The 2014 NASA Nuclear Power Assessment Study (NPAS): Safety, Environmental Impact, and Launch Approval Considerations and Findings

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Introduction

- **Near the outset of the 2014 Nuclear Power Assessment Study (NPAS), a Safety Team (ST) was formed**
    - Advise & support the Executive Council (EC), the System Study Team (SST) and the Mission Study Team (MST), including the MST ATLO Working Group, on safety, environmental impact, launch approval & security considerations & issues [Note: Security is addressed in a separate NETS-2015 Presentation]
    - Make observations & findings, as appropriate, and bring them to the attention of the EC
    - Brief efforts, observations, and findings as part of 2014 NPAS Final Briefing to NASA/SMD
    - Document ST efforts, observations, and findings within the 2014 NPAS Report
- **NASA and the Department of Energy have developed shared principles for safety and environmental considerations for the development and use of U.S. space nuclear power systems**
    - These key principles were important considerations during the 2014 NPAS
    - They served as a foundation for system studies of notional radioisotope power systems (RPS) and fission power systems (FPS) for two selected 2014 NPAS mission studies - TSSM and UOP

Overview of Presentation

- Summary of Launch History of U.S. Space Nuclear Systems
- Description of Key Safety & Environmental Principles & Processes
- Key Observations & Findings

HISTORY

- Nuclear systems have enabled tremendous strides in our country’s use & exploration of space.

- Since 1961, the US has launched forty-seven nuclear power systems & hundreds of radioisotope heater units in support of thirty-one navigational, meteorological, communications, experimental, as well as lunar, solar, Martian, Jovian, Saturnian, and outer solar system exploration missions.

- One mission (*SNAPSHOT* in 1965) involved a small 500W(e) reactor power system (SNAP-10A); the remaining missions were powered by radioisotope thermoelectric generators (RTGs) & radioisotope heater units (RHUs).

Space Nuclear Systems Launched by the US (1961 – 2014)

MISSION	MISSION TYPE	LAUNCH DATE	NUCLEAR SYSTEM (#Systems/Nominal Output)	STATUS
TRANSIT 4A	Navigational	Jun 61	SNAP-3B7 (1/2.7W(e))	Successfully achieved orbit; ops terminated 1966
TRANSIT 4B	Navigational	Nov 61	SNAP-3B8 (1/2.7W(e))	Successfully achieved orbit; ops terminated 1967
TRANSIT 5BN-1	Navigational	Sep 63	SNAP-9A (1/25W(e))	Successfully achieved orbit; ops terminated 1970
TRANSIT 5BN-2	Navigational	Dec 63	SNAP-9A (1/25W(e))	Successfully achieved orbit; ops terminated 1971
TRANSIT 5BN-3	Navigational	Apr 64	SNAP-9A (1/25W(e))	Failed to achieve orbit; SNAP-9A burned up on reentry as then designed/intended
SNAPSHOT	Experimental	Apr 65	SNAP-10A (1/500W(e))	Successfully achieved orbit; S/C voltage regulator failed after 43 days; SNAP-10A reactor shutdown permanently in 3000+ yr orbit
NIMBUS B-1	Meteorological	May 68	SNAP-19B2 (2/40W(e) ea)	Vehicle destroyed during launch; SNAP-19B2s retrieved intact; fuel used on later mission
NIMBUS III	Meteorological	Apr 69	SNAP-19B3 (2/40W(e) ea)	Successfully achieved orbit; ops terminated 1979
APOLLO 12	Lunar exploration	Nov 69	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
APOLLO 13	Lunar exploration	Apr 70	SNAP-27 (1/70W(e))	Mission aborted en route to moon; SNAP-27 survived reentry & in 7000+ ft of water in deep ocean
APOLLO 14	Lunar exploration	Jan 71	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
APOLLO 15	Lunar exploration	Jul 71	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
PIONEER 10	Solar system exploration	Mar 72	SNAP-19 (4/40W(e) ea)	Successfully placed on interplanetary trajectory; still operational
APOLLO 16	Lunar exploration	Mar 72	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
TRIAD-01-1X	Navigational	Sep 72	TRANSIT-RTG (1/30W(e))	Successfully achieved orbit; ops terminated 1977
APOLLO 17	Lunar exploration	Dec 72	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
PIONEER 11	Solar system exploration	Apr 73	SNAP-19 (4/40W(E) ea)	Successfully placed on interplanetary trajectory; still operational
VIKING 1	Mars exploration	Aug 75	SNAP-19 (2/40W(e) ea)	Successfully placed on Mars; ops terminated 1980
VIKING 2	Mars exploration	Sep 75	SNAP-19 (2/40W(e) ea)	Successfully placed on Mars; ops terminated 1980
LES 8	Communications	Mar 76	MHW-RTG (2/150W(e) ea)	Successfully achieved orbit; still operational
LES 9	Communications	Mar 76	MHW-RTG (2/150W(e) ea)	Successfully achieved orbit; still operational
VOYAGER 2	Solar system exploration	Aug 77	MHW-RTG (3/150W(e) ea)	Successfully placed on interplanetary trajectory; still operational
VOYAGER 1	Solar system exploration	Sep 77	MHW-RTG (3/150W(e) ea)	Successfully placed on interplanetary trajectory; still operational
GALILEO	Jovian exploration	Oct 89	GPHS-RTG (2/275W(e) ea) LWRHU (120/1W(t) ea)	Successfully placed in orbit around Jupiter; deorbited into atmosphere of Jupiter following end-of-mission
ULYSSES	Solar polar exploration	Oct 90	GPHS-RTG (1/275W(e))	Successfully placed in solar polar orbit; ops ended 2009
MARS PATHFINDER	Mars rover exploration	Dec 96	LWRHU (3/1W(t) ea)	Successfully placed on Mars; rover ceased ops in 1997
CASSINI	Saturnian exploration	Oct 97	GPHS-RTG (3/275W(e) ea) LWRHU (117/1W(t) ea)	Successfully placed in orbit around Saturn; still operational
MER-A	Mars rover exploration	Jun 03	LWRHU (8/1W(t) ea)	Successfully placed on Mars; ops ended 2010
MER-B	Mars rover exploration	Jul 03	LWRHU (8/1W(t) ea)	Successfully placed on Mars; still operational
NEW HORIZONS	Pluto/Kuiper Belt Exploration	Jan 06	GPHS-RTG (1/275W(e))	En-route to Pluto w/arrival in 2015
MSL	Mars rover exploration	Nov 11	MMRTG (1/110W(e))	Successfully placed on Mars; still operational

