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Received by USU

MAY 10 1989

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-16

LA-UR--89-1178

DE89 011192

TITLE SAFETY TESTING PROGRAM FOR THE GALILEO MISSION  
RADIOISOTOPE THERMOELECTRIC GENERATOR

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SUBMITTED TO 9th International System Safety Conference

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SAFETY TESTING PROGRAM FOR THE GALILEO MISSION  
RADIOISOTOPE THERMOELECTRIC GENERATOR

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I. INTRODUCTION

Radioisotope Thermoelectric Generators (RTGs) are devices that convert the heat created by the natural decay of a radioisotope directly into usable electric power. Because they are rugged, light weight, and compact, and because they contain no moving parts and do not depend on the sun for power, the National Aeronautics and Space Administration (NASA) decided to use RTGs to power scientific instrumentation and communication devices aboard interplanetary spacecraft. These power units are called upon to perform reliably for multiyear missions into deep space where the incident sunlight is negligible.<sup>1</sup> RTGs were used for the Apollo Lunar Surface experiments, the Viking Mars Lander, and the Pioneer and Voyager probes to Jupiter and Saturn. A history of RTGs in space is shown in Table 1.

As the space program evolved, so did the design of the RTGs. Table 2 lists the RTGs that have been used in the past and the RTG that will be used to power the NASA Galileo mission to Jupiter.<sup>2</sup> Each RTG is comprised of two major components; a heat source that provides thermal energy from the alpha decay of  $^{238}\text{Pu}$ , and a thermoelectric converter which converts the thermal energy into electric power. The heat source for the Galileo RTG is a modular unit called the General-Purpose Heat Source (GPIS). There are 18 GPIS modules in each GPIS-RTG. Each module contains about 7344 Ci of  $^{238}\text{Pu}$  (600 g  $^{238}\text{PuO}_2$ ) and generates about 250 watts of thermal energy ( $W_t$ ). The total thermal energy of each GPIS-RTG (4410  $W_t$ ) results in about 285 watts of electrical energy ( $W_e$ ) at the beginning of mission. Two GPIS-RTGs are

required to power the Galileo spacecraft.

## II. DESIGN

The major design requirement for any space nuclear power system is to minimize the potential for interaction of the radioactive materials with Earth's population and environment.<sup>3</sup> All previous space power systems were launched on expendable launch vehicles (ELVs), so the design emphasis for the GPHS was on surviving the most severe ELV accident environments (launch pad explosion and solid propellant fire) and on surviving accident environments resulting from spacecraft failure (reentry and land impact).

To protect it from the ablation, thermal shock, and thermal response of reentry, the GPHS (Figure 1) has a Fine-Weave Pierced Fabric\* (FWPF) graphite composite aeroshell. Within the aeroshell are two FWPF graphite impact shells (GISs) to provide impact protection, each of which is inserted in a carbon-bonded, carbon fiber (CBCF) sleeve for additional thermal insulation. There are two  $^{238}\text{PuO}_2$  pellets in each GIS encapsulated in high-temperature iridium-alloy shells designed to contain the fuel after accidental impact. The oxide form of the fuel was chosen to overcome incompatibilities associated with earlier RTG fuel forms.<sup>4</sup> Each capsule contains a fritted vent that allows the helium gas, that is generated during the decay of  $^{238}\text{Pu}$ , to escape without releasing any of the  $^{238}\text{PuO}_2$ .

The thermoelectric converter (Figure 2) is approximately 114 cm (45 in) long and 42 cm (16.5 in) in diameter. It includes an outer aluminum case, which serves as the main support structure

\*Fineweave Pierced Fabric - 3-D graphite composite, a product of AVCO Systems Division, 201 Lowell St., Wilmington, MA 01897.

for the thermoelements and the heat source stack; axial and midspan heat source supports; 572 silicon-germanium thermoelectric couples; and multifoil insulation. The thermoelectric couples are supported in a cantilever fashion from the outer case, and the couples in turn partially support the insulation packet.

