SAND2014-3510C

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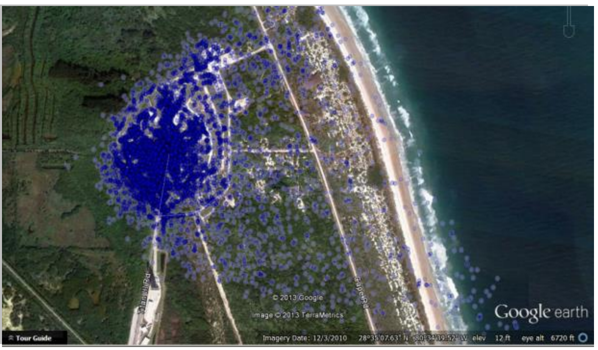

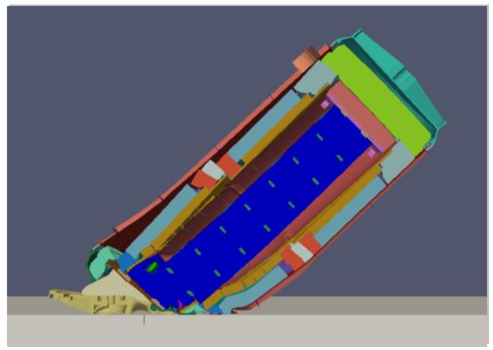

Risk Analysis for Launch of Radiological Power Systems

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IAPG Mechanical Working Group Meeting, Albuquerque, NM

May 13-15, 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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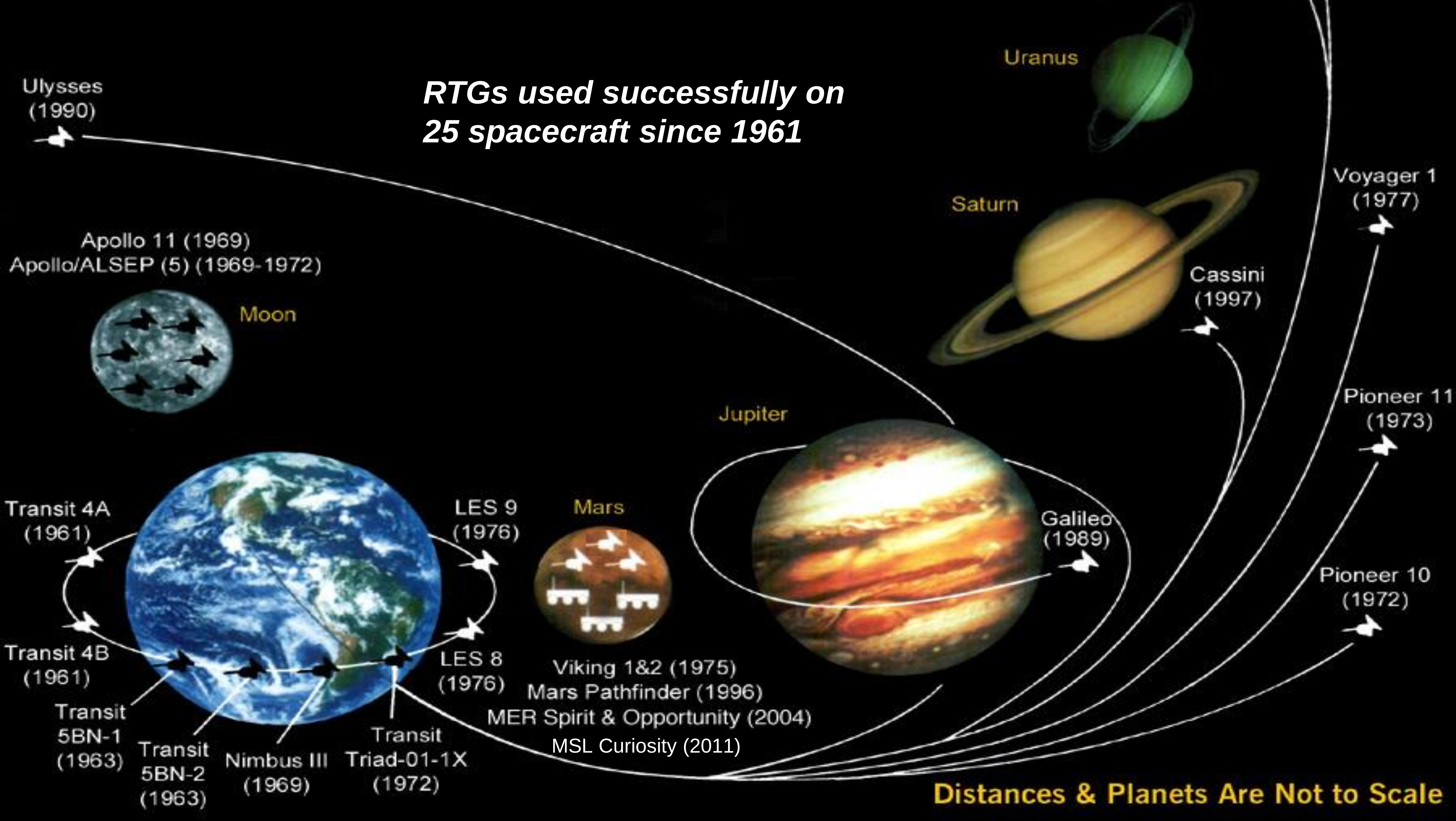
Radioisotope Thermoelectric Generators (RTGs) Enable Exploration of the Outer Solar System