Accidents / Malfunctions Involving U.S. Space Nuclear Systems

TRANSIT 5BN-3:	US Navy navigational satellite launched 21 Apr 1964. Failed to achieve orbit & reentered at ~120km over west Indian Ocean, N of Madagascar. SNAP-9A RTG burned up during reentry—as then designed). Release (17kCi of Pu-238) equivalent to Pu-238 released from all atmospheric weapons testing. As of Nov 1970, only 5% of original Pu-238 released from SNAP-9A burnup remained in atmosphere (removal half life ~ 14mo). Using this value indicates that ~2.5 pCi remains in the atmosphere as of Apr 2014. [Note: ~10kCi still in biosphere]
SNAPSHOT:	SNAP-10A reactor/electric propulsion experimental mission launched 3 Apr 1965. Reactor successfully started/operated for 43days; S/C voltage regulator malfunction caused reactor permanent/irreversible shutdown in 3000+ year orbit.
NIMBUS B-1:	Meteorological satellite launched 18 May 1968 from WTR. RSO destroyed LV due to errant ascent; all debris fell into Santa Barbara channel. SNAP-19 RTG (34 kCi Pu-238) recovered intact at ~100m depth. No release; fuel used on later mission.
APOLLO 13:	Manned lunar mission launched 11 Apr 1970. SNAP-27 RTG (44.5kCi Pu-238) reentered with LEM over south Pacific Ocean. RTG survived reentry; rests at 7000+ ft depth near Tonga trench.