### III. TESTING

Prior to flight production, the GPHS design was subjected to a series of engineering experiments that simulated the potential environments originating from an EIV failure. When the decision was made to use the GPHS-RTG for the shuttle-launched Galileo mission, the response of the GPHS-RTG to potential shuttle accident environments had to be analyzed. NASA provided a document, called the Shuttle Data Book, which included basic descriptions of the space shuttle, mission summaries, and possible failure scenarios, as background information for the safety analysis of the GPHS-RTG.<sup>5</sup> The RTG contractor, the General Electric Company (GE), was required by the Department of Energy (DOE) to prepare a safety analysis report (SAR) for the GPHS-RTG, and a safety test program was developed, supplemented by a safety analysis program, to provide data for the SAR. Since the test program was limited by time and resources, the analysis program encompassed the broad range of postulated accident environments that could not be tested.

#### A. INITIAL TEST PROGRAM

Prior to the scheduled May 1986 launch of Galileo, many tests were conducted on the GPHS-RTG to assess the ability of the GPHS modules to contain the plutonia in potential accident environments. At that time, a liquid-fueled Centaur rocket was to be the spacecraft propulsion unit and would have been transported with the spacecraft in the cargo bay of the space shuttle orbiter. A launch explosion, fueled by the space shuttle

and Centaur propellants, could have exposed the GPHS-RTG to high overpressures and to a field of high-velocity space shuttle fragments. The following accident environments were derived from the Shuttle Data Book:

Prelaunch, Launch, and Ascent Phases:

- Explosion overpressure
- Projectile and fragment collision
- Land or water impact
- Liquid propellant fire
- Solid propellant fire
- Sequential combinations of the above

Orbit and/or Flight Trajectory Phases:

- Reentry
- Land or water impact
- Postimpact environment (land or water)

Some of the tests that were conducted to determine the response of the GPHS-RTG to these environments were (1) explosion overpressure tests, (2) fragment tests, (3) solid propellant fire tests, and (4) bare clad impact tests. The results of these tests are discussed below. Where it was not possible to provide complete containment for plutonia-fueled heat sources, a simulant fueled (depleted  $^{238}\text{UO}_2$ ) heat source was tested.

#### 1. Explosion Overpressure Tests

Nine explosion tests were conducted at Sandia National Laboratories - Albuquerque (Sandia), in a 2-ft-diameter shock tube, to determine the effect of explosive overpressure on the GPHS-RTG.<sup>6</sup> At the highest overpressure tested, 2212 psi, the capsules did not release any fuel when exposed to the explosive overpressure alone. However, the tests showed that the graphite is completely stripped from the capsules at overpressures greater than about 500 psi, leaving the bare capsules vulnerable to subsequent collisions with explosive-generated space shuttle fragments or to impact with hard Earth surfaces.

## 2. Fragment Tests

Several fragment tests were also conducted to simulate the collision of explosive-generated space shuttle fragments with GPHS components. In one test series, 3.5-mm-thick space shuttle alloy plate fragments were explosively propelled flat-on into bare capsules at velocities up to 1170 m/s.<sup>7</sup> Capsule breaches and fuel releases were minimal. In another series of tests, the flyer plate fragments were propelled edge-on.<sup>8</sup> One fragment struck a GPHS module at 918 m/s causing a total fuel release. A bare capsule was impacted in a separate test at 142 m/s, releasing about 25 percent of its fuel.

A series of bullet-type fragment tests at Los Alamos indicated that an 18-g (.50 caliber) aluminum-alloy bullet fragment would have to impact a GPHS module at about 555 m/s to initiate a capsule breach.<sup>9</sup> A 3.25-g (.30 caliber) titanium bullet fragment, representing a titanium bolt used in the spacecraft mounting ring, would have to impact a bare capsule at about 425 m/s to initiate mechanical failure of the cladding.<sup>10</sup>

## 3. Solid Propellant Fire Tests

Because solid propellant fires are more severe than liquid propellant fires, a GPHS impact assembly (GIS) and a bare capsule were exposed in separate tests to a 10.5 minute single proximity solid propellant fire. Damage was minimal in both cases and no fuel was released.