RTGs used successfully on 25 spacecraft since 1961



Curiosity on Mars

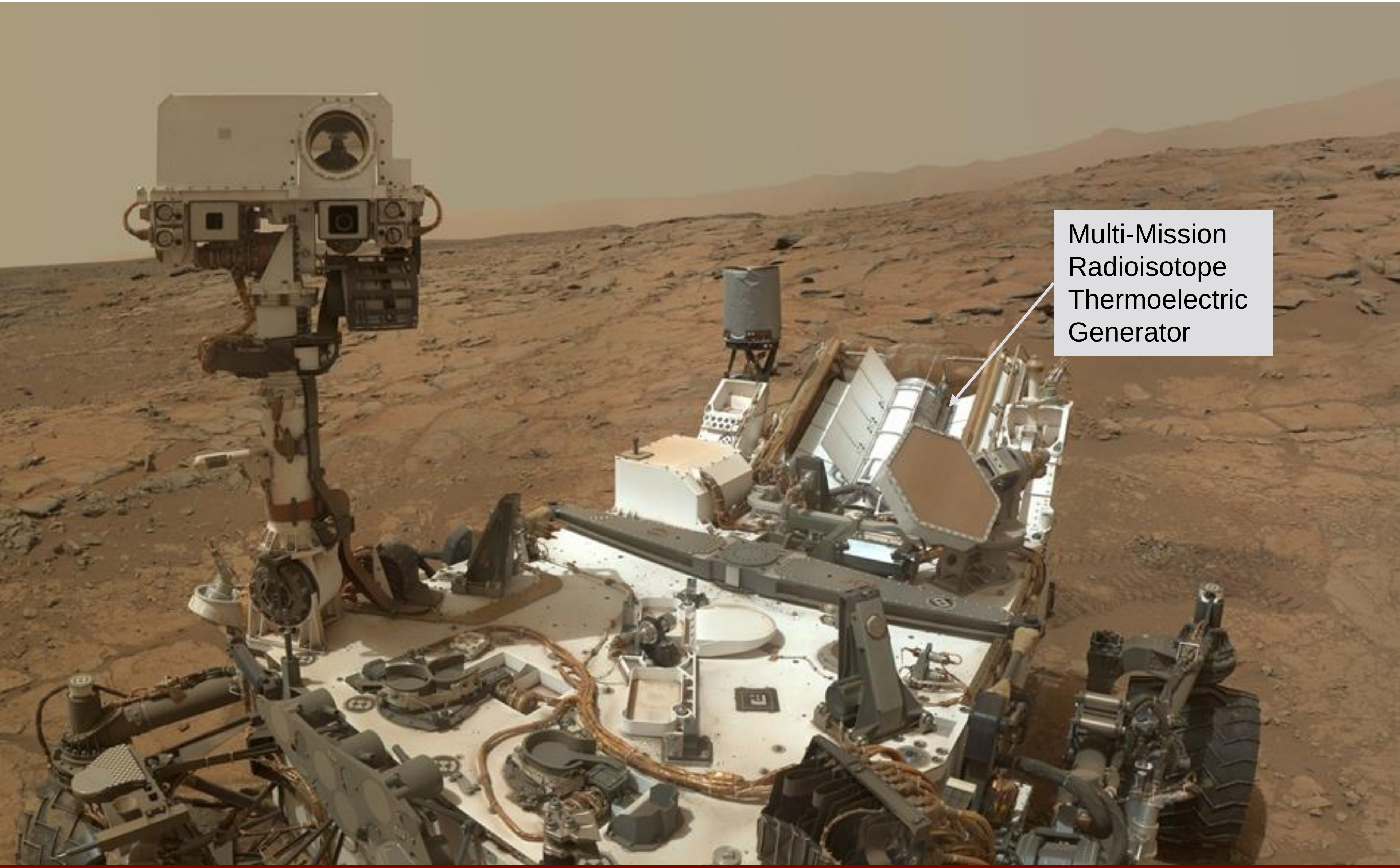
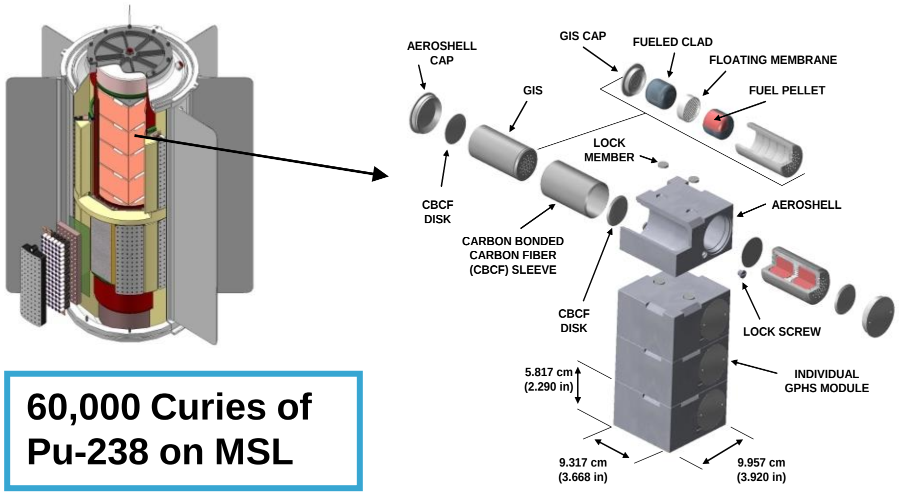


