General Safety Considerations

- **Overall Scope**

- **National Safety/Review Process for Nuclear Powered Space Missions**

- **US national review process (see figure)**

The US DOE (and its predecessors, ERDA and AEC) provide the nuclear power sources (NPS) and is responsible for the safety testing and analysis associated with their planned use.

Presidential Directive NSC/25 established the Interagency Nuclear Safety Review Panel (INSRP) which conducts an independent review of each proposed mission, prior to launch.

Note: The INSRP does not make a recommendation of launch approval or disapproval; it provides the risk evaluation to decision-makers who then balance risk against the potential benefits

- **The INSRP is formed when one agency has a mission which may require a nuclear power source and is chaired by 3 coordinators appointed by;**

    - **Secretary of Defense (usually from the AF)**
    - **Secretary of Energy**

- **Administrator of NASA**

Quite frequently, representatives from the NRC, EPA, and NOAA are invited to participate.

The INSRP forms several sub-panels to investigate the details of the NPS and to be in place over the entire mission.

See Galileo and Ulysses missions (the only two nuclear powered missions now under consideration)
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Space Nuclear Safety Review Process

• Process begins with the submission of a Safety analysis report from DOE ***See figure for review process***

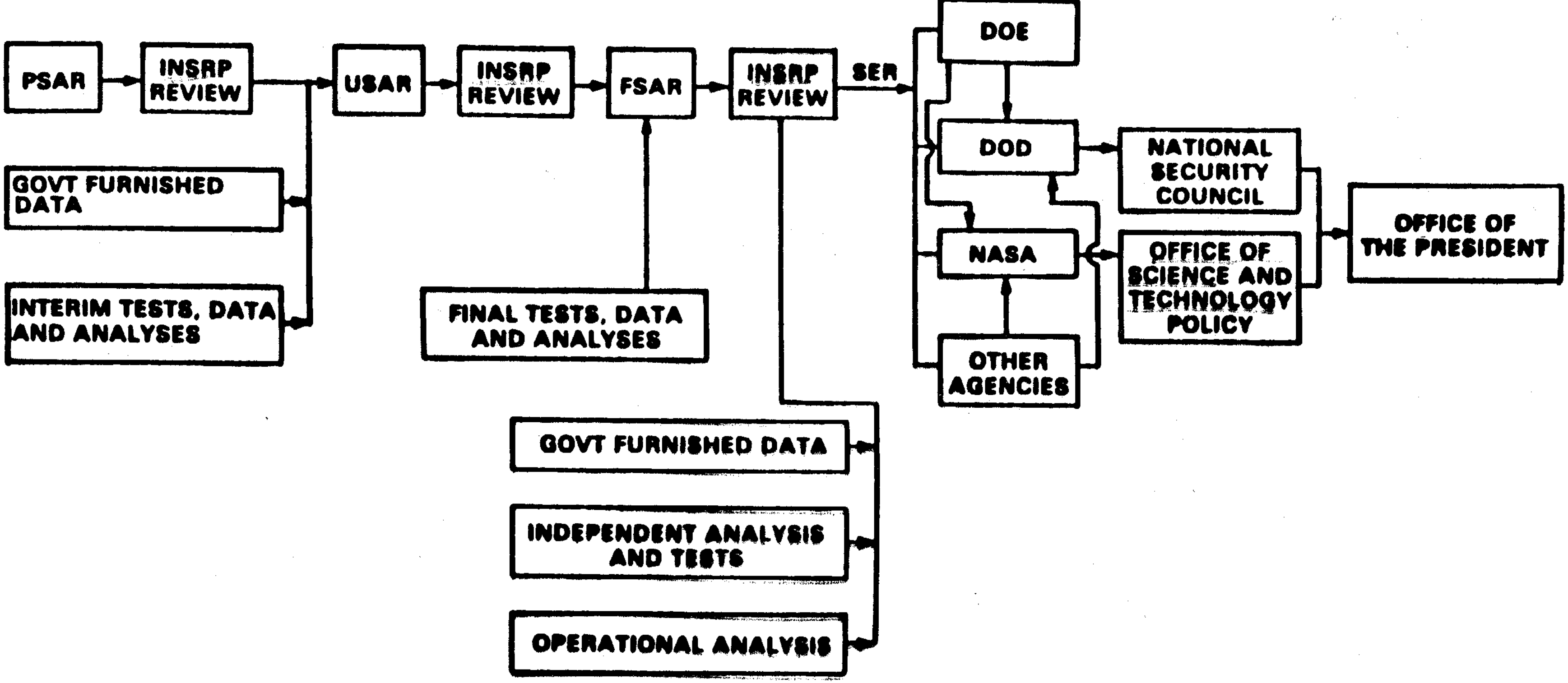
• There are at least three formal INSPR reviews;

(PSAR)- Preliminary Safety Analysis Report
(USAR)- Updated Safety Analysis Report
(FSAR)- Final Safety Analysis Report

In addition, INSPR reviews information on the launch vehicle and the launch site.