## 4. Bare Clad Impact Tests

To determine the response of bare capsules to impacts on different surfaces (steel, concrete, granite, and sand) at different velocities, we conducted a series of bare clad impact tests in a gas-gun at Los Alamos. Fueled clads that were impacted at 53 m/s against Kennedy Space Center concrete did not breach. However, clads impacted at 53 m/s against hardened steel

released a small amount of fuel. Impacts on sand at up to 250 m/s did not result in clad breaches.

#### B. EXTENDED SERIES SAFETY TEST PROGRAM

As a result of the Challenger 51-L accident in January 1986, the launch of Galileo was postponed, the liquid-fueled Centaur was replaced with a solid propellant inertial upper stage (IUS), and the spacecraft trajectory was modified. The changes prompted a reevaluation of mission accidents<sup>11</sup> and the initiation of an extended series safety test program.

The replacement of the liquid-fueled Centaur resulted in significantly less severe explosion environments at the GPHS-RTG location. However, the trajectory modification resulted in a more severe reentry attitude for the GPHS-RTG. The primary concerns in the extended series test program were (1) the interaction of the GPHS-RTG with large, heavy-walled solid rocket booster (SRB) fragments, such as would be generated in a SRB motor case rupture, and (2) the inadvertent reentry of the spacecraft during the modified trajectory.

Before evaluating the interaction of SRB fragments with the GPHS-RTG, the velocity and orientation of the fragments, when they reach the GPHS-RTG location, must be known. A series of tests was conducted to evaluate the interaction of SRB fragments with orbiter structural components.<sup>12</sup> The results showed that fragment velocity decreased significantly (up to 40 percent) after penetration of the orbiter section(s). The original fragment rotational rate and direction were also reduced and, in some cases, eliminated by the interactions, and rotations in other directions were usually initiated.

A series of large fragment tests was conducted to determine the response of the GPHS-RTG to the large fragment environment.

Four tests, conducted in the Los Alamos gas gun at velocities up to 120 m/s, demonstrated that no fuel release resulted. A 1.4-m-square (56-in-square) SiB fragment was propelled on a rocket sled (at Sandia) flat-on into a half-length GPHS-RTG at velocities up to 212 m/s. No fuel release resulted from the impact. In an edge-on impact at 95 m/s, only the forward fueled clads were breached.<sup>13</sup>

#### IV. ANALYSES

Three SARs, a preliminary SAR (PSAR), an updated SAR (USAR), and a final SAR (FSAR), were issued during the development, fabrication, and initial testing of the GPHS-RTG.<sup>14</sup> An updated FSAR was issued after completion of the extended series test program. The SARs contain failure sequence trees (FASTs) for each mission phase which include information on the postulated accidents for that phase, the probabilities of those accidents, and the response of the GPHS-RTG to those accidents. The top level FAST for phase 1, the ascent phase, is shown in Figure 3. The SARs are used by the Interagency Nuclear Safety Review Panel (INSRP) to make an independent evaluation of the risk of the mission. The review process for each mission containing a RTG is shown in Figure 4.

#### V. CONCLUSION

Approximately ten years of safety testing, analysis, and review were involved in the safety verification program of the GPHS-RTG, making it the most extensive program ever conducted for a RTG. The first use of the GPHS-RTG will be to power the Galileo spacecraft, currently scheduled for a shuttle launch in October 1989.

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Table 1. History of RTGs in Space