Image Courtesy NASA/JPL

1% of All Launches Fail near the Pad



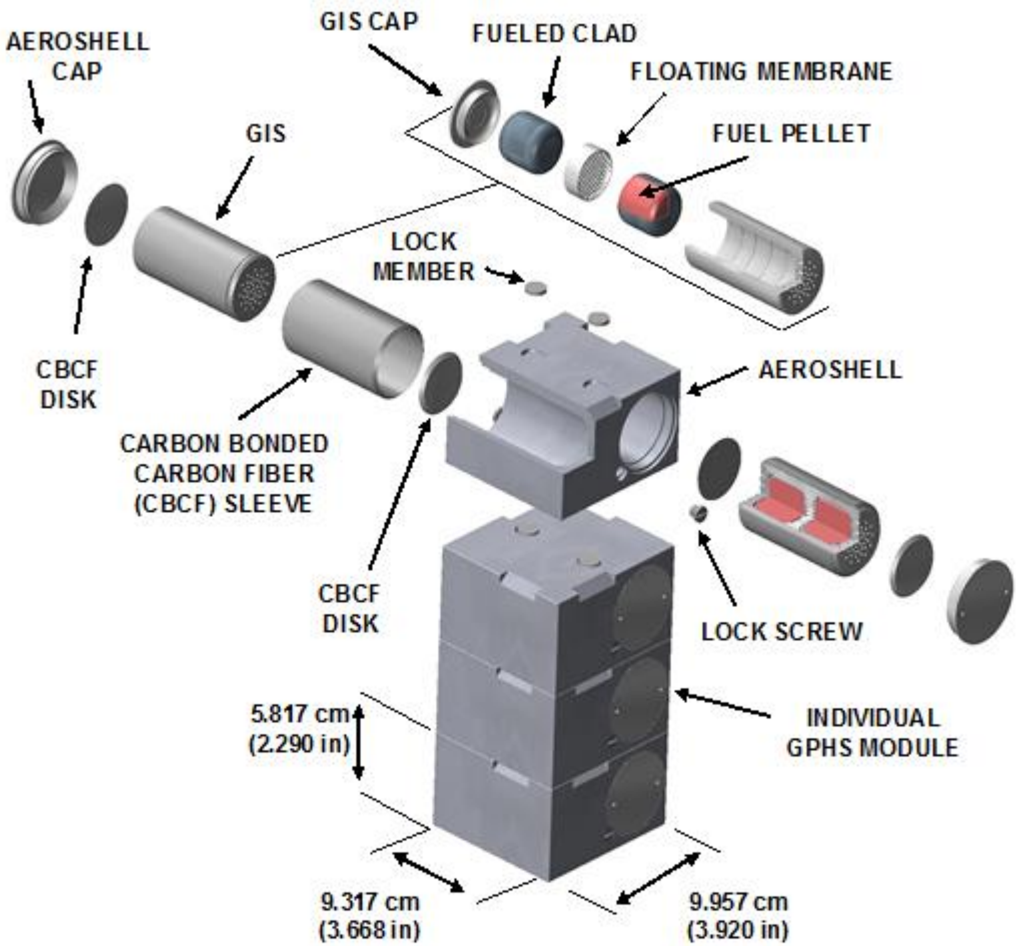
60,000 Curies of Pu-238 on MSL

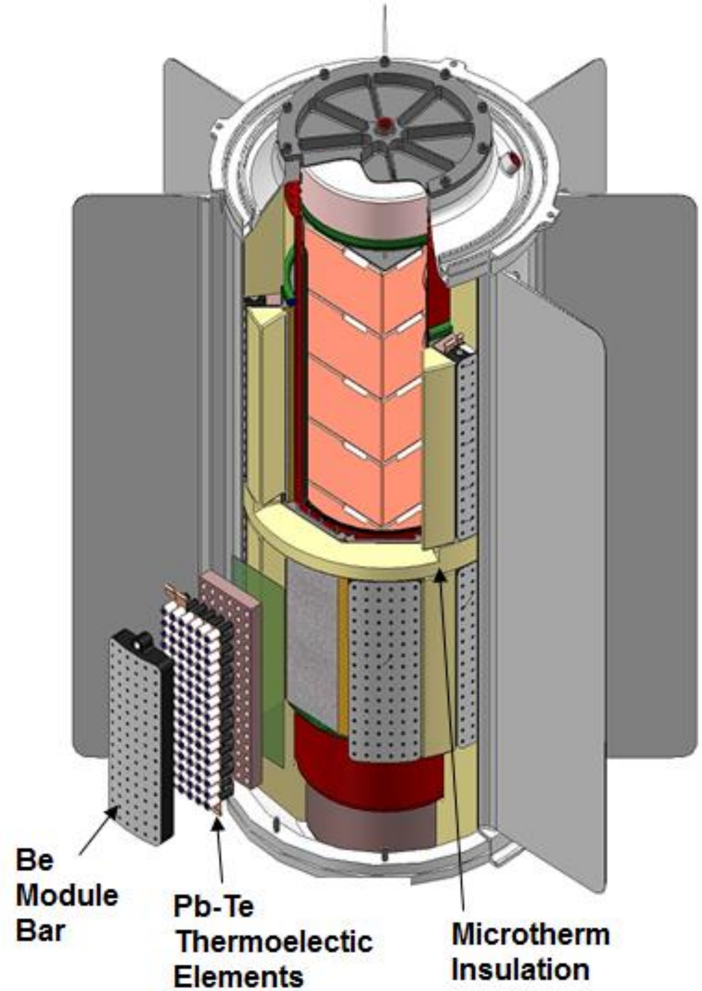
Delta 241 Jan 27, 1997

Atlas Fallback

Titan 34D

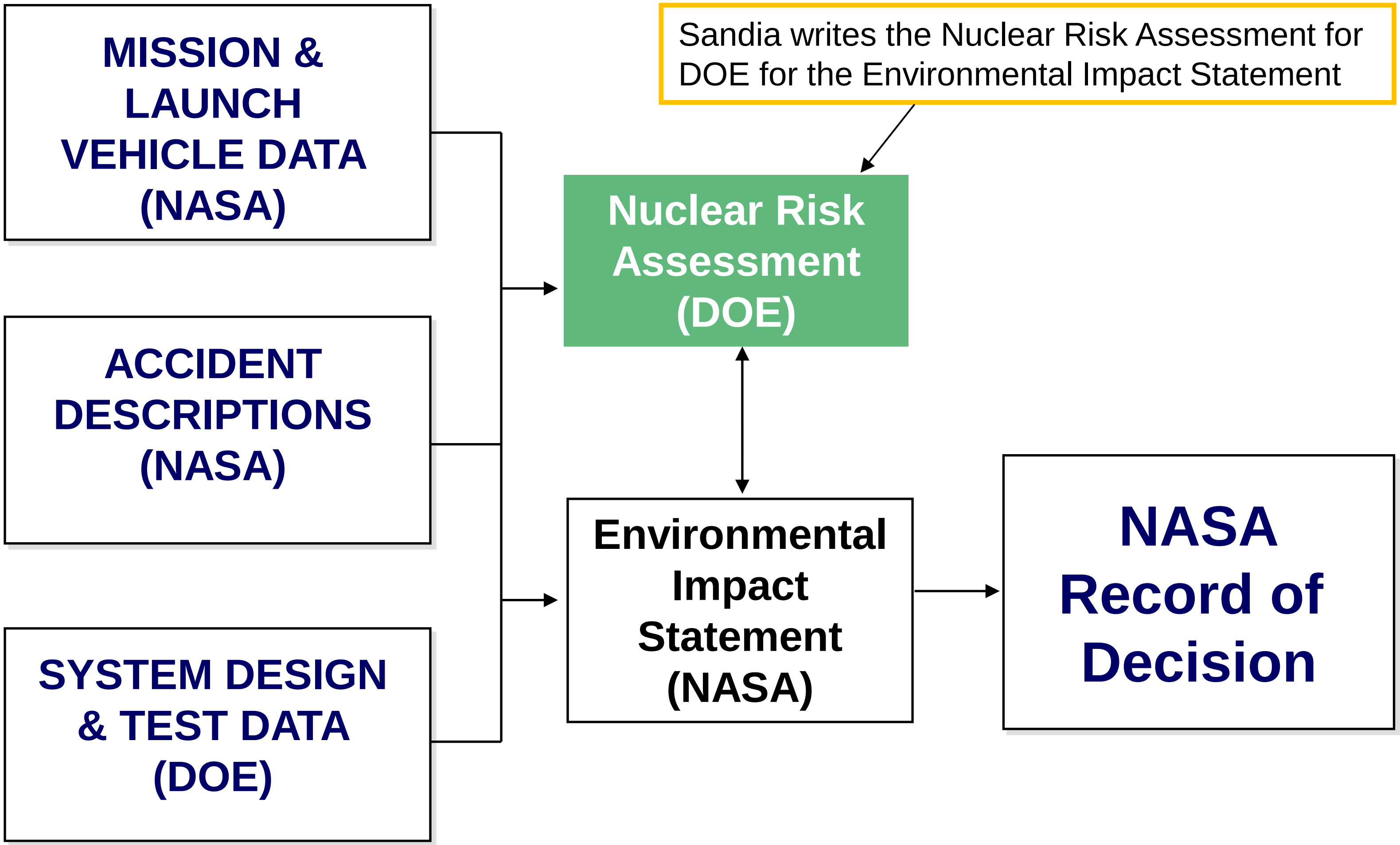
Step-2 GPHS Modules and MMRTG



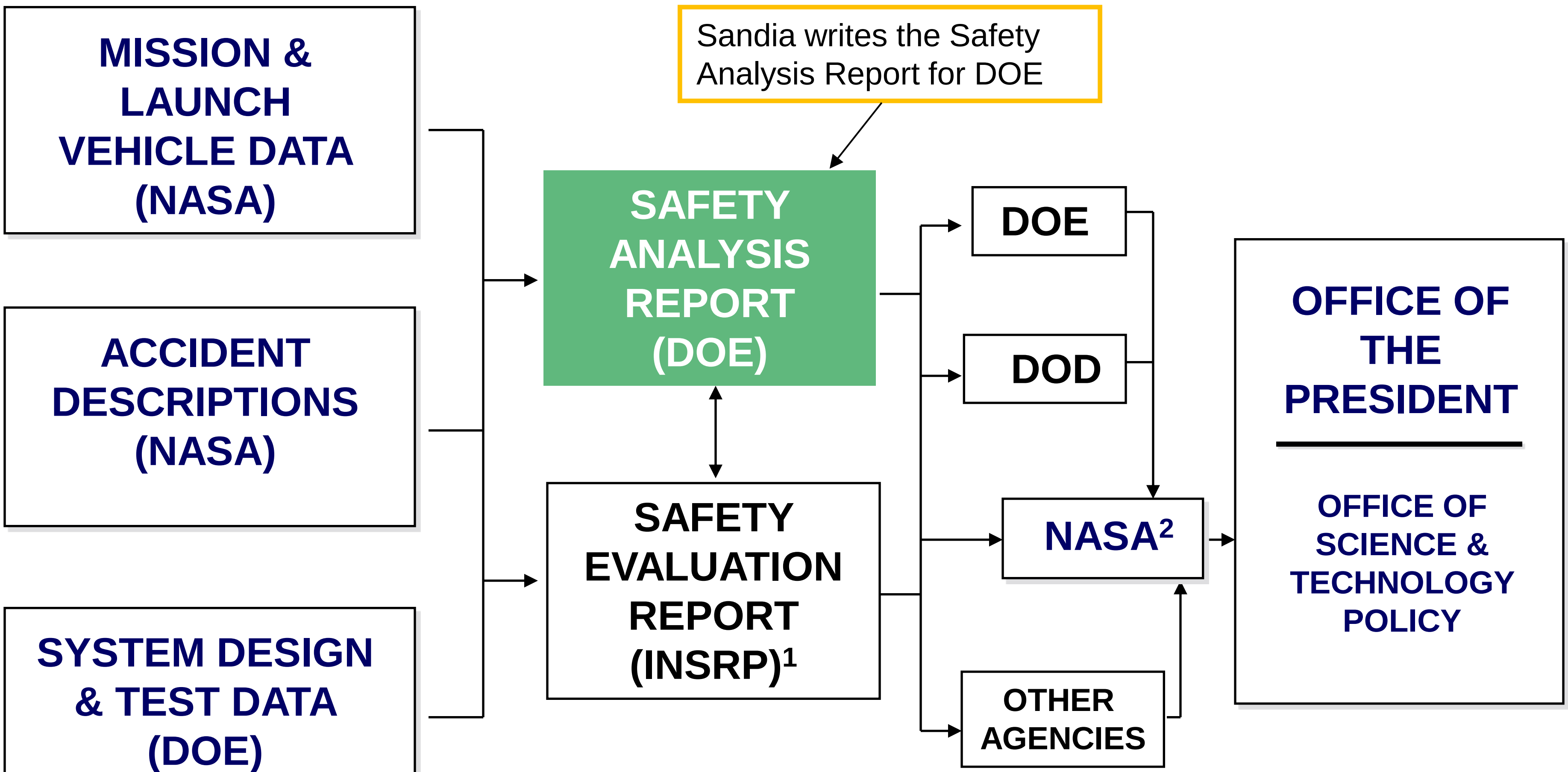


Safety is built from the inside out and from the outside in. Analysis must quantify this for decision makers.

