Aerospace Nuclear Safety at APL: 1997–2006

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NASA's Galileo, Cassini, Mars Exploration Rovers Spirit and Opportunity, and New Horizons spacecraft have returned spectacular planetary scientific findings, including tantalizing evidence of conditions that might support life on Europa, Mars, and Enceladus. These missions were all enabled by space nuclear power. Preparation for NASA missions carrying nuclear material must consider the possibilities of launch accidents and the subsequent disposition of the nuclear fuel regionally and worldwide. The formal safety effort centers on compliance with the National Environmental Policy Act and Presidential launch approval processes. These processes are rooted in sound management, engineering, physics, and public safety principles, requiring significant analytical, experimental, and scientific studies. APL has contributed to the aerospace nuclear safety of these and past missions for more than 35 years. This article describes highlights of APL's contributions to the government's aerospace nuclear safety activities associated with NASA's nuclear launches from 1996 to 2006.

BACKGROUND

The United States has successfully flown 24 spacecraft powered by 41 radioisotope thermoelectric generators (RTGs) and one reactor since 1961. The first RTG was flown on the Navy Transit 4A navigation satellite, launched on 29 June 1961, and the most recent RTG was flown on the NASA New Horizons probe to Pluto, launched on 19 January 2006. Other recent spacecraft with RTGs were NASA's Cassini mission to Saturn (1997 launch), the Ulysses mission to Jupiter and the Sun (1990 launch), and the Galileo mission to Jupiter (1989 launch).

The rationale for using nuclear power on spacecraft is simple: to provide electrical power and heat for operation of the scientific instruments where the insolation from the Sun is weak, the interplanetary radiation is severe, the temperatures are low, and long life (reaching to decades) and reliability are required. All of these conditions exist for scientific missions to the solar system's outer planets and beyond. The capability to provide electrical power in these conditions is supplied by the RTG. The type of RTG used for the New Horizons, Cassini, Ulysses, and Galileo missions is called the General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG). Each GPHS-RTG carries about 10.9 kg (24 lb) of plutonium in 18 GPHS modules, with about 130,000 curies (Ci) of radioactivity. RTGs for NASA space missions are supplied by the Department of Energy (DoE). The New Horizons Atlas V 551 launch vehicle (including the Centaur second stage and the STAR 48B third stage), spacecraft, RTG, and GPHS modules are shown in Fig. 1.

An RTG converts the heat from the radioactive decay of its nuclear fuel to electricity by thermoelectric unicouples using the Seebeck effect. The nuclear fuel chosen for the RTGs is plutonium dioxide (PuO_2) in a ceramic form, consisting mostly of plutonium 238 (Pu-238), which is a nonweapons grade of plutonium. Many safety features are designed into the RTG, including impact resistance, thermal resistance, and multiple layers of protection. Details on safety design features and operation and construction of the RTG can be found in Refs. 1 and 2, respectively. An overview of nuclear safety review processes is given in the boxed insert.

NEW HORIZONS NUCLEAR SAFETY

APL is the mission and spacecraft manager of the NASA New Horizons mission to the Pluto-Charon planetary system and the Kuiper Belt objects beyond. This presented a prime opportunity for the Laboratory to make contributions on a total mission basis, including the area of nuclear safety.

New Horizons is a mission that literally depends on the planets' proper alignment. Pluto's eccentric orbit around the Sun takes 248 years, with its most recent perihelion in 1989. Its atmosphere is expected to be active until it freezes around 2020, as its orbit carries it farther from the Sun. The window of opportunity to study Pluto's atmosphere up close by a space probe starts to close around 2020. But sending a space probe to Pluto via a direct trajectory takes over a decade as it is more than 4.3 billion kilometers (2.7 billion miles) from Earth. A Jupiter gravity assist (JGA) flyby could increase the probe's speed and shorten its travel time by 3 years, but JGAs were available only for launches in 2004, 2006, and 2018. During mission planning in 2001, a 2004 launch was considered to be too soon for various programmatic reasons, and one in 2018 was obviously too late. A launch in 2007 would fly a direct trajectory without a JGA, but then the Pluto encounter would not occur until 2019 or 2020.