Accidents/Malfunctions Involving USSR/Russian Space Nuclear Power Systems

KOSMOS ?:	RORSAT launch attempted 25 Jan 1969. Believed to be a launch failure on/at the pad.
KOSMOS 300:	Lunikhod S/C launched 23 Sep 1969. Failed to achieve escape trajectory. S/C w/small Po-210 source reentered atmosphere and burned up on 27 Sep 1969.
KOSMOS 305:	Lunikhod S/C launched 22 Oct 1969. Failed to achieve escape trajectory. S/C w/small Po-210 source reentered atmosphere and burned up on 24 Oct 1969.
KOSMOS ?:	RORSAT launched 25 Apr 1973. Believed to fail to achieve orbit; falling into Pacific Ocean N of Japan.
KOSMOS 954:	RORSAT launched Sep 1977. Reactor successfully separated from S/C following end of operations, but did NOT boost to a higher, long-lived orbit. Reactor reentered over Pacific Ocean & crashed near Great Slave Lake in northern Canada on 24 Jan 1978. ~65kg of debris, radioactive objects, and fuel recovered.
KOSMOS 1402:	RORSAT launched 30 Aug 1982. Anomaly indicated; S/C intentionally separated into 3 parts. Reactor is believed to have reentered & fallen into the south Atlantic ~1600km E of Brazil on 7 Feb 1983. No radioactivity detected from reentry of any parts.
KOSMOS 1900:	RORSAT launched 12 Dec 1987. On 13 May 1988, USSR reported that contact was lost in Apr 1988 & reactor could not be boosted via ground signal to higher orbit. On 30 Sep 1988, reactor automatically separated and boosted to higher (~720km) orbit.
MARS 96:	Mars explorer launched 16 Nov 1996. Failed to achieve escape trajectory. S/C w/small Pu-238 fueled RTG reentered on 17 Nov 1996 and fell near the coast of Chile/Bolivia. RTG designed to survive reentry; no radioactivity detected from reentry or impact.

Safety Considerations & Principles for Space Nuclear Systems

Safety Considerations

- An integral part of any nuclear system
- Encompasses the entire system/mission lifecycle from initial conceptual design, development; through launch, insertion, operation & final disposition

Safety Principles

Purpose

- Protection of the public, the environment, workers, property, and other resources from undue risk or harm

Objectives

- Create a safe product
- Demonstrate safety – convincingly
- Obtain the necessary approvals for successful development, ground test, launch, and space mission use

Strategy

- Design & build safety into every nuclear heat source & system at the outset, considering its potential applications
- Demonstrate the safety of each nuclear heat source and system through rigorous analysis and limited, judicious testing
- Separately, quantitatively assess the environmental impact, as well as the level of risk for each proposed nuclear system & nuclear-powered space mission

Building Safety in at the Outset
Safety Issues & Strategies for Space Nuclear Systems

RPS:

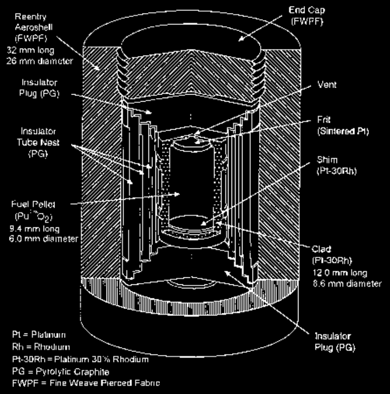
- Safety issues:
  - Potential release of the radioactive fuel material into the Earth’s biosphere as a result of a postulated pre-launch, launch, ascent, or reentry accident; and
  - Potential loss of physical security or positive control/cognizance over the system and its SNM.
- Safety strategies:
  - Design & build the nuclear heat source to be robust, with multiple containment barriers that are rugged—to prevent fuel release under normal, off-normal & credible accident situations;
  - Incorporate a stable fuel form with a high melting point & low solubility to minimize fuel vaporization and transport in the environment, as well as minimize fuel retention within the human body, should a fuel release occur.
  - Take appropriate measures & incorporate special features into the design—to prevent sabotage & terrorism against, as well as theft, loss & diversion of the system & its SNM prior to achieving the planned orbit/trajectory in space.

FPS (for in-space power and/or propulsion):

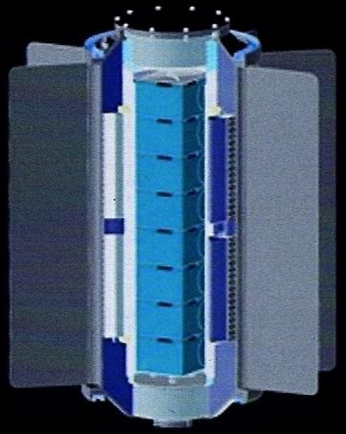
- Safety issues (more complex than those for space radioisotope systems):
  - Potential inadvertent criticality as a result of a pre-launch, launch, ascent, or reentry accident prior to achieving the planned startup/operational orbit in space;
  - Potential dispersal of nuclear material into the biosphere, including land contamination;
  - Potential reentry of a radioactively “cold” or “hot” reactor into the Earth’s atmosphere;
  - Potential release of fission & activation products, generated during planned reactor operation in space or an inadvertent criticality, into the Earth’s biosphere; and
  - Potential loss of physical security or positive control/cognizance over the system and its SNM