• After the FSAR is completed, INSPR prepares a Safety Evaluation Report (SER)

• The SER is submitted to the Office of Science



NOTE: FOR EXISTING NUCLEAR SYSTEMS, THE PSAR MAY NOT BE NEEDED.

PSAR = PRELIMINARY SAFETY ANALYSIS REPORT

USAR = UPDATED SAFETY ANALYSIS REPORT

FSAR = FINAL SAFETY ANALYSIS REPORT

SER = SAFETY EVALUATION REPORT

INSRP = INTERAGENCY NUCLEAR SAFETY REVIEW PANEL

Figure 2. Flight Safety Review and Launch Approval Process for Space Nuclear Power Systems

and Technology Policy (OSTP), within the office of the president.

The director of OSTP is empowered to approve the launch. If necessary, consultation and deferral to the president for launch approval can also occur.

International Considerations

- **The use of NPS's in space has been subject to U.N. Committee on the Peaceful Uses of Outer Space (COPUOS) scrutiny since the 1978 Cosmos -954 accident. COPUOS operates on a consensus basis meaning that there can be no disagreement in the text of the reports.**

However, there is no treaty covering NPS's at this time !

- **There are 4 related treaties to this subject;**

  - **Treaty on the Principles Governing the Activities of States in the Exploration and use of Outer Space, including the Moon and other Celestial Bodies. (1967)**

  - **Agreement on the Rescue of Astronauts, the Return of Astronauts,**

and the Return of Objects in Launched into Outer Space (1968)

•• Convention on International Liability for Damage Caused by Space Objects (1973)

•• Convention on the Registration of Objects Launched into Outer Space (1976)

In addition there is the 2 post - Chernobyl Conventions that also cover NPS's:

- ***Convention on the Early Notification of a Nuclear Accident***

- ***Convention on Assistance*** **in the Case of a Nuclear Accident or Radiological Emergency**

General Safety Considerations (cont.)

<u>A.) Methods of Meeting Safety Criteria</u>

1.) Confinement and Containment
('bring it back alive')

2.) Delay and Decay (see figure)

3.) Dilution and Dispersion (explosives, chemical reagents, materials that burn up in space)

Minimum Safety Documentation Required

(see figure)

Timing of SAR's

- **PSAR-Issued as soon as a design concept is selected for a given mission**

- **USAR- Issued as soon as possible after the design freeze.**

- **FSAR - Issued about 1 year before launch**

Table 1 *Lifetime of Parking Orbits.*

Altitude (Nautical Miles)	Expected Time In Orbit (Days)
85	1/2
100	3
150	35
200	200
300	4000