As a result, the New Horizons team targeted the January 2006 launch opportunity. This included completing National Environmental Policy Act (NEPA) compliance and obtaining Presidential launch approval by then. The author wrote a plan for NEPA/launch approval in the

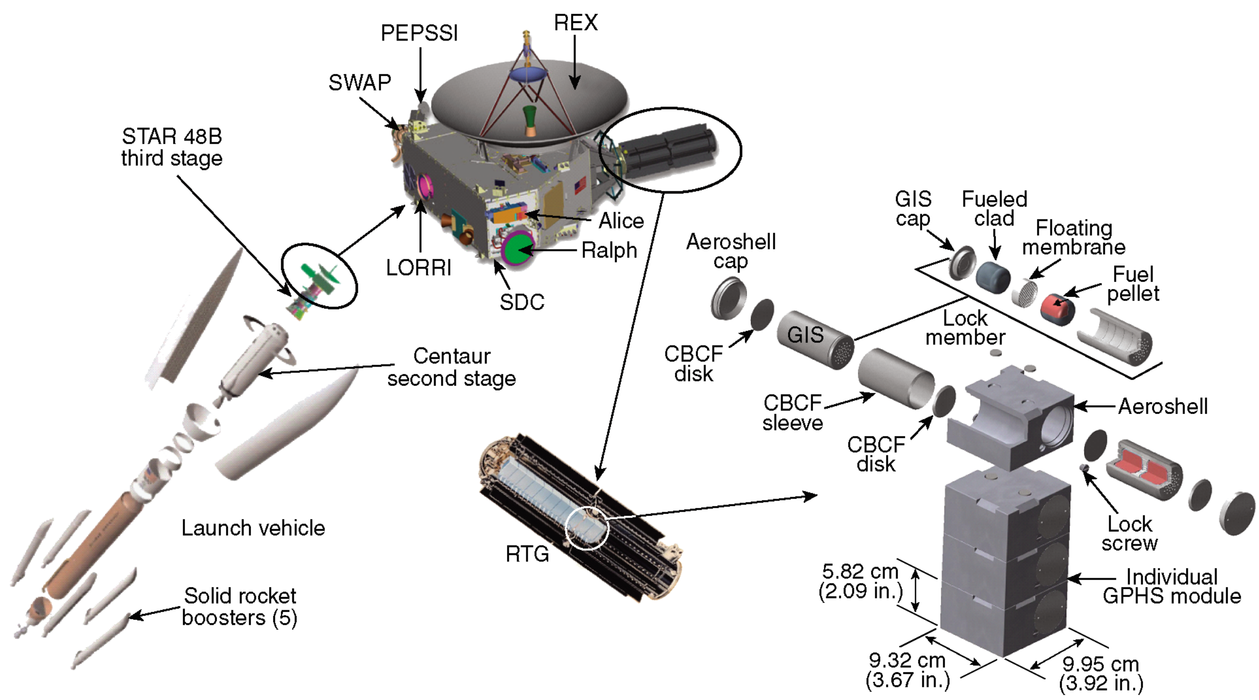


Figure 1. New Horizons Atlas V 551 launch vehicle, spacecraft, RTG, and GPHS modules. There are 4 fuel pellets per GPHS module and 18 GPHS modules in the RTG, for a total of 72 fuel pellets. The launch vehicle measures 59.7 m (196 ft) and its gross liftoff weight is 573,160 kg (1,263,600 lb). (Alice = the New Horizons UV mapping spectrometer; CBCF = carbon-bonded carbon fiber; GIS = graphite impact shell; LORRI = Long Range Reconnaissance Imager; PEPSSI = Pluto Energetic Particle Spectrometer Science Investigation; Ralph = a collection of detectors along with their common electronics, housing, etc.; REX = Radio Science Experiment; SDC = Student Dust Counter; SWAP = Solar Wind Around Pluto.)