Power Source	Sponsoring Agency and Spacecraft	Mission Type	Launch Date	Outcome
SNAP-3A	Navy-Transit 4A	Navigational	June 29, 1961	Successfully achieved orbit
SNAP-3A	Navy-Transit 4B	Navigational	Nov. 15, 1961	Successfully achieved orbit
SNAP-9A	Navy-Transit-5BN-1	Navigational	Sept. 28, 1963	Successfully achieved orbit
SNAP-9A	Navy-Transit-5BN-2	Navigational	Dec. 5, 1963	Successfully achieved orbit
SNAP-9A	Navy-Transit-5BN-3	Navigational	April 21, 1964	Mission aborted; burned up on reentry
SNAP-19B2	NASA-Nimbus-B-1	Meteorological	May 18, 1968	Mission aborted; heat source retrieved
SNAP-19B3	NASA-Nimbus-III	Meteorological	April 14, 1969	Successfully achieved orbit
SNAP-27	NASA-Apollo 12	Lunar	Nov. 14, 1969	Successfully placed on lunar surface
SNAP-27	NASA-Apollo 13	Lunar	April 11, 1970	Mission aborted on way to moon; heat source returned to South Pacific Ocean
SNAP-27	NASA-Apollo 14	Lunar	Jan. 31, 1971	Successfully placed on lunar surface
SNAP-27	NASA-Apollo 15	Lunar	July 26, 1971	Successfully placed on lunar surface
SNAP-19	NASA-Pioneer 10	Planetary	Mar. 2, 1972	Successfully operated to Jupiter and beyond
SNAP-27	NASA-Apollo 16	Lunar	April 16, 1972	Successfully placed on lunar surface
Transit-RTG	Navy-"Transit" (TRIAD-01-1X)	Navigational	Sept. 2, 1972	Successfully achieved orbit
SNAP-27	NASA-Apollo 17	Lunar	Dec. 7, 1972	Successfully placed on lunar surface
SNAP-19	NASA-Pioneer 11	Planetary	April 5, 1973	Successfully operated to Jupiter, Saturn, and beyond
SNAP-19	NASA-Viking 1	Mars	Aug. 20, 1975	Successfully landed on Mars
SNAP-19	NASA-Viking 2	Mars	Sept. 9, 1975	Successfully landed on Mars
MHW	AF-LES 8	Communications	Mar. 14, 1976	Successfully achieved orbit
MHW	AF-LES 9	Communications	Mar. 14, 1976	Successfully achieved orbit
MHW	NASA-Voyager 2	Planetary	Aug. 20, 1977	Successfully operated to Jupiter, Saturn, and beyond
MHW	NASA-Voyager 1	Planetary	Sept. 5, 1977	Successfully operated to Jupiter, Saturn, and beyond

Table 2. History of RTG Development

Parameters	SNAP-3B	SNAP-9A	SNAP-19	SNAP-27	TRANSIT-RTG	MHW-RTG	GPHS-RTG
MISSION	TRANSIT 4	TRANSIT-5BN	PIIONEER	APOLLO	TRIAD	VOYAGER	GALILEO
BCM <sup>a</sup> POWER PER RTG, W/E <sup>1</sup>	2.7	26.8	40.3	73.4	35.6	158.0	292.0
THERMOELECTRIC MATERIAL	PbTe 2N/2P	PbTe 2N/2P	PbTe 2N/TAGS-8	PbTe 3N/3P	PbTe 2N/3P	SiGe	SiGe
Pu-238 FUEL FORM	METAL	METAL	PMC <sup>b</sup>	OXIDE MI-CROSPHERES	PMC <sup>b</sup>	PRESSED OXIDE	PRESSED OXIDE
CONVERSION EFFICIENCY, %	5.1	5.1	6.2	5.0	4.2	6.6	6.6
SPECIFIC POWER, W/E) KG	1.29	2.2	3.0	2.3 <sup>c</sup>	2.6	4.2	5.2

<sup>a</sup> Beginning-of-Mission

<sup>b</sup> Plutonia Molybdenum Cermet (Cermet: a heat-resistant alloy formed by compacting and sintering a metal and a ceramic substance).

<sup>c</sup> The SNAP-27 Specific Power is calculated with the mass of the fuel cask included.