CURRENT U.S. SPACE NUCLEAR SYSTEMS

LWRHU



MMRTG



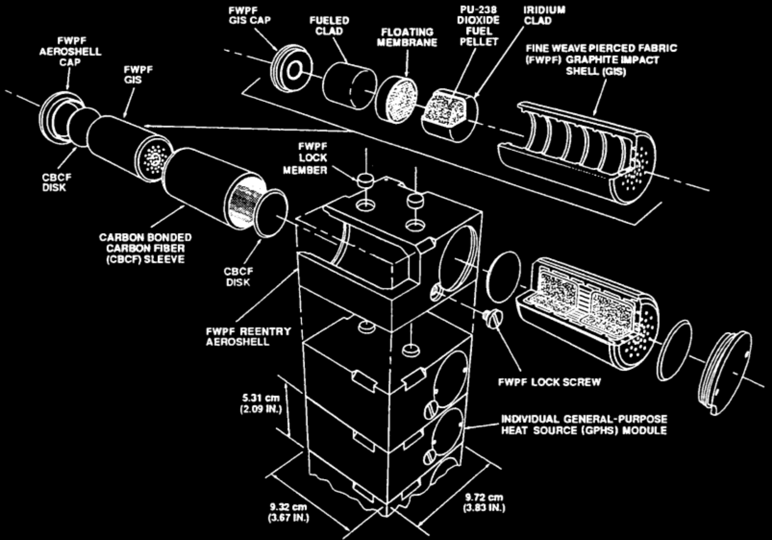
MMRTG Cross Section

MMRTG

110W(e); ~45kg
~2.0ft long x1.0ft(housing)/2.0ft(fins) OD
8 GPHS Step-II Modules
~4.9kg Pu-238 Oxide; ~59.5kCi

LWRHU

1W(t); 40g
~1inx1.25in
0.37inx0.25in fuel pellet
clad w/Pt-30Rh
2.7g Pu-238 Oxide fuel;
~30Ci



GPHS Module (Step-II)

~4inx4inx2in aeroshell of
FWPF w/2 FWPF GISs
2FCs/GIS
FC: 1.1inx1.1in fuel pellet
clad w/DOP-26 Ir alloy
~151g Pu-238 Oxide/FC
612g Pu-238 Oxide/Module
~1860Ci/FC; ~7440Ci/Module

Building Safety into the Design of U.S. Space Nuclear Systems

- Clear, sound safety criteria must be in place at the outset to guide designers and mission planners

- Such top-level safety criteria should be functional in nature, as opposed to prescriptive, so that designers and mission planners are afforded maximum flexibility to consider a wide spectrum of options regarding how the criteria are to be met

- These safety criteria will be different for RPS & FPS, primarily because the safety issues associated with RPS vary from those for FPS
  - Safety issues for RPS are well understood & fully-vetted safety criteria are currently in-hand
  - Although safety issues for FPS are understood, fully-vetted safety criteria do not yet exist
  - Such FPS safety criteria are termed herein *Functional Design & Operational Safety Criteria,* to ensure that FPS safety criteria, when developed & put in place, are functional in nature & address operational situations that could occur during the FPS life cycle

Demonstrating Safety by Analyses & Testing

- **In an accident, nuclear system hardware can be exposed to a number of threat environments – sometimes alone, but often in concert with others; typically sequentially**
  - Blast overpressure & impulse
  - Fragment impacts (small & large)
  - Earth surface impact (including water immersion)
  - Debris impact from above
  - Solid & liquid propellant fires
  - Reentry heating and ablation

- **Impossible to test all credible sequences of environments**
  - Tests of nuclear hardware are extremely expensive & time consuming
  - Testing must be used sparingly & judiciously
    - Obtain materials property data
    - Verify response(s) of hardware (limited)
    - Benchmark analysis codes -- so that codes can be used to predict hardware response(s)

- **Analysis, therefore, must be relied upon to predict hardware responses**

- **Analyses (substantial in breadth & depth) required for:**
  - NEPA compliance
  - Ground test authorization
  - Nuclear safety launch approval (SARs & SER)

Assessing the Environmental Impact & Risk Associated with the Development & Use of Space Nuclear Systems