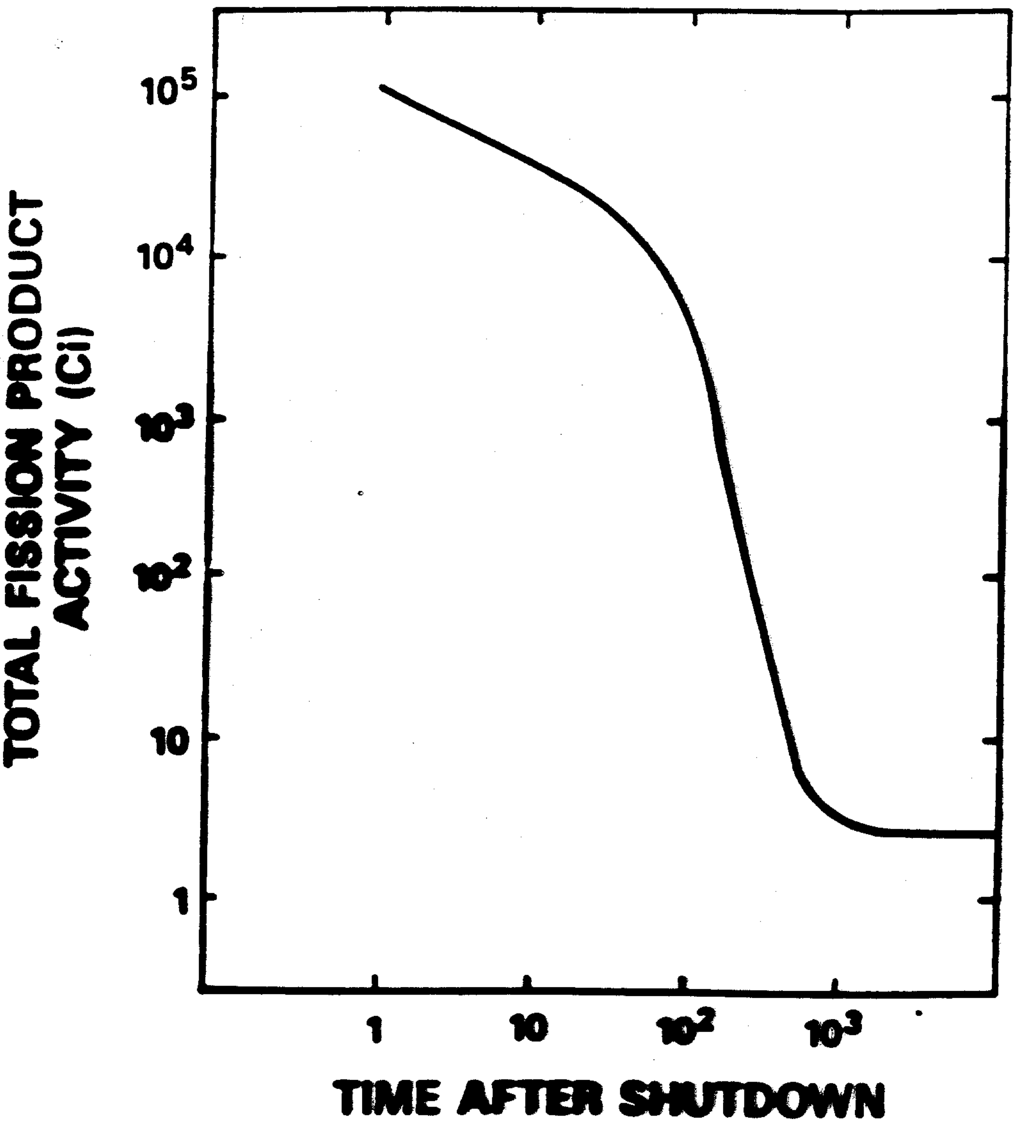


Figure 3. Calculated Radionuclide Activity after Shutdown for a Hypothetical Space Nuclear Reactor which has Operated at 1,000 kWth for 10 Years with a Fuel Mixture of 90% ^{235}U and 10% ^{238}U

Minimum Safety Documentation Required

Safety Assessment Report
Defines Safety Aspects of Design

Safety Program Plan
Outlines Total Safety Program to Achieve Safety Objectives

Radiological Protection Plan
Presents Radiological Protection and Health Physics Program to Protect People

Ground Safety Analysis Report (GSAR)
Assesses Safety of Site Specific Operations, Facilities, Personnel, Training and Equipment

Criticality Assessment Report
Assesses Criticality Aspects of RTG/Heat Source, Multiple Storage/Transportation Configuations

Safety Analysis Reports (Flight)
Provides Overall Nuclear Risk Analysis of the Mission

Safety Analysis Report For Packaging (SARP)
Qualifies the Shipping Container for Issuance of " Certificate of Compliance" for Transportation

Emergency Preparadness and Response Plan
Protection of People in Accident Conditions

Overall Outline of SAR's

Vol. 1 -REFERENCE DESIGN DOCUMENT

- **Mission/Flight System Summary**
- **Nuclear Power Source Description**
- **Spacecraft/Launch Vehicle/Trajectory Description**
- **Launch Site/Range Safety/Radiological Safety Data**

Vol. 2 -ACCIDENT MODEL DOCUMENT

- **Models/Data**
- **Event Tree Analysis**
- **Nuclear Power Source Response**

Vol. 3 -Nuclear Risk Analysis Document (only in the FSAR)

- **Probabilistic Description of Risk**

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Accident Environments Considered by SAR's

Pre-launch, Launch, and Ascent Phases

- **Explosion Overpressure**
- **Projectile Impact**
- **Land or Water Impact**
- **Liquid Propellant Fire**
- **Solid Propellant Fire**

- **Sequential Combinations of Above**

Orbit and/or Flight Trajectory Phases

- **Reentry**
- **Land or Water Impact**
- **Post-impact Environment (land or water)**

--

Examples of Postulated Mission Accident

--

Risk Analysis

For any given mission or mission phase it is possible to postulate a spectrum of accidents, some of which may lead to deleterious consequences.

$$R = \sum_{ijk} P_i \, P_j \, P_k \, N_{ijk}$$

R = Overall Mission Risk Index in terms of an expectation of the number of persons receiving a dose greater than a given dose D