NUCLEAR SAFETY REVIEWS

The United States requires that any proposed launch of a NASA spacecraft carrying appreciable amounts of radioactive material undergo two safety processes. The first is governed by the National Environmental Policy Act (NEPA) of 1969 and is known as "NEPA compliance." NEPA compliance requires production of an environmental impact statement (EIS). The second process is launch approval by the Executive Branch as directed by Presidential Directive/National Security Council Memorandum No. 25 (PD/NSC-25). Both of these safety procedures are collaborative efforts by NASA and DoE.

The purpose of NEPA compliance is to inform the public of any major government activity that has the potential to significantly affect the environment. Launch accidents of a NASA spacecraft carrying radioactive material, while of low probability, fall into this category. Major milestones for NEPA compliance are as follows:

1. NASA provides the mission's design information and potential accident conditions in an "EIS databook."
2. DoE uses the databook information to produce a nuclear risk assessment (NRA) for the EIS.
3. NASA incorporates the NRA and other safety and environmental information into a draft EIS for public distribution, review, and comments.
4. NASA produces a Final EIS (FEIS).
5. The NASA Associate Administrator for the Science Mission Directorate renders a Record of Decision (ROD) on whether to proceed with the mission based on the FEIS. (The FEIS and the ROD for the New Horizons mission can be found in Ref. 3).

The purpose of PD/NSC-25 is to establish the process for obtaining White House nuclear safety launch approval for any NASA spacecraft carrying more than specified levels of radioactive material; for Pu-238 the level is 5 Ci. Major milestones for launch approval are as follows:

1. NASA selects the launch vehicle.
2. NASA provides the mission's design information and potential accident conditions in a "Safety Analysis Report (SAR) databook." This information is usually refined and updated from that provided for the NEPA process.
3. DoE prepares a Preliminary SAR.
4. NASA produces Revision A of the SAR databook.
5. DoE uses the SAR databook as input to produce a Draft Final Safety Analysis Report (FSAR).
6. NASA and DoE conduct Radiological Contingency Planning.
7. DoE produces the FSAR.
8. An ad hoc Interagency Nuclear Safety Review Panel (INSRP), consisting of subject matter experts from the DoD, DoE, NASA, EPA, industry, and academia, reviews the SAR databook and the FSAR, and documents its findings in a Safety Evaluation Report (SER).
9. The SER is presented to the NASA Administrator, who uses it to verify the results of the DoE FSAR.
10. After reviewing the SER and the FSAR, and considering any other information such as Radiological Contingency Planning, the NASA Administrator, in consultation with the Secretary of Energy, the Secretary of Defense, and the EPA Adminstrator, determines whether to seek nuclear safety launch approval from the Office of Science and Technology Policy (OSTP) at the White House. If the NASA Administrator decides to seek launch approval, then the Director of OSTP can render the launch approval decision or refer the matter to the President.[1]

Past RTG launch approval processes have taken 4–8 years each.

2001 New Horizons Concept Study Report. This plan was presented at the mission's kickoff meeting at NASA Headquarters in January 2002. The plan was basically for APL to help manage, coordinate, and contribute to the major DoE and NASA milestones (see the boxed insert). Some APL contributions are described in the following sections.

Spacecraft Responses to Accident Conditions

In addition to providing the as-designed New Horizons spacecraft and third-stage descriptions for the Safety Analysis Report (SAR) databook, APL also provided assessments of the spacecraft responses to various accident conditions. These can be separated into accidents near the launch pad, accidents leading to spacecraft reentry from orbit or suborbit, and accidents leading to Earth escape into a heliocentric orbit.