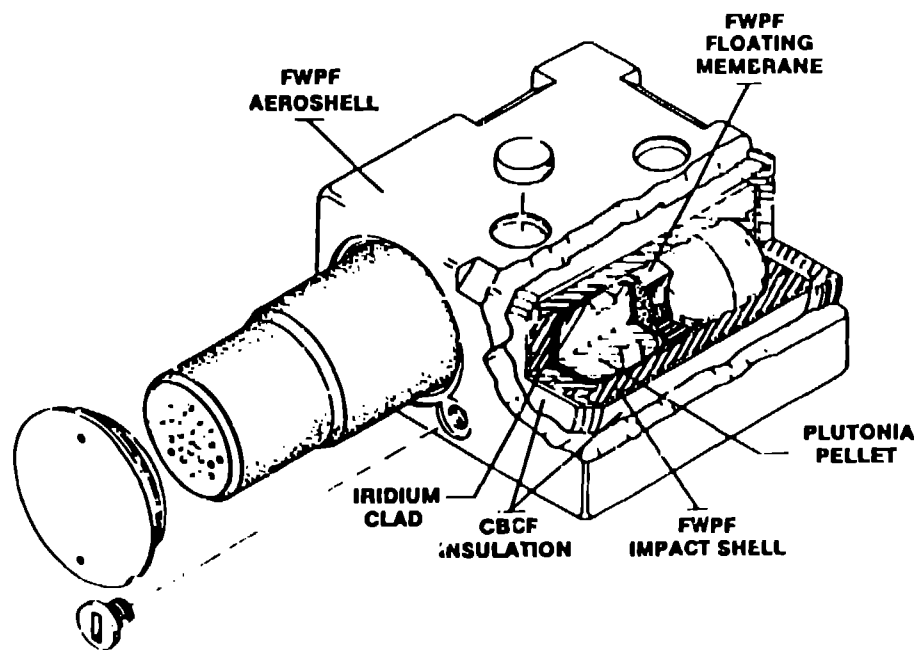


Figure 1. The General-Purpose Heat Source (GPHS).

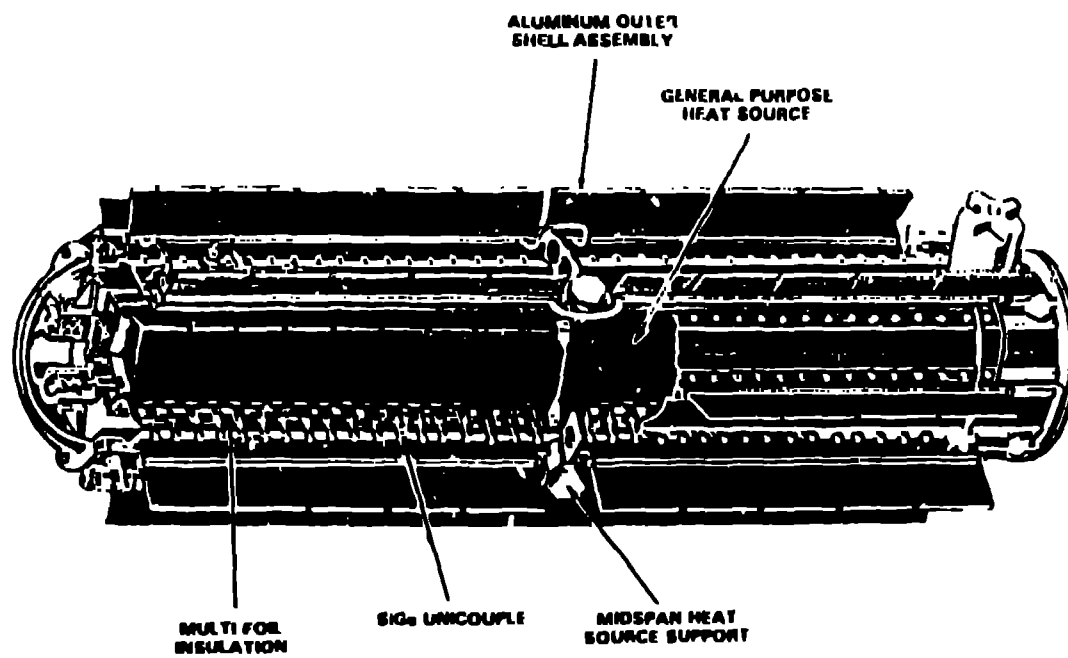


Figure 2. The General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG).