P_i = Probability of accident type i

P_j = Conditional probability of release type j given accident type i

P_k = Conditional probability of exposure pathway

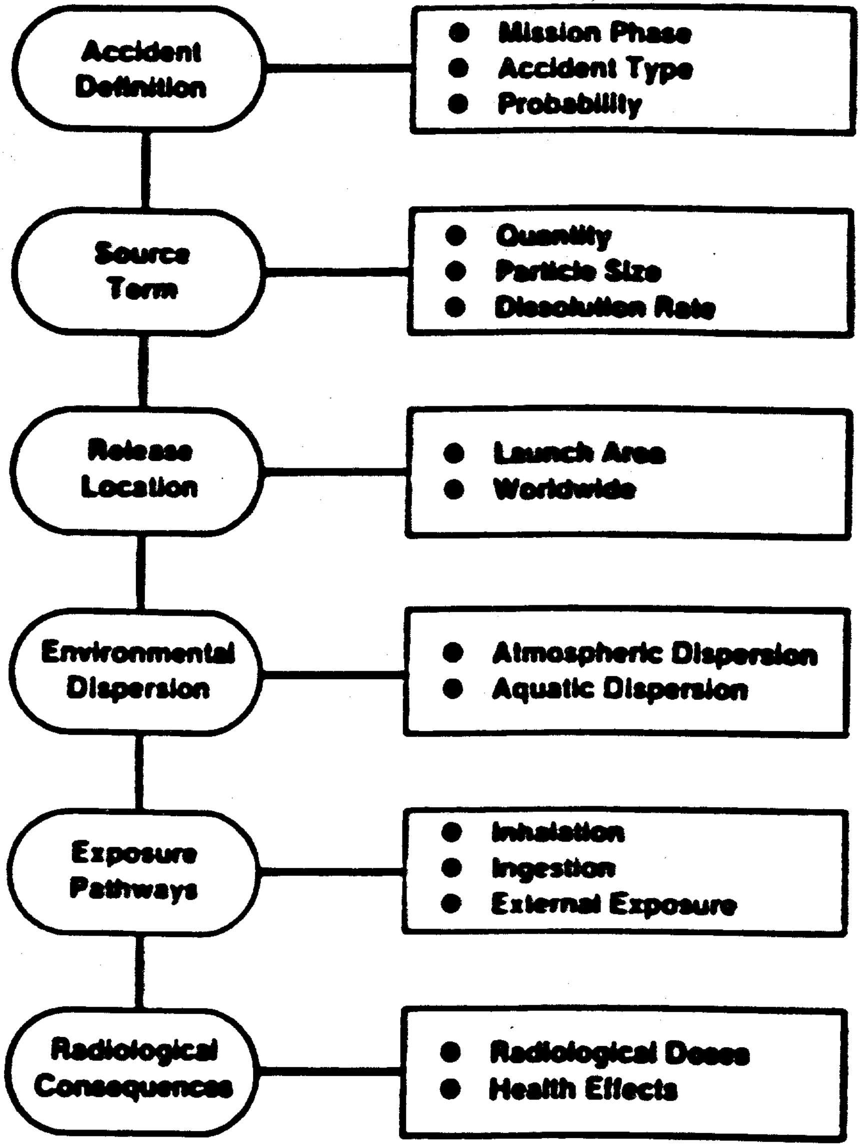

Figure 6. Process for Conducting Radiological Consequence Analysis

k given accident type i and release type j

N_{ijk}=Number of persons receiving dose >D given accident i, release type j, and exposure path k.

- **See process for conducting radiological consequence analysis figure.**
- **See distribution of dose exposures (figure)**

--

Use of Event Trees (see figure)

Define FAST = Failure/Abort Sequence Tree

--

Methods of Reporting Radiological Consequence

- **Maximum Individual Dose**
- **Number of persons receiving a dose above a given limit**
- **Total population exposure in person-rem**
- **Health effects**

For the Most Recent Galileo Launch, 3 Types of Potential Fuel Releases Were Identified

• Most Probable Release

That FAST sub-branch in a phase with predicted fuel release having the highest probability

• Maximum Case

The combination of events in a FAST sub-branch having the largest total release

• Release Expectation Case

Characterized by a probability weighted source term based on all the identified predicted fuel release events

In general, emergency planners are most interested in the;

'most probable' and

'maximum' cases.

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Decision makers are most interested in the Release Expectation Case because it represents a balanced overall assessment of the mission risk