The immediate response to a near-pad launch accident would most likely be automatic or commanded activation of the New Horizons launch vehicle's flight termination system (FTS), which consists of explosive destruct charges on all stages and boosters. The FTS is a safety feature meant to break up and disperse the launch vehicle's liquid and solid propellants, render the stages nonpropulsive, and prevent further errant flight. As a result of FTS activation, a number of outcomes could occur. Explosive overpressure from activation of the conical shaped charges (CSCs) of the STAR 48B breakup system (BUS), which is part of the FTS, would cause the main body of the spacecraft to break up and separate from the RTG attached to its pyramid-shaped mounting fixture. The RTG would then fall back ballistically to the ground. APL calculated the probabilities of ground impact conditions (orientation and impact velocity) of the RTG attached to its mounting fixture.[4] These results were used in the New Horizons Final SAR (FSAR) sensitivity analysis and cited by the Interagency Nuclear Safety Review Panel (INSRP) in the New Horizons Safety Evaluation Report (SER).

For near-pad launch accidents where the BUS does not activate but the remainder of the FTS does, the spacecraft connected to the third stage would fall back ballistically. APL calculated that the high gain antenna would separate from the spacecraft for failure altitudes starting above 1920 m (6300 ft). The probabilities of near-pad ground impact conditions (orientation and impact velocity) of the spacecraft and third stage as a function of time of accident were reported in the SAR databook. The FSAR used these impact conditions in determining the responses of the RTG upon hitting the ground.

If the spacecraft attains park orbit, but an accident prevents it from escaping orbit, then the spacecraft's orbit will decay because of atmospheric drag and it will reenter within days. For reentry breakup from orbital decay, APL calculations showed that the RTG and spacecraft would break up and separate from the CSCs before the CSCs' thermally induced auto-ignition. Reentry breakup analyses of the spacecraft and RTG were also conducted for the launch contingency effort[5] and are described later in this article.

If the spacecraft is injected into a heliocentric orbit following an accident, it could potentially impact Earth in the future. APL conducted a study on long-term Earth reentry probabilities, where "long term" is defined as 1000 years. Considering that the half-life of Pu-238 is 87.7 years, 1000 years translates into 11.4 half-lives, and the activity of the Pu-238 at the end of 1000 years would be about 0.04% of its activity at the beginning. The results of the study showed that the probability of a long-term Earth reentry, once the spacecraft was in heliocentric orbit, was on the order of 10^{-4}; this can be reduced by 3 orders of magnitude if a trajectory correction maneuver with a ΔV of 100 m/s is applied.[6] These probabilities of long-term reentry were used in the accident probabilities section of the New Horizons SAR databook.

CSC Testing

Two CSCs, each with 500 g of plastic explosive, are part of the New Horizons STAR 48B BUS, which in turn is part of the launch vehicle's FTS. In the event of an FTS activation, including a BUS activation as described in the last section, the CSCs could eject backside metal casing fragments toward the RTG at estimated velocities of around 3.0 km/s (1.9 mi/s). Thus CSC testing was initiated by NASA to determine if these fragments would have any harmful effects. APL participated in the CSC testing, which was conducted at China Lake, California.

The CSC test setup (Fig. 2a) followed an April 2004 APL-written test proposal, which also predicted that the CSC fragments would not be harmful to the RTG because of the oblique angles at which the fragments would impact the RTG housing. The test setup replicated the flight configuration, specifically the material, structural, and geometric arrangements of the two CSCs inside the bottom of the lower payload attach fitting (PAF) and the simulant packs for the RTG. Because of cyclical symmetry, four simulant packs can each represent the RTG location for each test firing. APL designed and fabricated the simulators for the PAFs, as well as the internal brackets for the CSCs and shields. Southwest Research Institute (SwRI) conducted independent CSC tests at their facility in San Antonio, Texas, which provided valuable insight in designing the China Lake tests. For the China Lake tests, SwRI also provided the design and fabrication of the boron carbide shields (Fig. 2b), which would be incorporated as third-stage flight hardware if the unmitigated CSC fragments turned out to be harmful.

There were three identical test firings without the shields at China Lake in November 2004, for a total of 12 RTG simulant test articles. These test results showed that the fragments generated by the detonation of the CSCs were unlikely to damage the graphitic material of the GPHS modules encasing the nuclear fuel of the RTG. Thus the proposed shields were not implemented on the flight hardware. These conclusions were reported in the New Horizons SAR databook and cited by the INSRP in the New Horizons SER.