NEPA Requires EIS for the Mission



Presidential Directive / NSC-25 Requires Presidential Approval (or Designee) for All Launches with Nuclear Payload



[1] Interagency Nuclear Safety Review Panel (DOE, NASA, DoD, EPA, NRC (advisory))

[2] Responsible mission agency makes launch recommendation

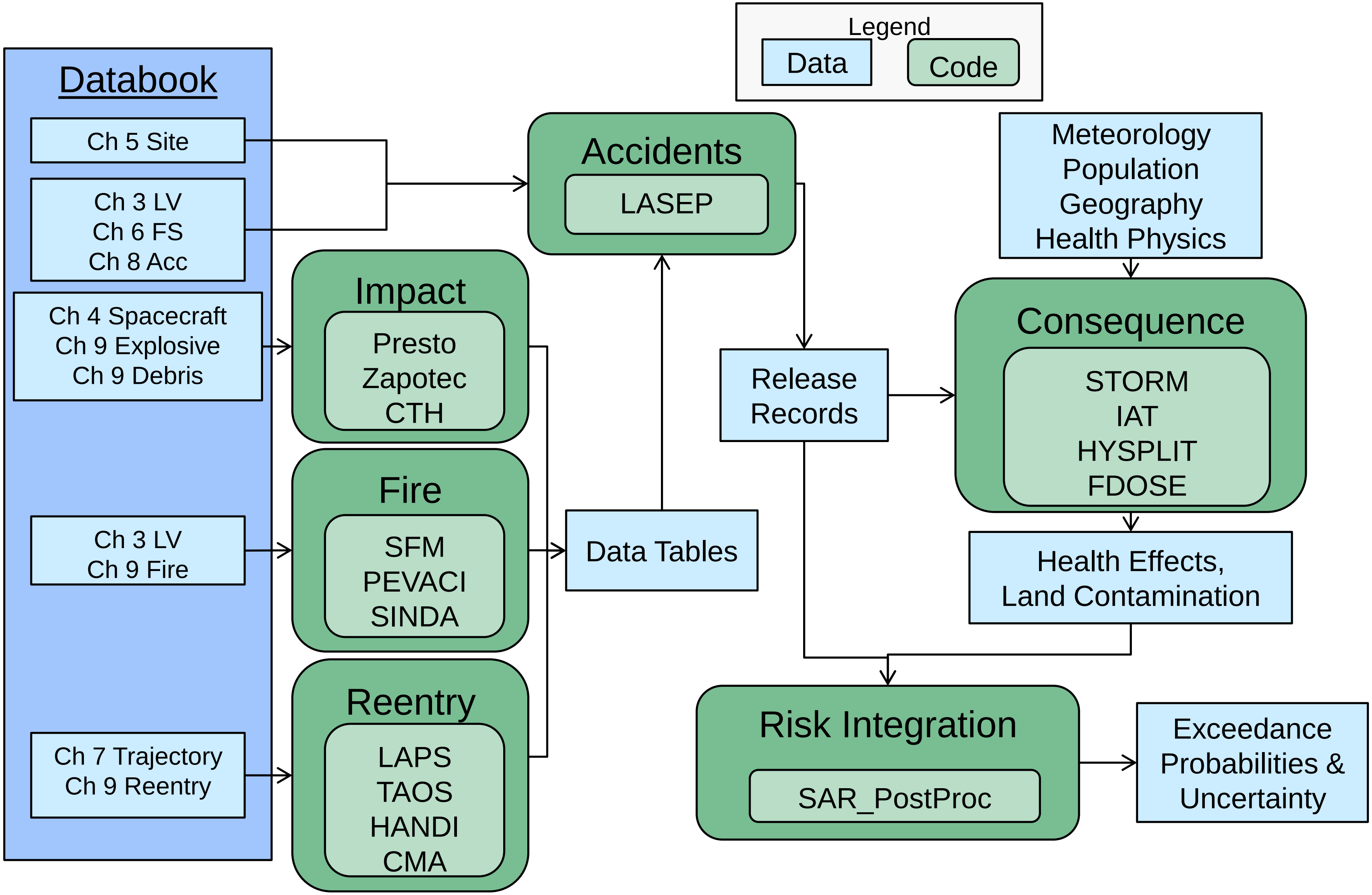
Launch Safety Analysis Approach

- Goal: Quantitative estimate of the risk for use by decision maker
  - Mean probability of release of PuO_2
  - Amount of PuO_2 released ("source term")
  - Health effects (dose, latent cancer fatalities over 50 years)
  - Land contamination (e.g. square km of > 0.2 microCi/m^2)
  - All expressed as mean values, percentile values, and exceedance probability graph (Complementary Cumulative Probability Distribution)
- Numerous phenomena need to be modeled
  - Blast and impact
  - Fire and thermal
  - Reentry
  - Accident sequence options
  - Atmospheric transport and consequences

Each area needs a highly specialized expert to model the phenomena and respond to questions from DOE, NASA, INSRP, or OSTP

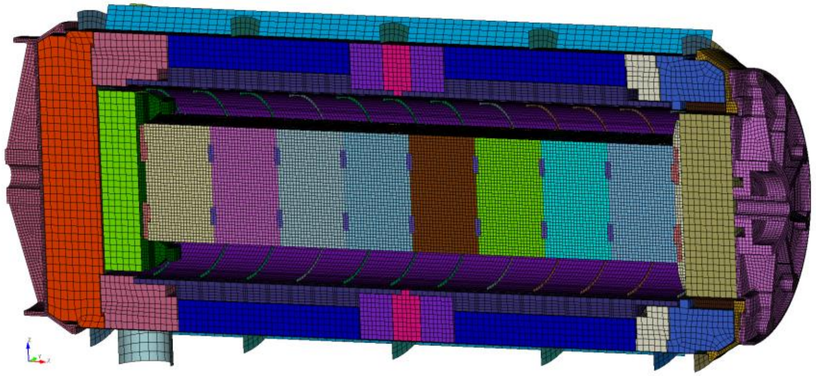
- Start with detailed understanding of the response of RPS to insults
- Perform detailed simulations and Monte Carlo sequence codes used to develop the probabilistic risk analysis

Launch Safety Code Suite



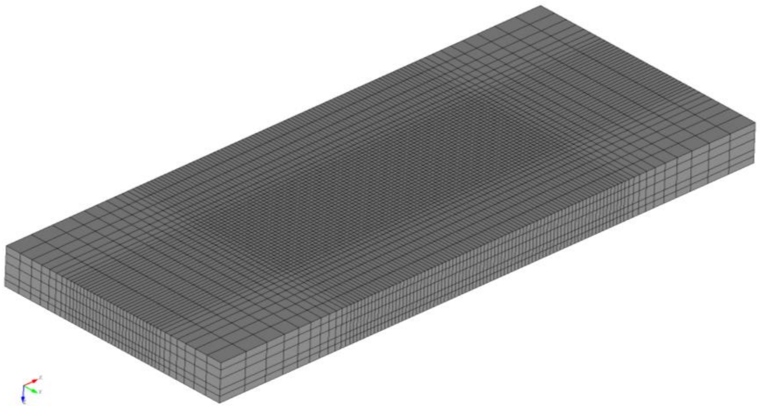
Blast and Impact Modeling

- Blasts from launch destruct and ground impact of propellant tanks or solid propellant fragments
- Ground impact of MMRTG
- Impact of spacecraft and launch vehicle debris on MMRTG and components
- Impact of solid propellant fragments on MMRTG and components
- SNL's Sierra/SM used for analyses
- Hundreds of parallel processors, days to weeks of run time for each configuration