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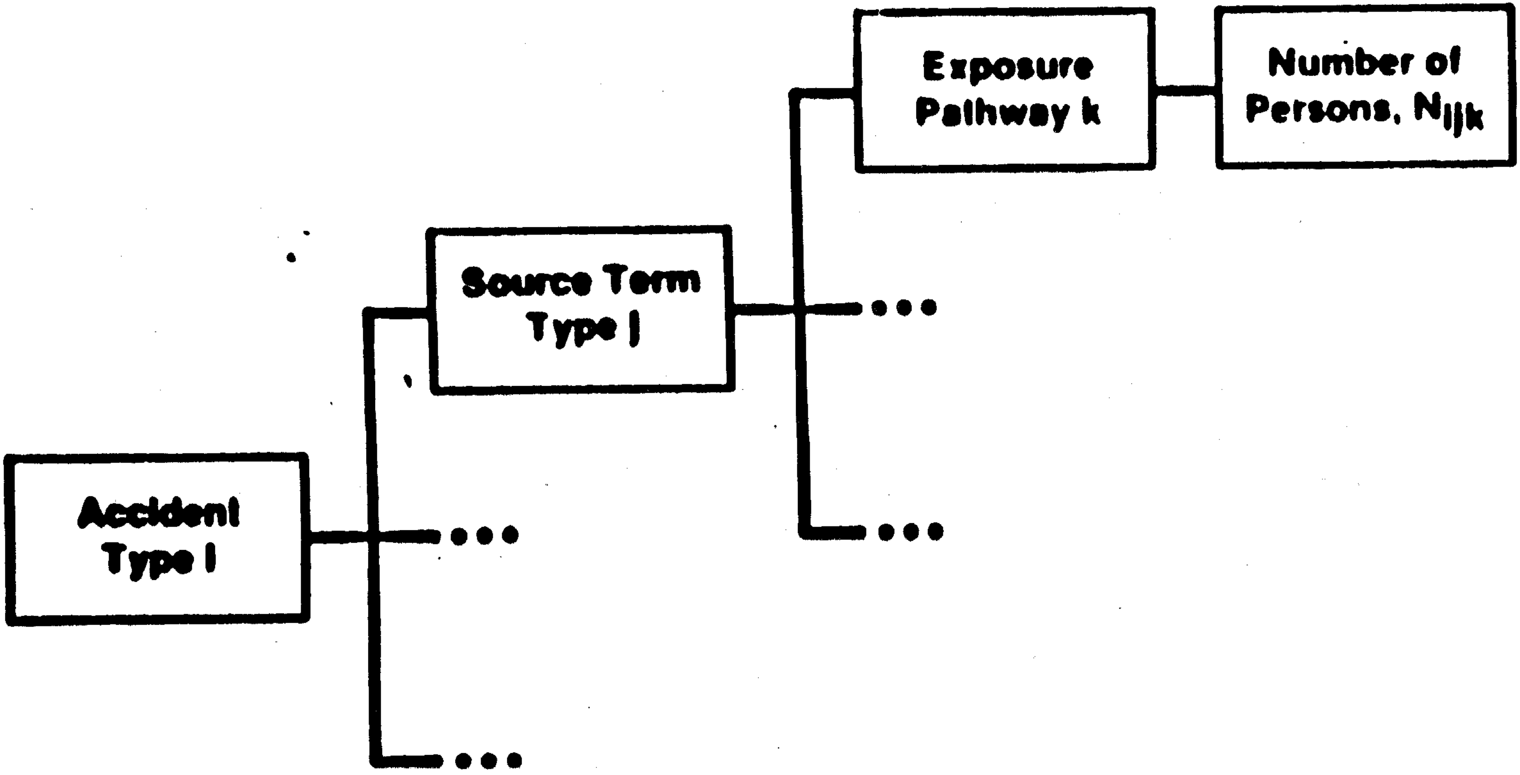
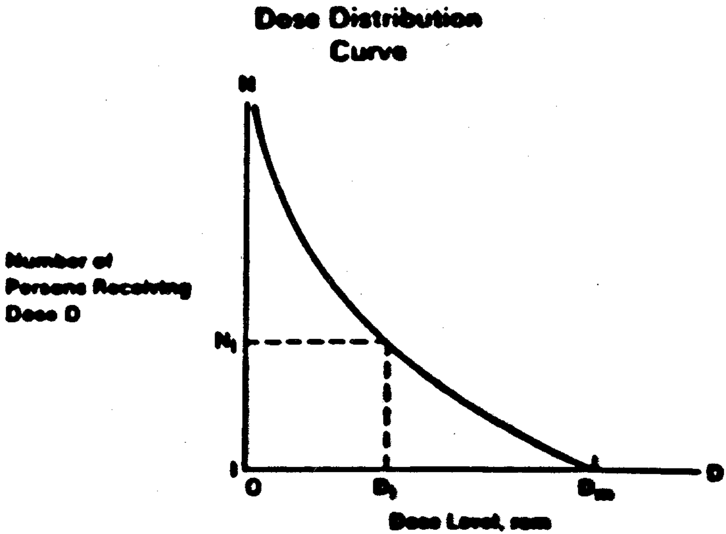
See accident scenarios

Note: Only accident in which > 0.01 % of Pu



$$R = \sum_{ijk} P_i P_j P_k N_{ijk}$$



- Maximum Individual Dose, D_m
- Number of Persons, N_i, Receiving Dose $\geq D_i$
- Total Population Dose in Person-rem