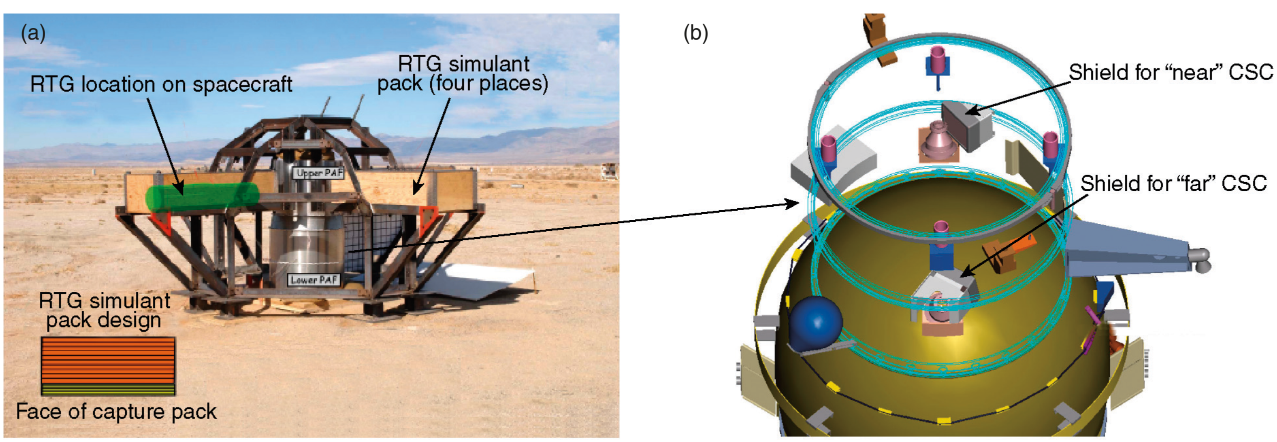


Figure 2. (a) CSC test setup at China Lake. The RTG simulant pack is constructed with a 2219 aluminum face sheet and 1.27-cm-thick (0.5-in.-thick) Celotex sheets. (Any Celotex damage was a criterion for adding shielding to the next test.) (Photo courtesy of NASA/JPL.) (b) CSC boron carbide shield configuration in the third-stage PAF.

SOLID PROPELLANT FIRE

The 17 January 1997 near-pad in-air explosion of the Delta II 241 rocket over Cape Canaveral reinforced the concept that a near-pad launch accident can result in solid rocket propellant burning in ambient atmospheric conditions on the ground, possibly near the RTG or RTG components. Characteristics of burning solid propellant are high temperature, long duration (up to several minutes), and persistence (does not dissipate). Earlier characterizations of solid propellant fires were of less energetic propellants (about 7000 kJ/kg) compared to the more energetic propellants (about 9300 kJ/kg) used in modern solid rocket propellant formulations.[7] Earlier tests characterized the environment above a propellant fragment burning only on its top surface. However, the at-risk hardware of the RTG most likely would be on the ground, underneath or adjacent to a propellant fragment burning on its top, bottom, and side surfaces. Thus there was a need to better characterize the nature of solid propellant fires.

To address this need, APL conducted a solid propellant fire-testing program in 1999–2001 using more than 25 individual burns with various geometries, burn configurations, and instrumentation. The test setup of a 91-kg (200-lb) cylinder of propellant is shown in Fig. 3a. The vertical rod attached to the top of the propellant test article allowed vertical movement but prevented lateral movement if the hot gasses emanating from the propellant underside were forceful enough for the block to self-levitate. The *in situ* instrumentation installed in the ground under and surrounding the propellant mass consisted of rod calorimeters, slug calorimeters, witness materials, bare thermocouples, and a two-color pyrometer operating in the near-IR. The remote instrumentation consisted of UV/visible and mid-wave IR (MWIR) spectroradiometer measurement systems and visible, MWIR, and longwave IR (LWIR) cameras. The MWIR wavelength range was 3–5 μm, and the LWIR range was 8–12 μm. A LWIR test image is shown in Fig. 3b. Post-test analysis of the LWIR data and the calorimeter and thermocouple data indicated that plume temperatures reached 3000 ± 100 K and heat fluxes reached 200 ± 80 W/cm^2.