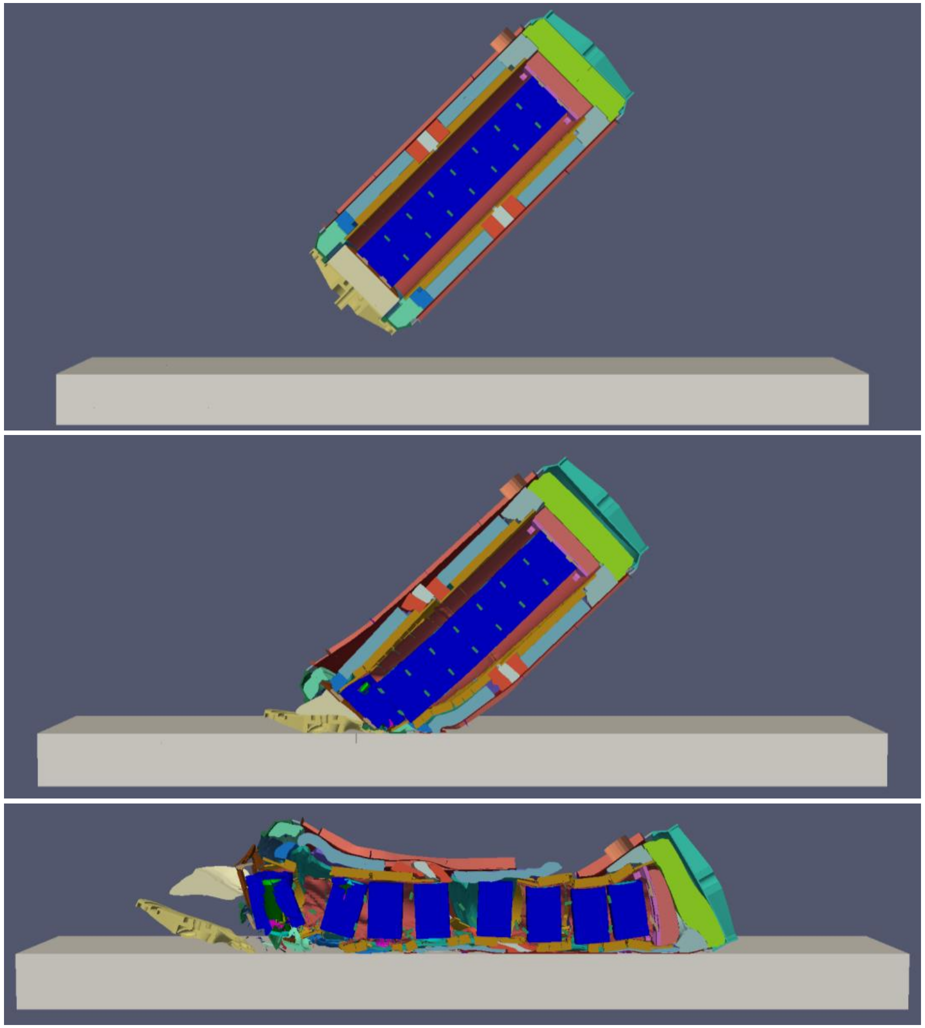


Ground Impact

- Model placed above a steel target with an initial velocity downward.
- Target refined at impact area, coarsened near edges.
  - Contact algorithm requires similar element size.