$$PD = \int_0^{D_m} N \, dD$$

- Potential Health Effects

$$H = k \times PD$$

Figure 7. Measures of Radiological Consequences

could be released were the near launch pad accidents

Also note: probability of inadvertent reentry during VEEGA is 5×10^{-7}

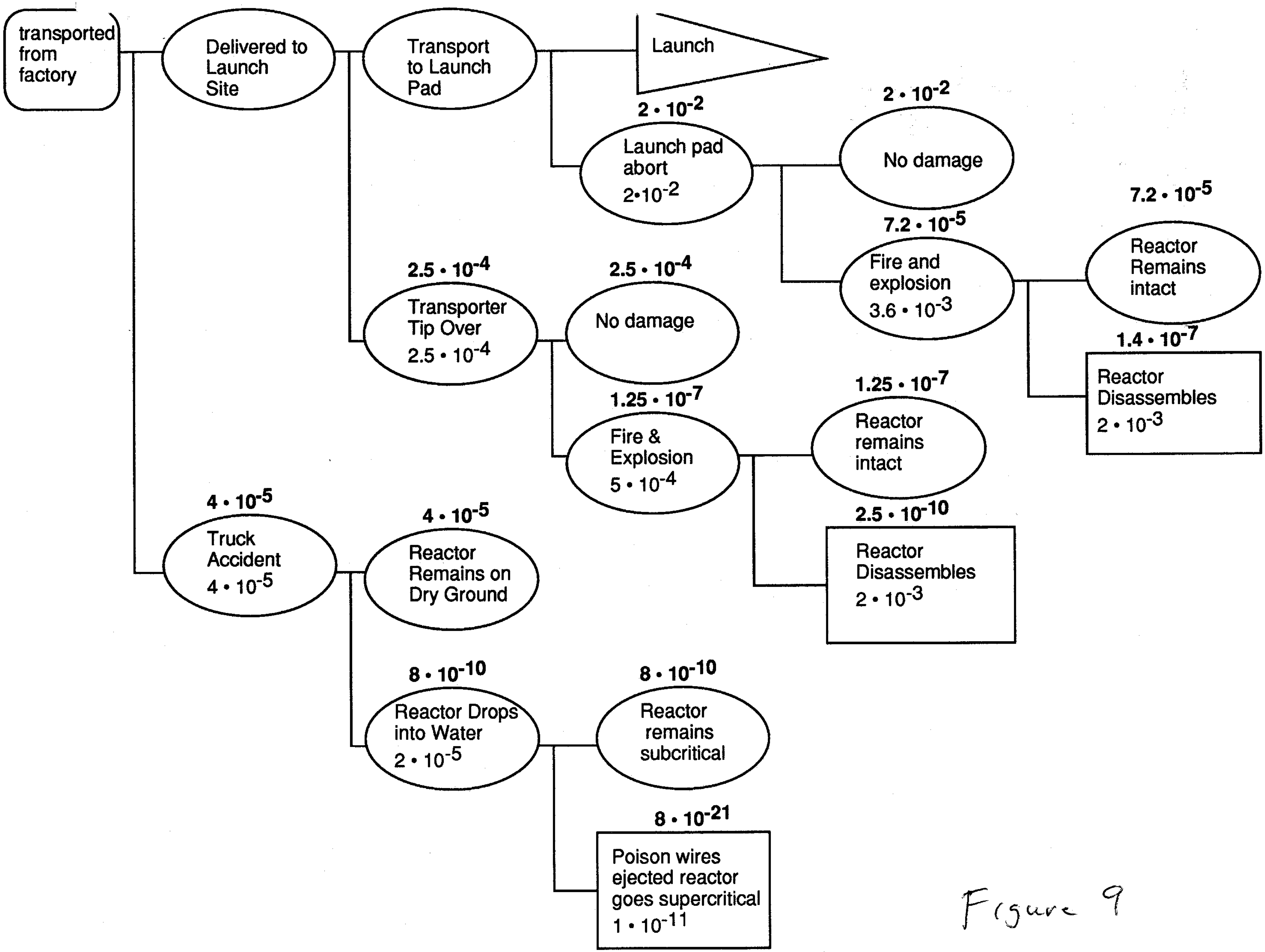
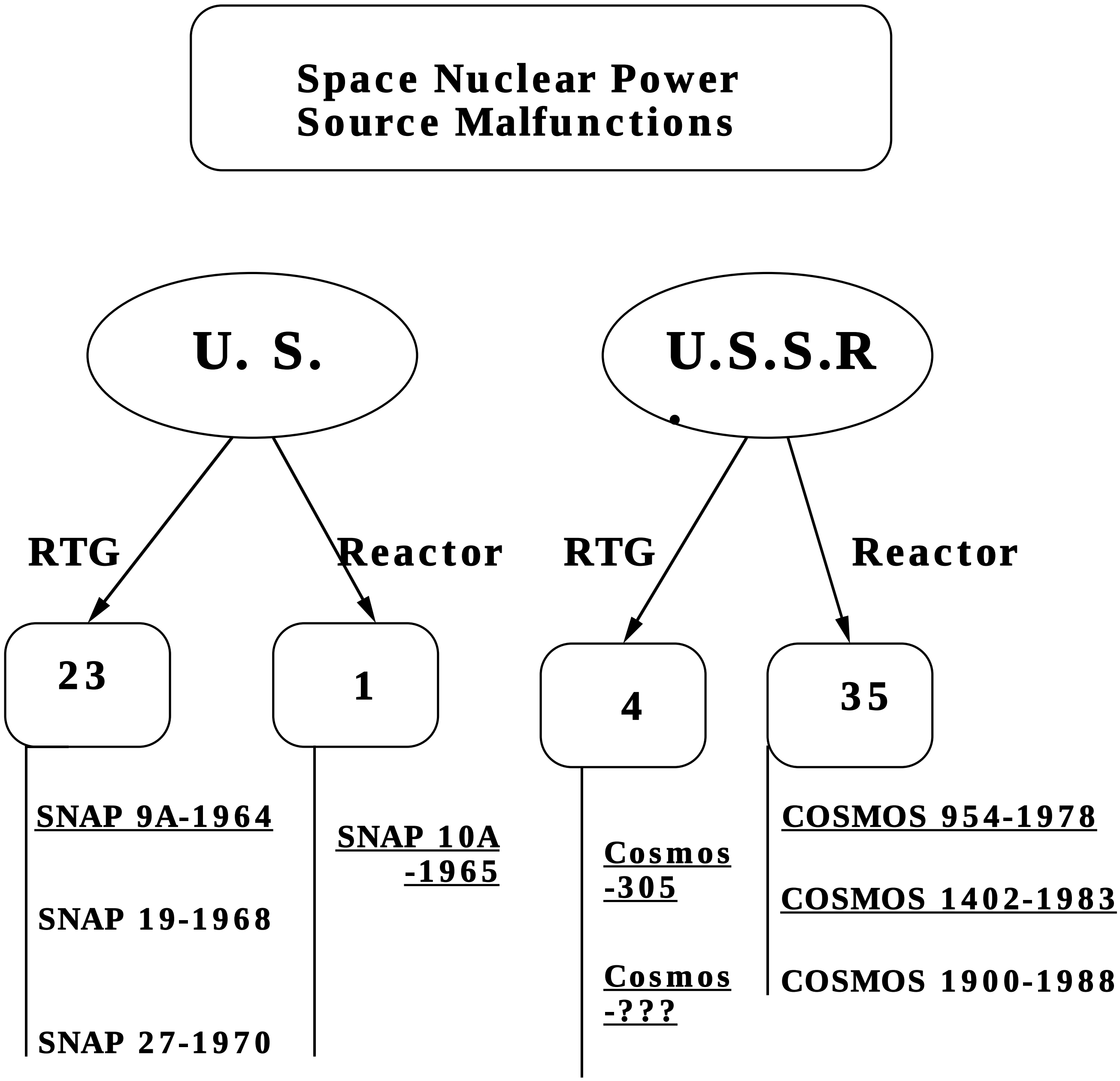