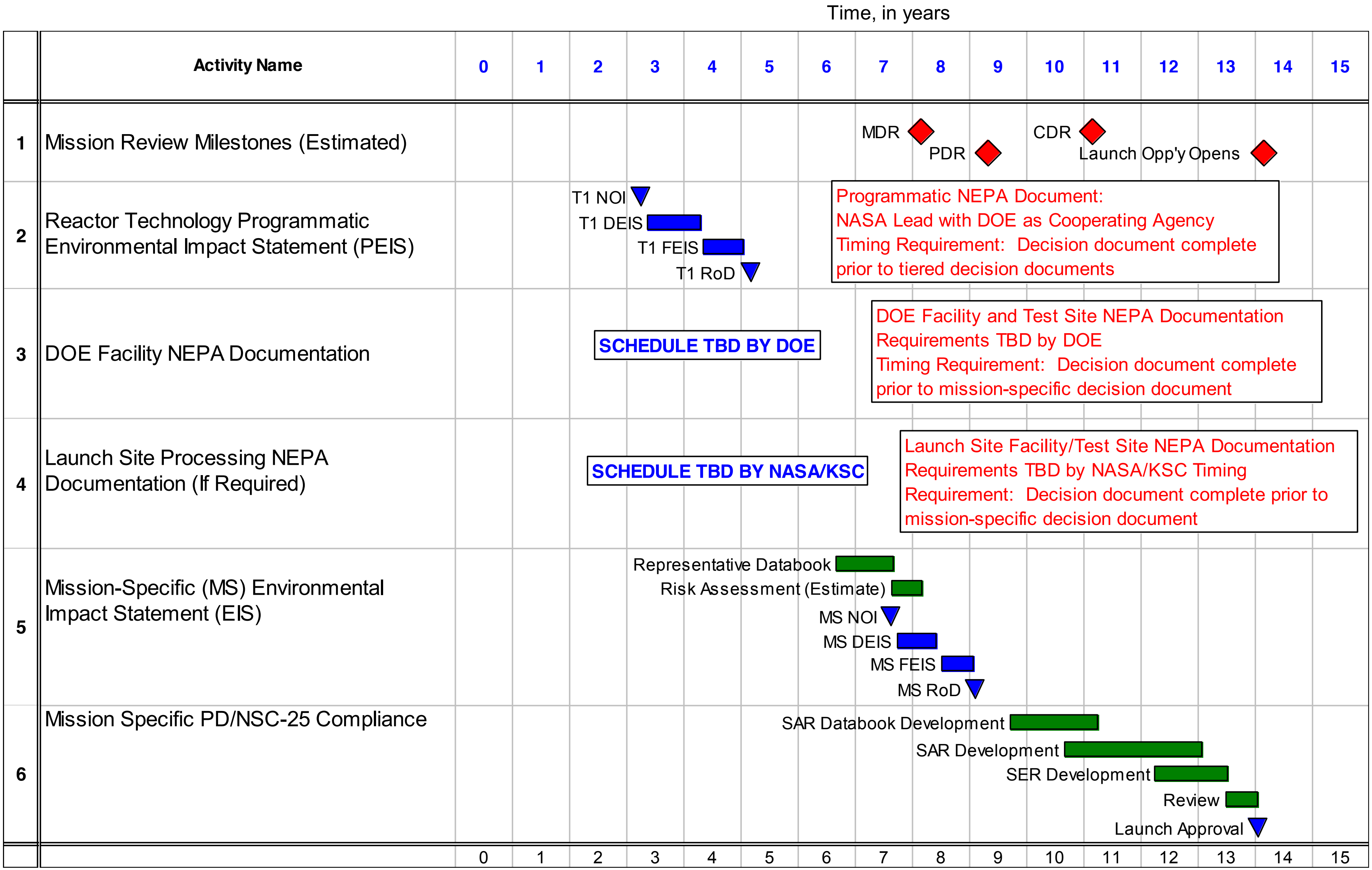
Mandated Protocols & Processes for Space Nuclear Systems / Missions

NEPA Process (for development as well as space mission use)

- *Federal Register* notice must be issued
- EIS w/opportunity for public involvement
- Record of Decision required for action to proceed

- **Safety Review & Launch Approval Process (for space mission use)**
  - INSRP (DoD, DOE, NASA, EPA & NRC Tech Advisor) formed at request of mission-sponsoring agency
  - PSAR, DSAR & FSAR prepared by DOE for mission-sponsoring agency over ~3-year period
  - INSRP reviews PSAR, DSAR & FSAR
  - INSRP prepares SER for its agencies & mission-sponsoring agency for their individual review
  - Based on the FSAR & SER, together with the agency reviews, the mission-sponsoring agency decides if it will formally request nuclear safety launch approval from the White House
  - White House makes informed nuclear safety launch decision based on thorough consideration of risks & benefits; FSAR & SER are key inputs