Target model for MMRTG impacts

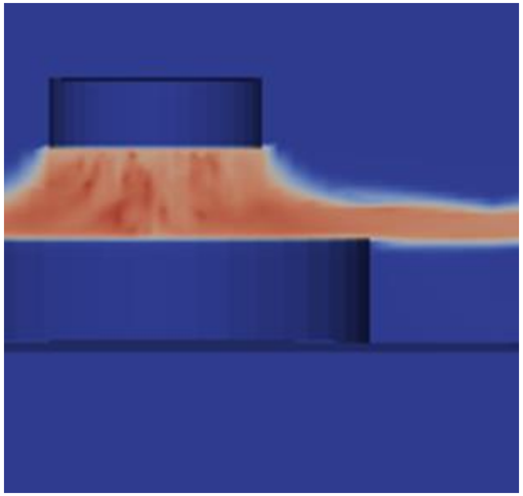


MMRTG 45° Impact at 100 m/s
(terminal velocity is 60 m/s)
No fuel release

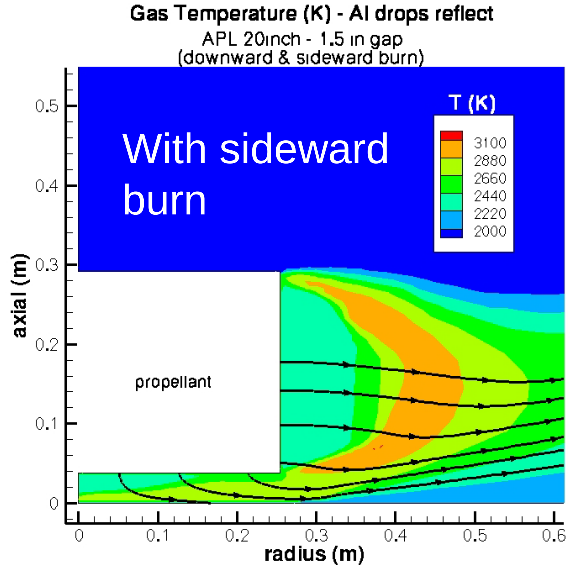
Solid Propellant Burn Modeling

- 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

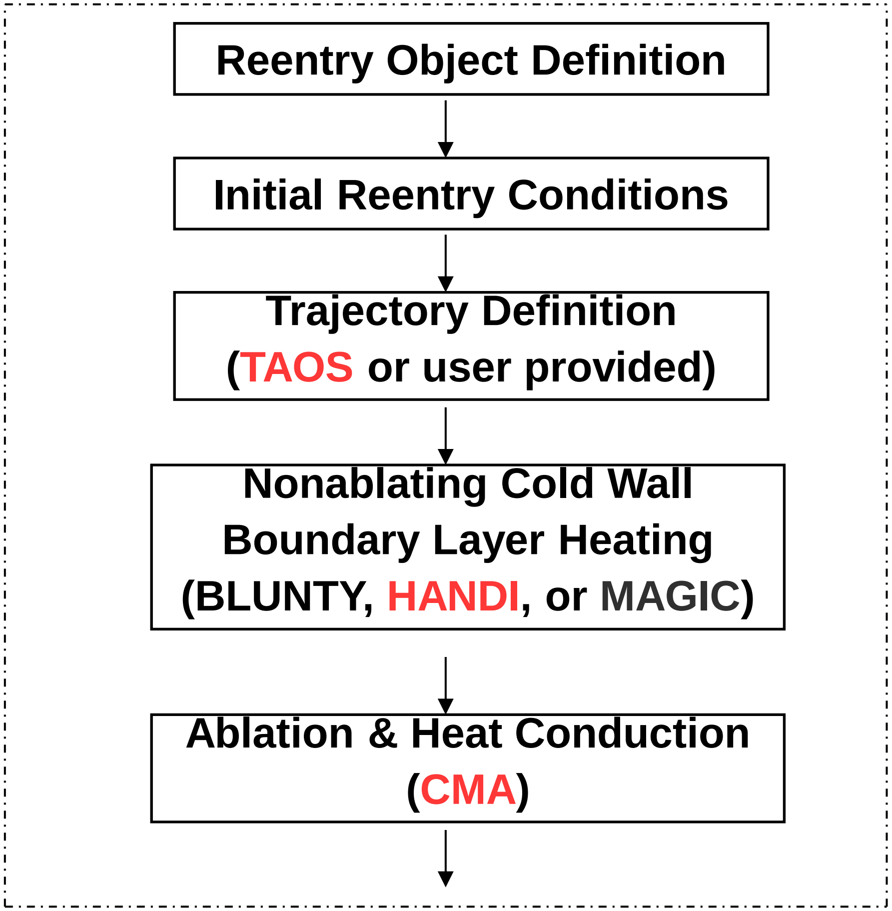


Sierra/Fuego Simulation

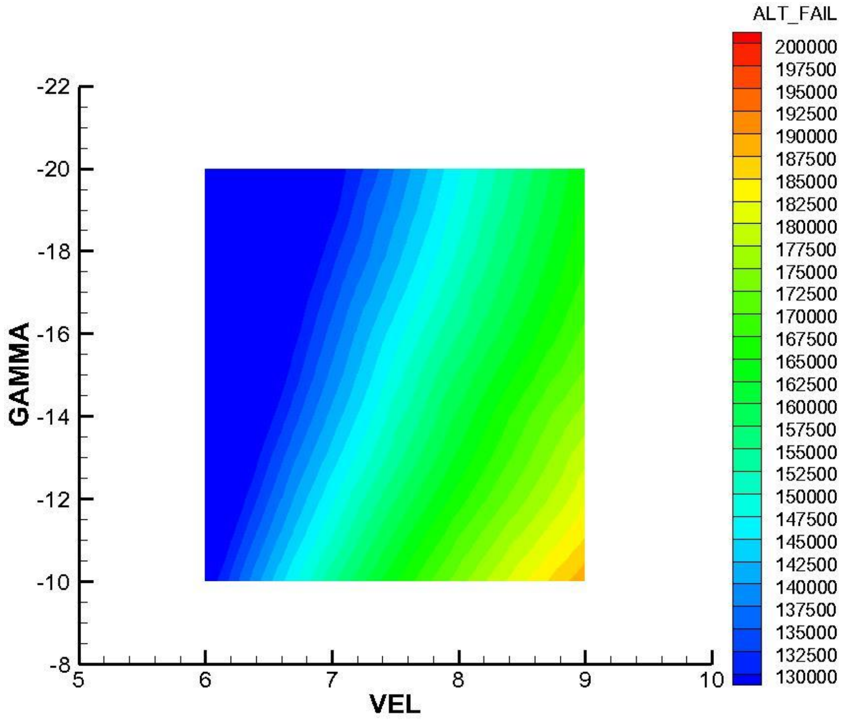


Fluent with physics module from Fuego

LAPS Reentry Code Description

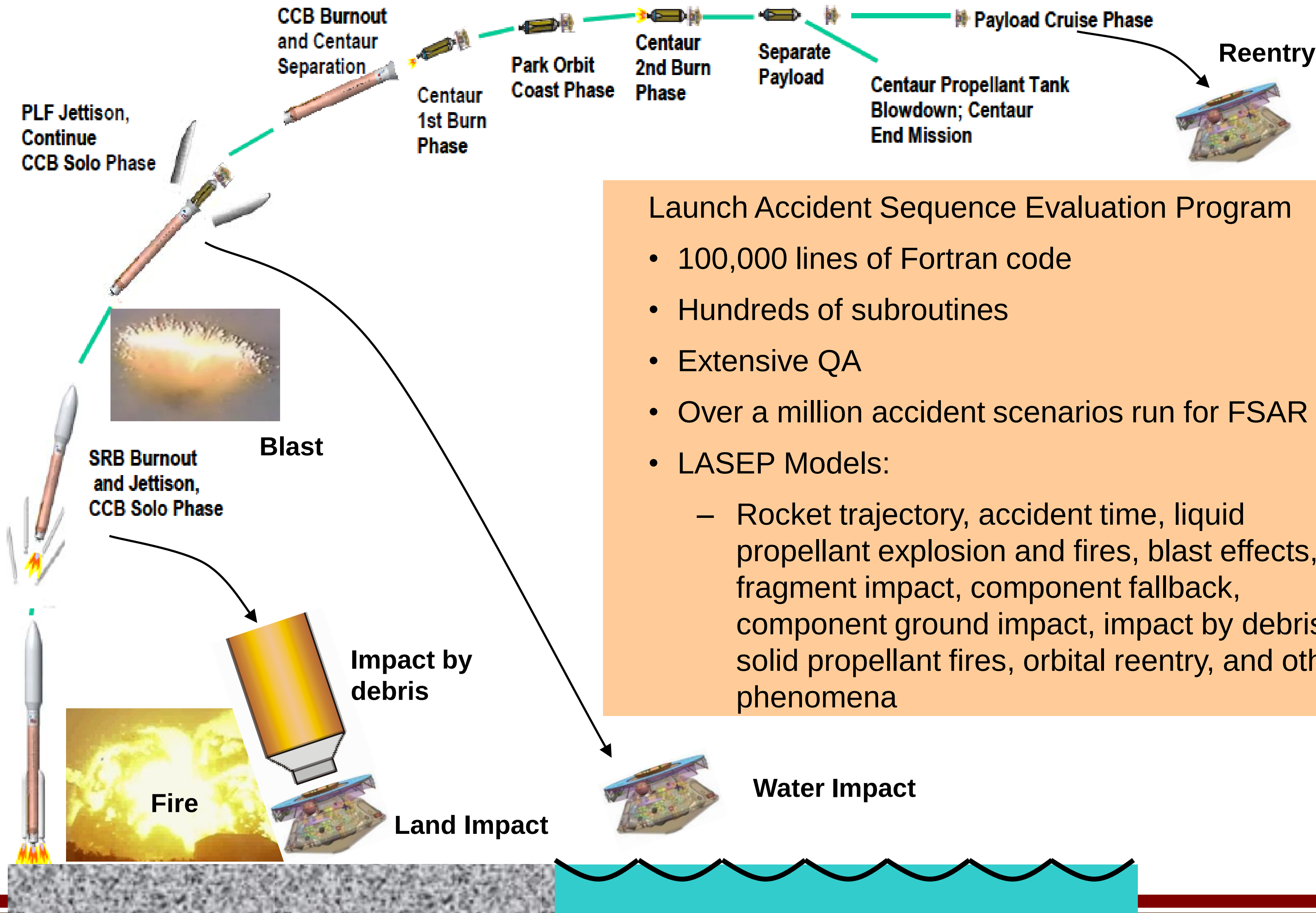


MMRTG Breakup v-gamma Map
(gamma is entry angle)