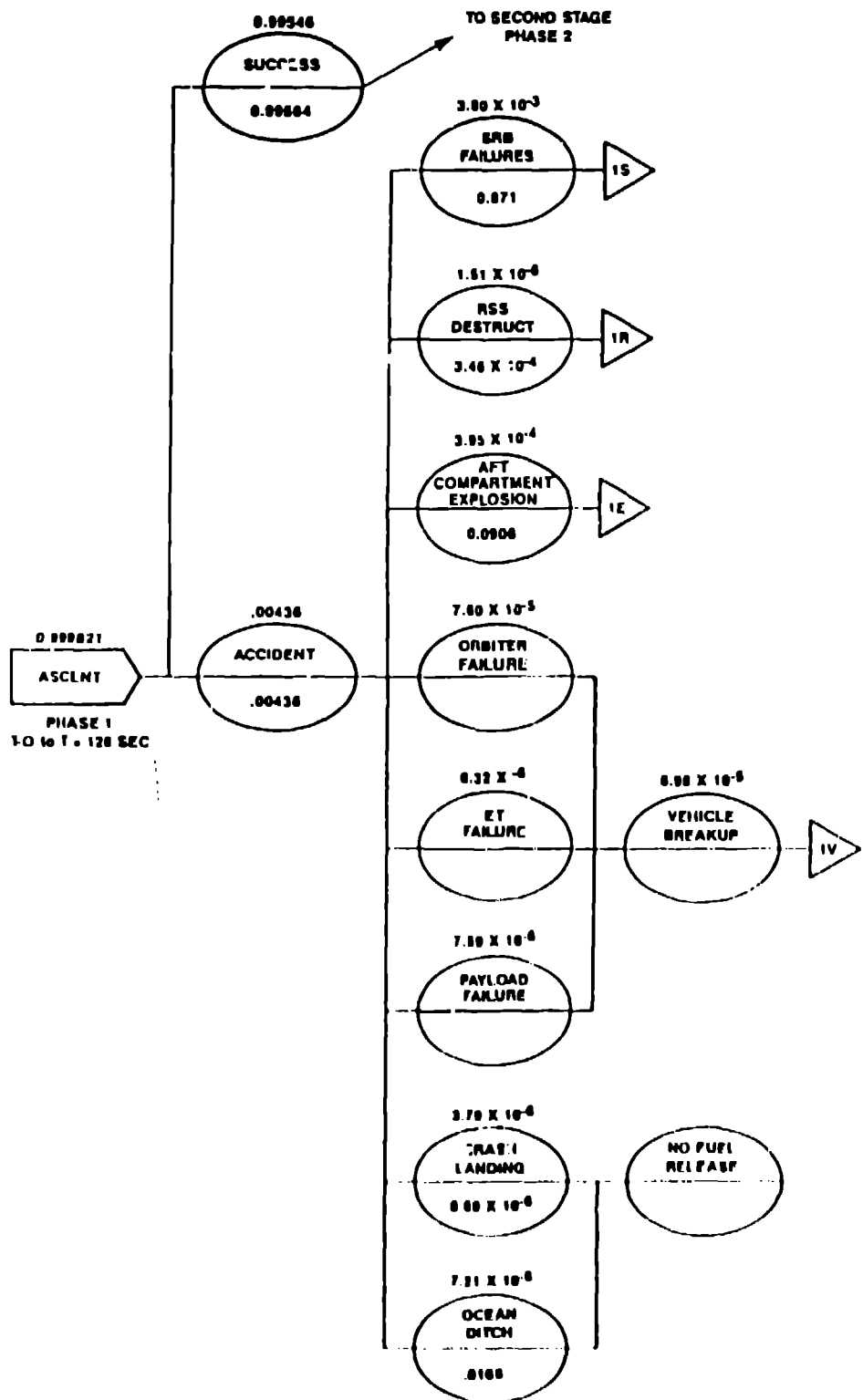


Figure 3. Top Level Failure Sequence Tree (FAT) for phase 1 (Ascent Phase).