Notional Programmatic NEPA Strategy



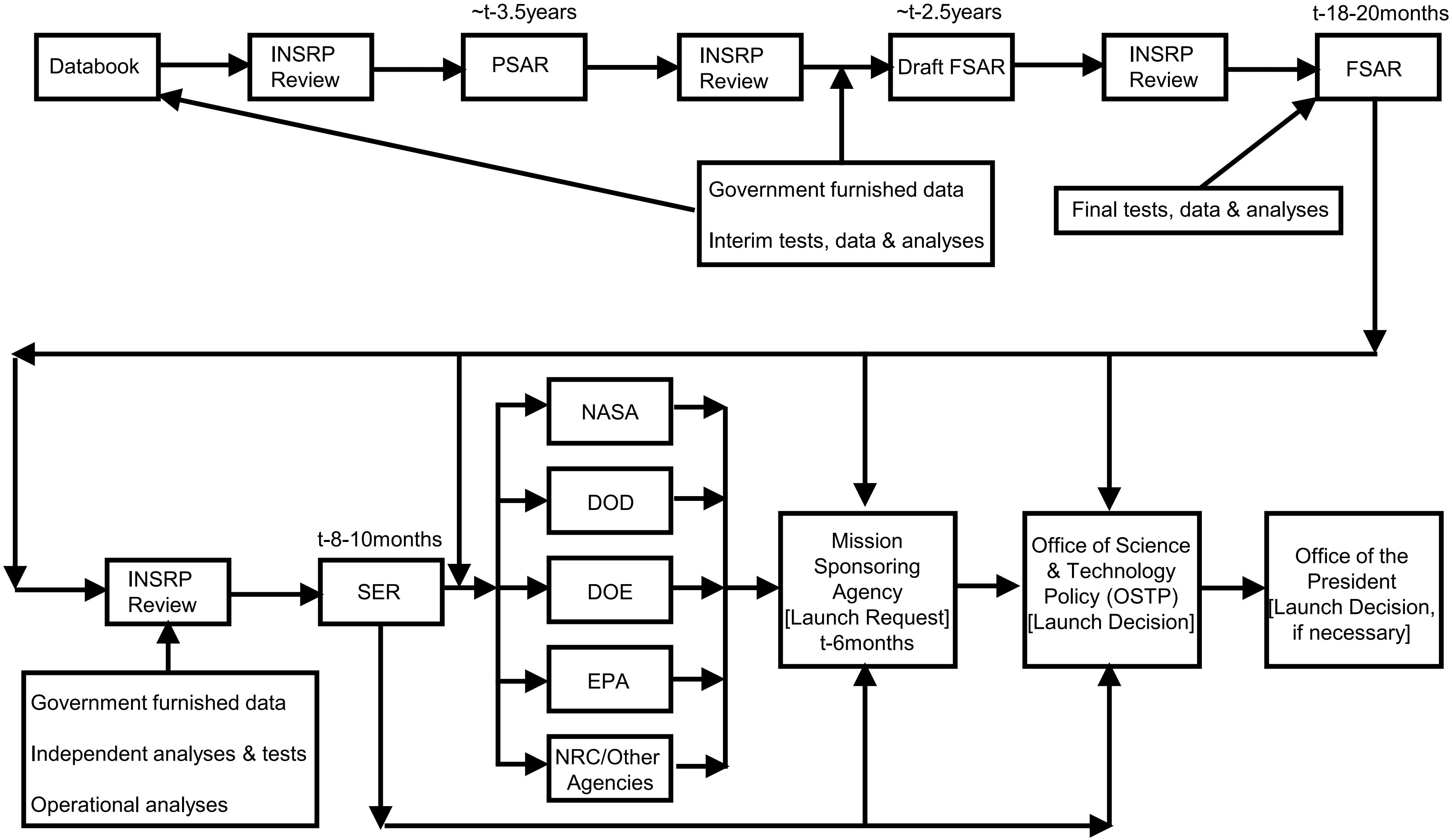
Programmatic NEPA Document:
NASA Lead with DOE as Cooperating Agency
Timing Requirement: Decision document complete prior to tiered decision documents

DOE Facility and Test Site NEPA Documentation Requirements TBD by DOE
Timing Requirement: Decision document complete prior to mission-specific decision document

Launch Site Facility/Test Site NEPA Documentation Requirements TBD by NASA/KSC Timing Requirement: Decision document complete prior to mission-specific decision document