LASEP Stochastically Simulates the Range of Potential Launch Accidents

Launch Accident Sequence Evaluation Program

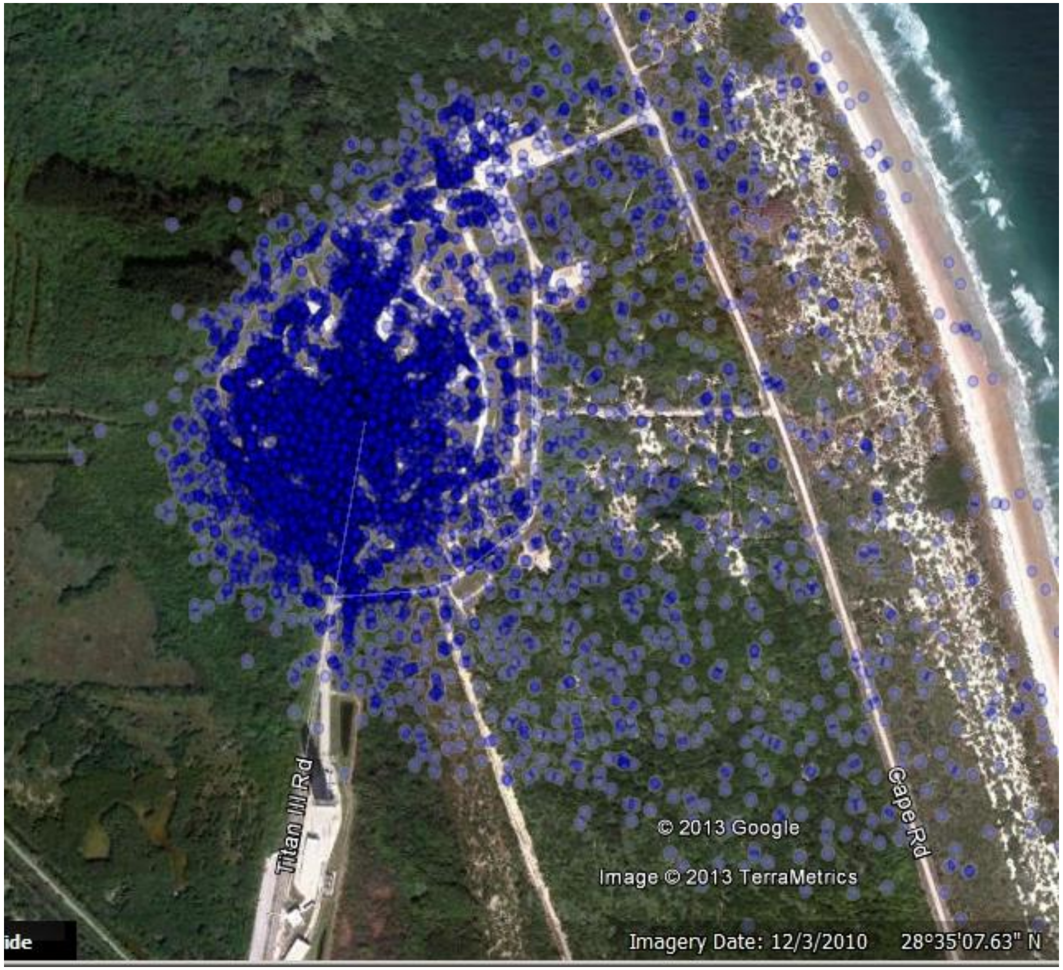


Launch Accident Sequence Evaluation Program

- 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

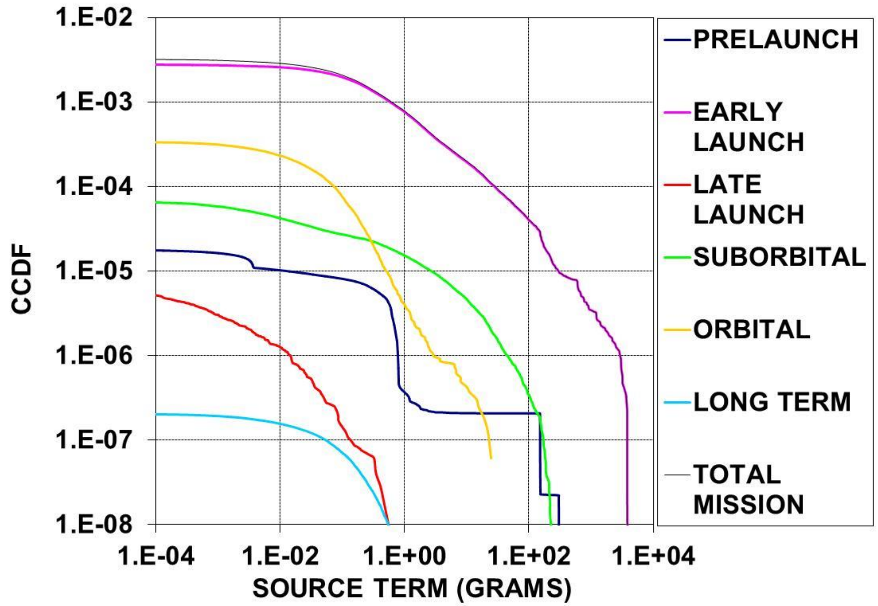


Potential release locations from numerous LASEP launch simulations, SLC-41

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**

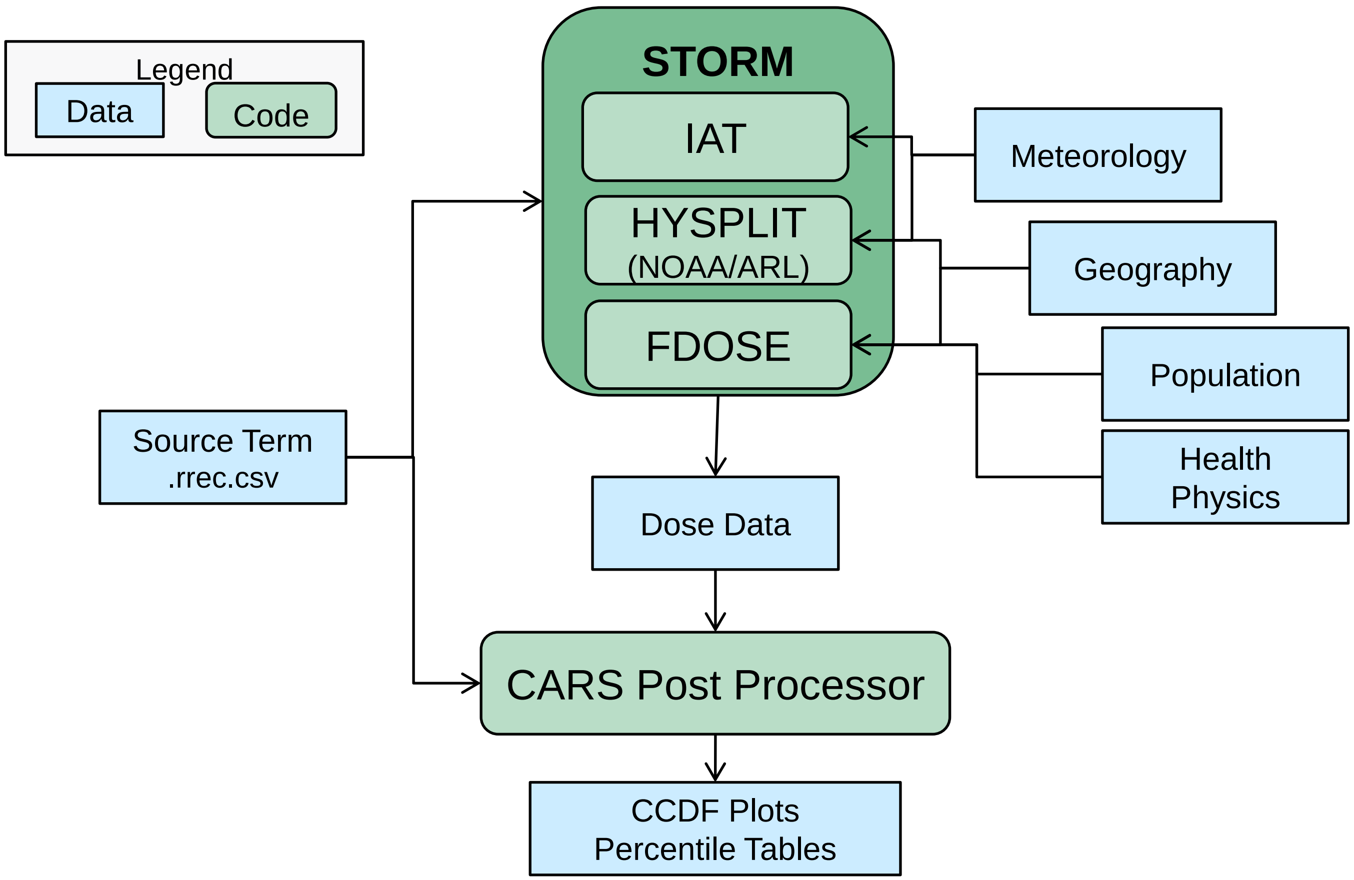
Source Term Excedance Graph



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

Consequence Modeling

Sandia Transport Of Radionuclides Model (STORM) uses NOAA's HYSPLIT code, leveraging NOAA's extensive investment and readily accessing NOAA's weather database