# Radioisotope Thermoelectric Generator Review Process

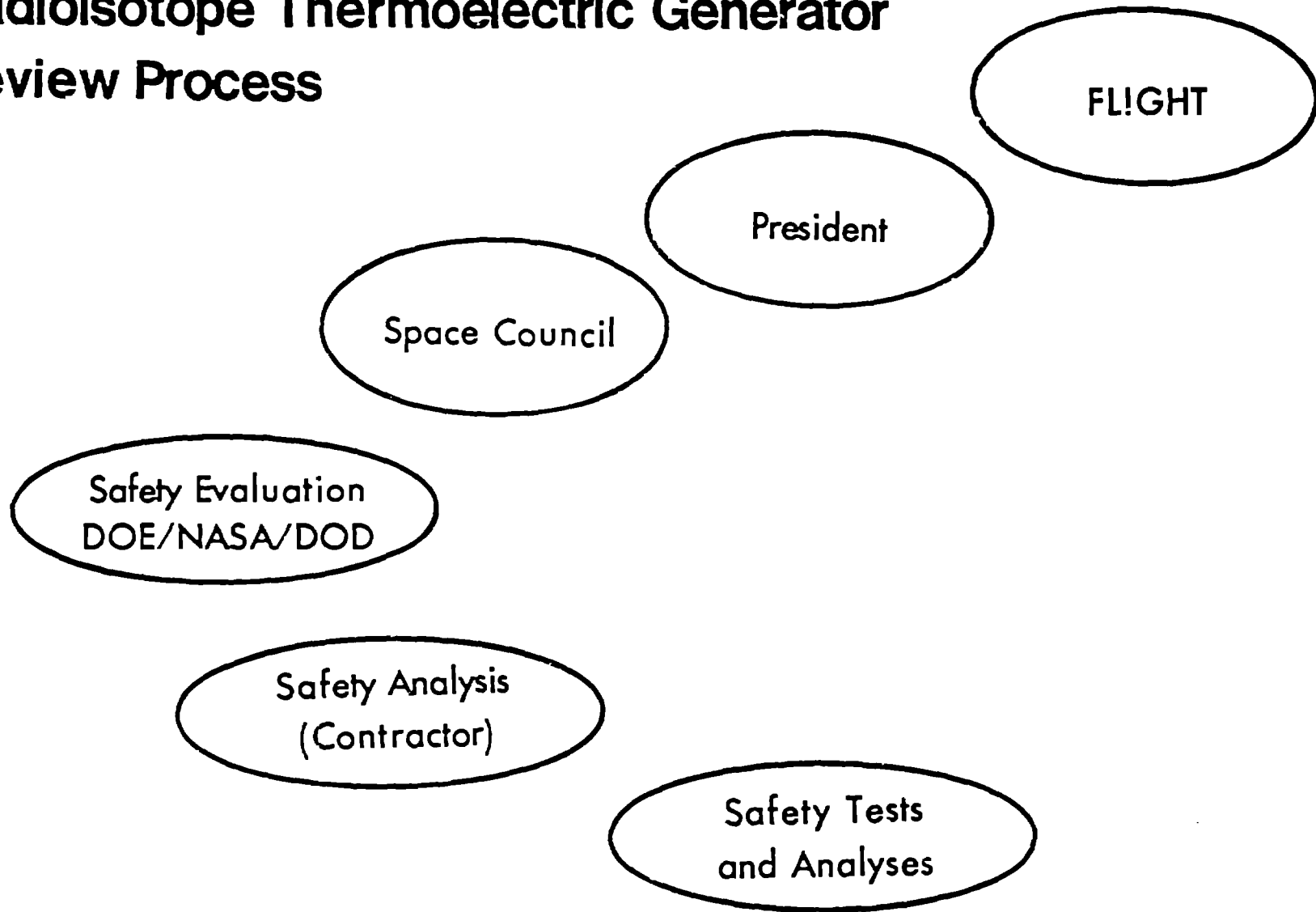


Figure 4. Review process for space missions containing a RTG.