transported from factory
Delivered to Launch Site
Transport to Launch Pad
Launch
2 • 10-2
Launch pad abort
2•10-2
2 • 10-2
No damage
7.2 • 10-5
Fire and explosion
3.6 • 10-3
7.2 • 10-5
Reactor Remains intact
1.4 • 10-7
Reactor Disassembles
2 • 10-3
2.5 • 10-4
Transporter Tip Over
2.5 • 10-4
2.5 • 10-4
No damage
1.25 • 10-7
Fire & Explosion
5 • 10-4
1.25 • 10-7
Reactor remains intact
2.5 • 10-10
Reactor Disassembles
2 • 10-3
4 • 10-5
Truck Accident
4 • 10-5
4 • 10-5
Reactor Remains on Dry Ground
8 • 10-10
Reactor Drops into Water
2 • 10-5
8 • 10-10
Reactor remains subcritical
8 • 10-21
Poison wires ejected reactor goes supercritical
1 • 10-11

Figure 9



Space Nuclear Power
Source Malfunctions
U. S.
U.S.S.R.
RTG
Reactor
RTG
Reactor
23
1
4
35
SNAP 9A-1964
SNAP 19-1968
SNAP 27-1970
SNAP 10A
-1965
Cosmos
-305
Cosmos
-???
COSMOS 954-1978
COSMOS 1402-1983
COSMOS 1900-1988

U. S. Navigational Satellite, TRANSIT 5BN-3 (SNAP-9A) 1964

==

- **Launched April 21, 1964**

- **17,000 Ci, Pu-38 metal**

- **Failed to Achieve Orbit**

- **Reentered at 120 km altitude and burned up (as designed) over the West Indian Ocean, North of Madagascar**

- **Aug-1964, U.S. balloon detected Pu-38 in stratosphere (32 km) in southern hemisphere.**

- **May 1965, Radioactive dust detected in Northern Hemisphere at aircraft altitudes. There was 4 times more Pu-38 in the Southern Hemisphere as compared to the Northern Hemisphere**

- **Nov 1970- Only 5% of the original Pu-38 left in the atmosphere (removal half life ≈ 14 months). Radioactivity detected on all continents and at all latitudes.**