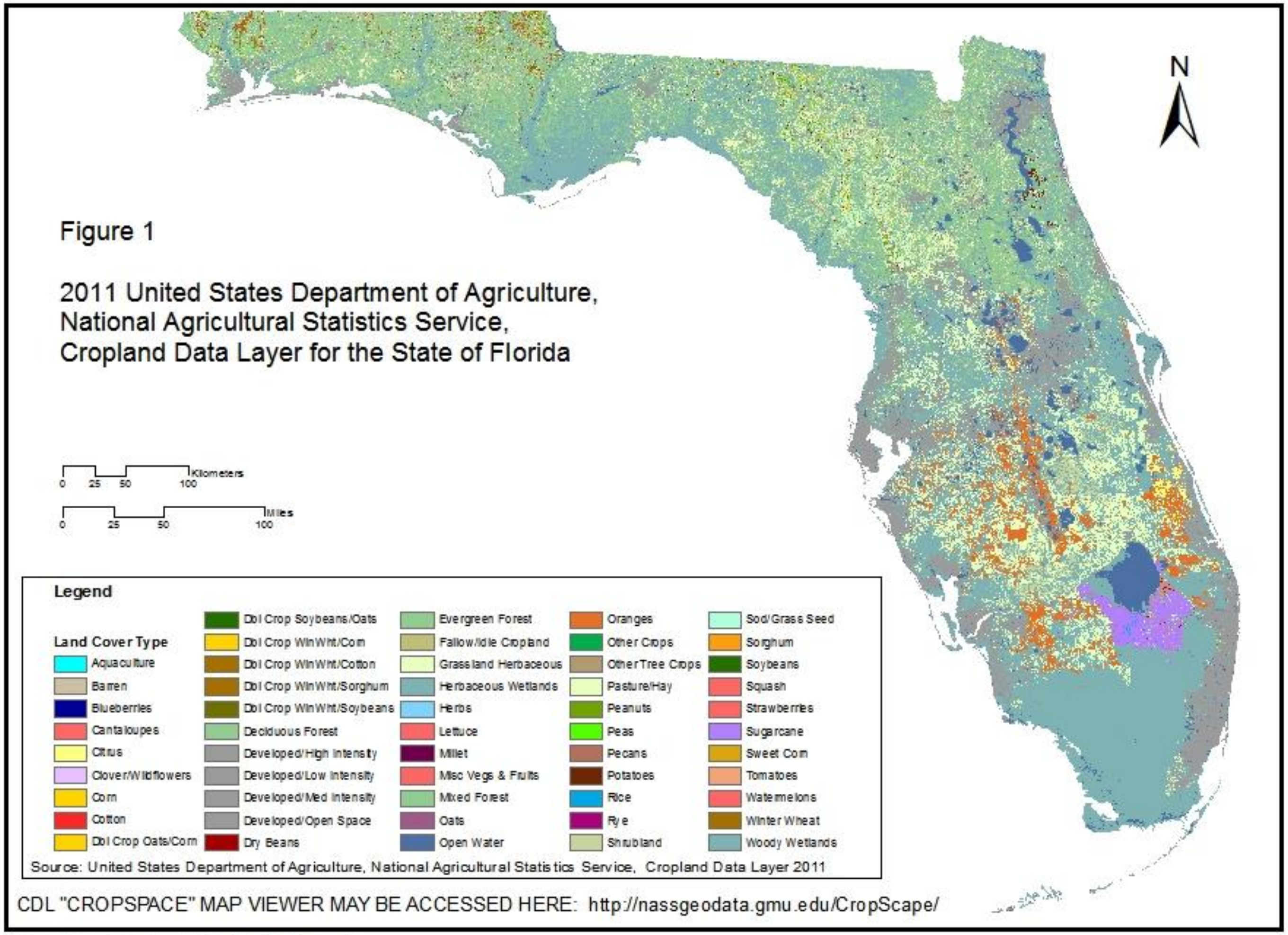
FDOSE (Fortran DOSE Program)

- FDOSE calculates health effects from inhalation, cloud shine, ground shine, and ingestion
- Reads a HYSPLIT deposition and air concentration grid file
- Sampling is done externally by varying input parameters
- Currently has population database integrated
  - Includes spectator and resident information
  - Similar format to LandScan to facilitate future implementation
- Contains the GLC-2000 land-use database
- Ingestion factors implemented using COMIDA-2 (NRC supported code)

COMIDA2 Food Ingestion Model

- Developed at INL to support MACCS2 ingestion modeling
- Well documented and widely used in consequence analyses, mainly for nuclear power plants
- Treats a relatively complete set of mechanisms for food contamination
- Considers nine food types

Florida Crop Use Data



Map Document: (K:\GProject\SPACE_2011\Maps\FL_Landuse.mxd)

Example of MSL Consequences

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

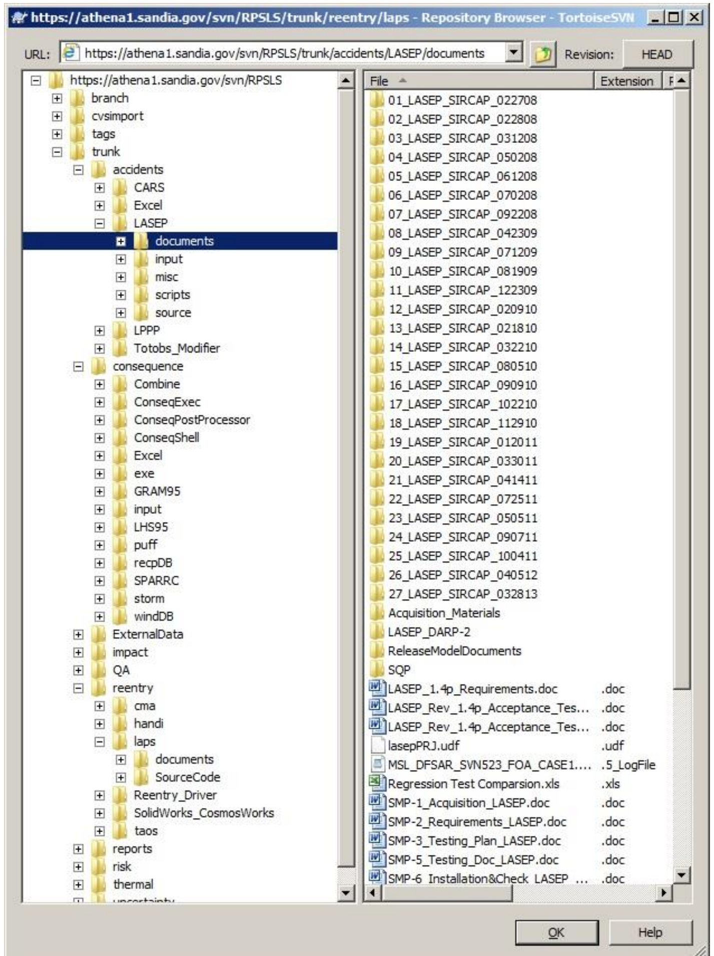
Mission Phase No.	Mission Phase Description	Proba-bility of Release	Health Effects[a] without de Minimis	Risk[b] without de Minimis	Land Area[a] Exceeding 0.2 μCi/m^2 (km^2)
0	Prelaunch	1.79E-05	1.38E-01	2.46E-06	2.43E-01
1	Early-Launch	2.78E-03	3.45E-01	9.59E-04	1.63E+00
2	Late-Launch	6.78E-06	1.14E-04	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

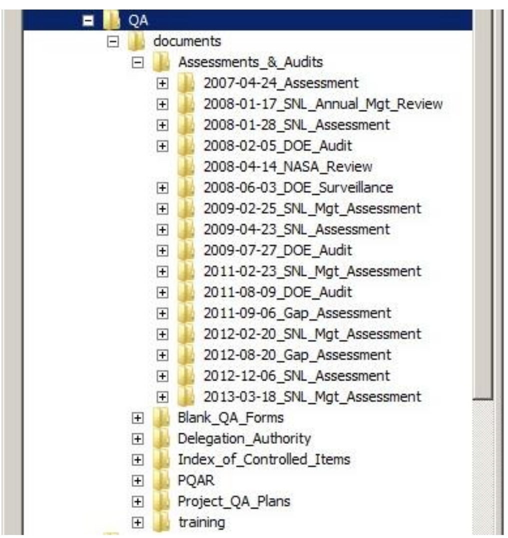
a. Values are the means conditional on a release occurring.
b. Risk is the expectation value of health effects. It is calculated as the product of the probability of release and the mean number of health effects given a release.

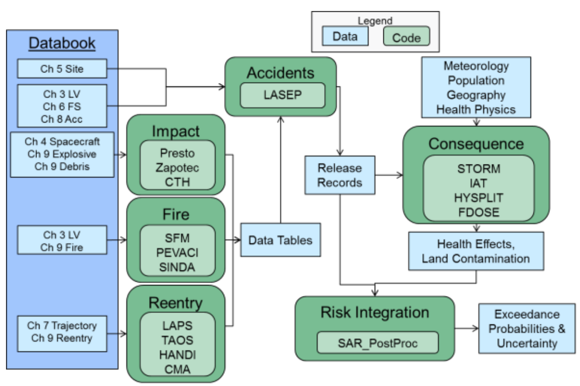
N. E. Bixler, et al, NETS-2013, paper 6793

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

- Safety analyses are required, and enabling, for the use of radioisotope power systems
- The EIS and launch safety review process is well established and well exercised
- A suite of codes exists to handle the diverse phenomena
  - Blast and impact
  - Propellant fires
  - Reentry
  - Diverse accident sequences
  - Atmospheric transport and consequences
  - Probabilistic modeling of accident sequences and atmospheric transport