Two Separate Processes For U.S. Space Nuclear Systems / Missions

- **US Safety Review & Launch Approval Process**



~t-3.5years

~t-2.5years

t-18-20months

Databook

INSRP Review

PSAR

INSRP Review

Draft FSAR

INSRP Review

FSAR

Government furnished data

Interim tests, data & analyses

Final tests, data & analyses

INSRP Review

t-8-10months

SER

NASA

DOD

DOE

EPA

NRC/Other Agencies

Mission Sponsoring Agency [Launch Request] t-6months

Office of Science & Technology Policy (OSTP) [Launch Decision]

Office of the President [Launch Decision, if necessary]

Government furnished data

Independent analyses & tests

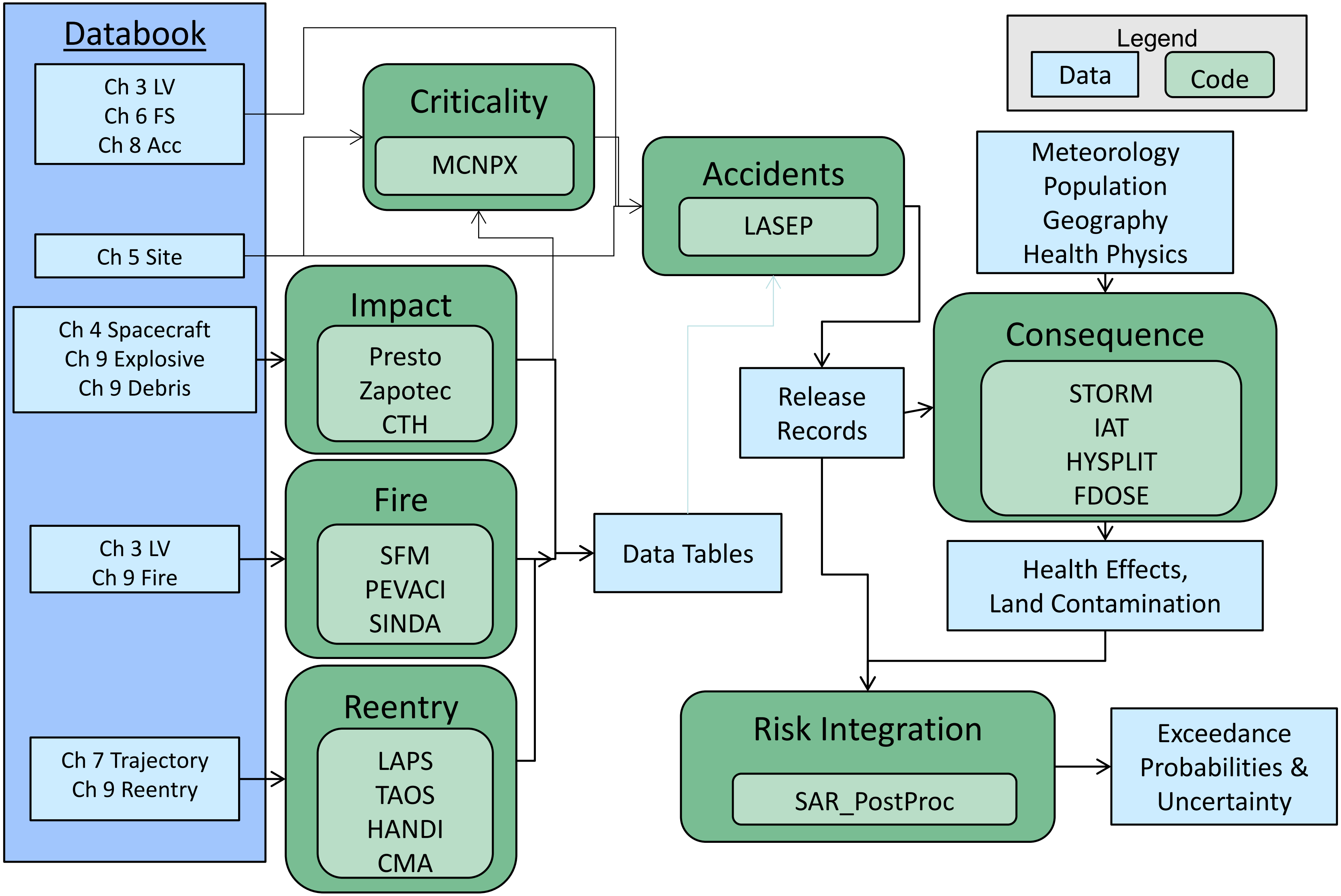
Operational analyses

CONDUCTING A MISSION SAFETY ANALYSIS OR RISK ASSESSMENT

The Analysis Steps

1. Segment mission into meaningful sequential phases
2. Identify & characterize accidents & accident environments in each phase
3. Determine nuclear system response to each accident & its associated accident environments
4. Project nuclear system consequence (e.g., source term, radiation field & duration, etc.) for each accident
5. Identify exposure & land contamination pathways for each accident
6. Project individual & collective doses, and any land contamination, for each accident
7. Project consequences (prompt & LCF), injuries & cleanup costs for each accident
8. Graphically display & textually explain results (e.g., CCDFs for the mission; CCDFs for each phase; CCDFs for major risk contributors; footprint isopleths for land contamination; etc.)
9. Document effort & results

Safety Analysis Code Suite



Legend
Data
Code

Databook

Ch 3 LV
Ch 6 FS
Ch 8 Acc

Ch 5 Site

Ch 4 Spacecraft
Ch 9 Explosive
Ch 9 Debris

Ch 3 LV
Ch 9 Fire

Ch 7 Trajectory
Ch 9 Reentry

Criticality
MCNPX

Impact
Presto
Zapotec
CTH

Fire
SFM
PEVACI
SINDA

Reentry
LAPS
TAOS
HANDI
CMA

Accidents
LASEP

Data Tables

Release Records

Meteorology
Population
Geography
Health Physics

Consequence
STORM
IAT
HYSPLIT
FDOSE

Health Effects,
Land Contamination

Risk Integration
SAR_PostProc

Exceedance Probabilities & Uncertainty

Key Observations & Findings

- RPS & FPS safety issues, although different and more complex for FPS, are well understood
- Fully-vetted *Functional Design & Operational Safety Criteria* have been established and applied to RPS, and this should continue
- *Functional Design & Operational Safety Criteria* have not been established for FPS
  - Sound, fully-vetted *Functional Design & Operational Safety Criteria* must be developed and applied to any future FPS design as soon as a commitment is made to develop FPS technology in earnest for flight; they should be:
    - Developed by experts, along with stakeholders, for intended application; *Criteria* must be non-prescriptive [Note: Specific *Design & Operational Specifications/Requirements* will ultimately emerge during iterative system design & analysis effort]
