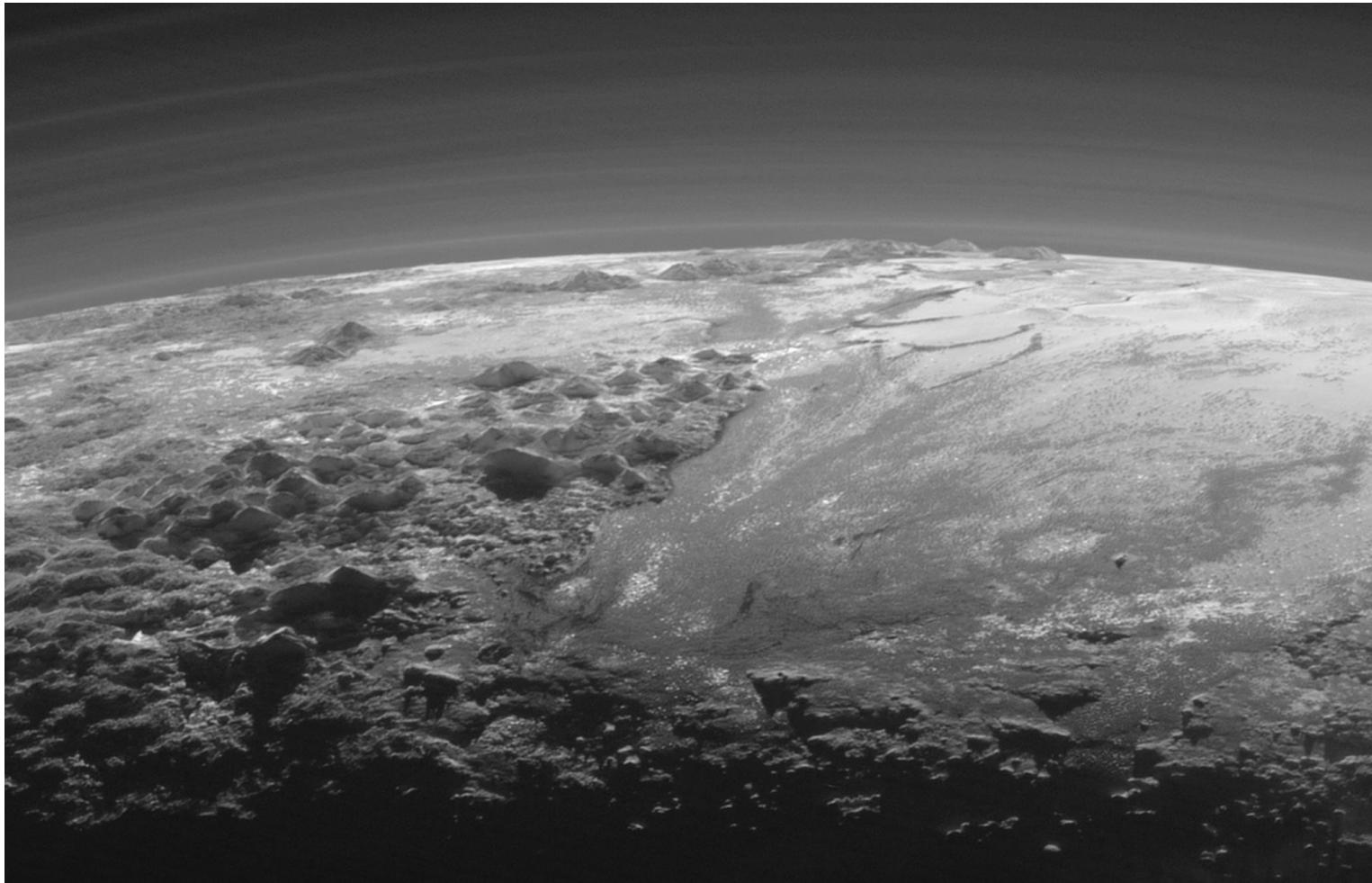
Best Hubble Image 2006

2-mile high ice mountains

Photo courtesy of NASA and JHU/APL

Spacecraft power courtesy of DOE/NE-75