- **Amount of Pu-39 from nuclear atmospheric tests is 180,000 Ci.**

- **Amount of Pu-38 from nuclear atmospheric tests is 8,000 Ci. (≈ half that of the (SNAP -9A)**

See Table of RTGs still in Orbit

NIMBUS B-1 (SNAP-19) 1961

- **Launched May 18, 1968 from Vanderberg, CA**
- **34,000 Ci of Pu-38 in form of oxide**
- **Destroyed by Range Safety Officer at altitude of 30 km**
- **Fell into Santa Barbera Channel off the coast of CA**
- **Recovered from 100 m depth, intact, no leakage, reused fuel**

Apollo 13 (SNAP-27) 1970

- **Launched April 11, 1970, to the Moon**
- **44,500 Ci Pu-38-oxide microspheres**
- **Oxygen tank explosion, had to come back to Earth**
- **Purposely jettisoned the RTG over the South Pacific Ocean**
- **No radioactivity detected**
- **Now resides in 6000 m of water, TONGA trench**

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See 4 Curves on Radioactivity

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Table on potential radioisotopes to come back

Cosmos 954(Nuclear reactor) 1978

- Launched Sept. 18, 1977
- RORSAT- Marine radar
- 100 kW thermal power, ≈ 10 kW electric power
- Reactor designed to separate the core from the satellite, boost core into higher orbit (had worked 13 times earlier). However, did not work this time.
- Jan 24, 1978, reentered over the Pacific Ocean
- Glowing object detected by telescope in Hawaii,
- Continued for 12 minutes and 5500 km before impacting over Canada
- USSR said it was designed to burn up, but several glowing objects were observed over Canada.
- Operation "Morning Light" conducted in -40°C weather.
- Radioactivity spread out over 600 km path from Great Slave Lake to Baker Lake-124,000 km^2
- >50 radioactive objects (steel plates, Be cylinders, Be rods) ranged from 0.6 to 200 Rad/hr
- Total weight = 65 kg (initial mass ≈ several tonnes)
- Some spent fuel recovered
- Some enriched U35 detected in atmosphere

Cosmos 1402 (Nuclear Reactor) 1983

- Launched August 30, 1982

- Jan 1983, some info showed a malfunction, satellite intentionally split into 3 parts; A, B, and C.

- Part B (probably radar antenna) entered atmosphere on Dec. 30, 1982

- Part A fell into the Indian Ocean, Jan 23, 1983

- Part C (probably the reactor)entered Feb 7, 1983, fell into the ocean 1,600 km east of Brazil

- If the part had entered 20 minutes earlier, it would have impacted over central Europe

Cosmos 1900 (Nuclear Reactor) 1988

- USSR reported May 13,1988, that it has lost contact in April 1988 and could not send reactor into a higher orbit.

- Probably the same as COSMOS 954

- 37 cyl. fuel rods with Be rods
- 6 Be cylinders (3.6 kg) each

- On Sept. 30, 1988, Nuclear Power Unit separated and sent to 720 km orbit

- Rest came in over Indian Ocean

Final Environmental Impact Statement for Galileo

- **Development of the Galileo Mission started in October, 1977**

- **Launched in October, 1989**
  (if not launched then, next window is May, 1991)

Important feature of the Galileo, Mission is the use of gravity assists;
Venus -Earth -Earth -Gravity Assist (VEEGA)

Radioactive Components

*** Two RTG's (284 Watts each, 568 Watts total),**

- **120 Radioisotope Heater Units (RHU's) , ≈ 1 Watt each and 2.7 g Pu -238 each- (131 units used in calculations)**

--

Composition of RTG and RHU Fuel

			RTG		RHU	
Pu Isot.	Half-Life-Y	Ci/g Pu	wt %	Tot Ci	wt %	Tot Ci
236	2.85	532	$< 10^{-6}$	<1	<10-6	<1
238	87.7	17.1	83.88	130,050	82.47	3990
239	24,100	0.062	13.49	80.2	14.8	2.6
240	6560	0.227	1.9	41.3	2.1	1.35
241	14.4	103.2	0.379	2650	0.29	84.8
242	376,000	0.0039	0.124	<1	0.14	<1
other TRU	---	----	0.228	3.3	0.2	1.90
Total			100	132,825	100	4801

Worldwide Pu Levels

- 2 main contributors - above ground testing and the 1964 launch accident

Source	Amount (Ci)	% by Isotope 238	239	240
Atm Test(45-74)				
• Dep. Near Test Site	110,000	3	58	38
• Dep. World -Wide	330,000	3	58	39
SNAP- 9A, 1964	17,000	100		
Total		457,000		
Total Outside Test Site	347,000			

Note : 440,000 Ci ≈ 4-5 tonnes of Pu

17,000 Ci of Pu-238 ≈ 1 kg Pu -238