    - Reviewed by decision-makers (e.g., agency heads)
    - Approved by OSTP
- Any space nuclear power system development program must include a vibrant safety program from the very outset
  - Beyond safety considerations & principles identified herein, safety program should include:
    - Hierarchical set of requirements
    - Clear lines of authority, responsibility, and communications
    - Feedback mechanisms (for continual monitoring and evaluation)
    - Independent safety oversight
  - Moreover, to build a "safety culture" within the development program, management at all levels should foster a safety consciousness among all program participants and throughout all aspects of the space nuclear system development program
- There is every reason to believe that new RPS & FPS can be designed & developed which will satisfy all established *Functional Design & Operational Safety Criteria, as* well as all Safety Objectives

Key Observations & Findings

Summary of Schedule & Cost Impacts

NEW RPS

Schedule Impacts - Might start processes a little sooner (~1 year sooner) because it's a new system (relative to historical process schedules). [Note: Databook drives the NEPA & Launch Approval schedules; if Databook is not available, add ~2-3years to the front of those schedules; however, timing of a new RPS development vis-à-vis its first use would be a significant factor in developing the overall plan for NEPA and Nuclear Safety Launch Approval processes]

Cost Impacts – Costs are not expected to vary much from historical costs for NEPA Or Nuclear Safety Launch Approval - if Databook is available.

Key Observations & Findings

Summary of Schedule & Cost Impacts

NEW FPS

Schedule Impacts - Might start processes a little sooner (~1 year sooner) because it's a new system (relative to historical NEPA & Launch Approval process schedules). [Note: Databook availability usually drives these process schedules; however, timing of a new FPS development vis-a-vis its first use would be a significant factor in developing the overall plan for NEPA and Nuclear Safety Launch Approval processes] RTGF security modifications, or new RPS/FPS facility will require ~3-4 years; must be completed prior to shipment of fuel to the Cape for first FPS mission.

Cost Impacts – Costs are not expected to vary much from historical costs for NEPA or Launch Approval processes. [Note: A programmatic EIS for FPS development would be needed; Cost: ~$2-4M]

Final Thought

“For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.”

-- Richard P. Feynman
Nobel Laureate
from: “Personal Observations on the Reliability of the Shuttle,” Appendix to Roger’s Commission Report on the Space Shuttle Challenger Accident