Test results, which were reported in the databooks and in Ref. 7, provided the peak temperatures (up to 3100 K) for the solid propellant fire specification in the Mars Exploration Rovers (MER) SAR databook in 2002. APL's analysis of the test results continued into 2004. The Laboratory developed a fire model for aluminized propellant fires based on the physics of the phenomena in an aluminized propellant fire.[8] Model predictions were consistent with test results. The APL fire model was then used to produce a solid propellant fire specification for the New Horizons SAR databooks in 2004 and 2005; this specification was carried over into the Mars Science Laboratory (MSL) SAR databook in 2006. The specification provided a range of propellant fragment sizes and masses, specified the temperatures as functions of time and location for each propellant size, and was used to develop the New Horizons FSAR. In addition, the test results were deemed to be accurate by INSRP in the New Horizons SER and were a sufficient basis to develop the specification.

APL also provided test observations, based on post-test materials analysis, that were included in the SAR databooks' solid propellant fire specification. A calorimeter of solid molybdenum metal melted at 2896 K served as a temperature marker. Aluminized solid propellant fires produce aluminum oxide (Al_2O_3, or alumina). The responses of various witness materials near the propellant showed that aluminum oxide tended to dissolve and merge with other oxides, such as silicon dioxide (silica) or sand, yttrium oxide (yttria), and cerium oxide (ceria). The merged liquid alumina and silica would be much more viscous than liquid alumina alone. An endothermic reaction of alumina with carbon was identified that could lower the temperatures of materials enclosed in carbon (such as a GPHS) by about 150 K.

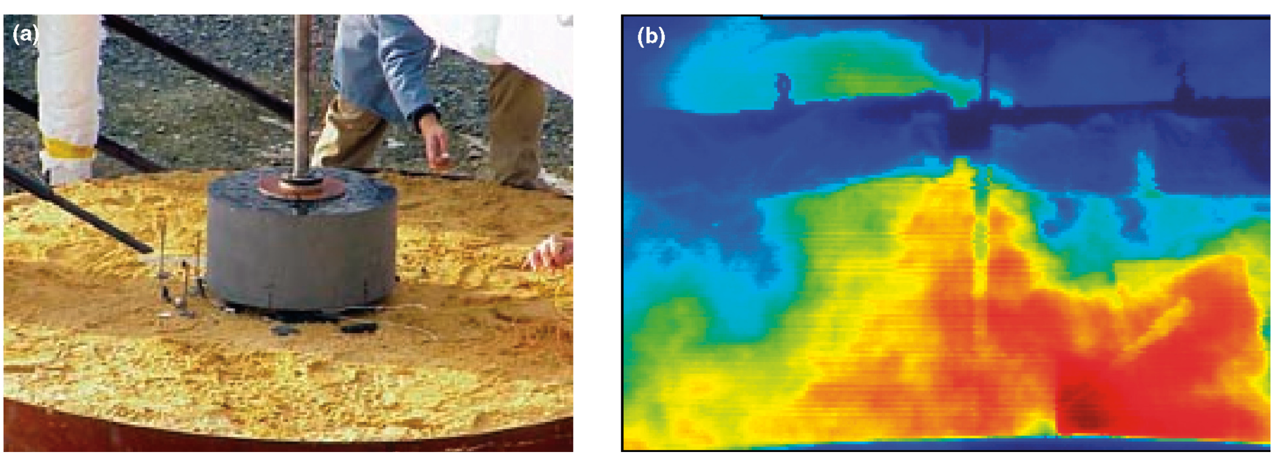


Figure 3. (a) Test setup with propellant block and *in situ* instrumentation. (b) LWIR image of a solid propellant fire test.

The following test observations were also reported in Ref. 7. Measurements of the deposits downstream and on a vertical rectangular witness board (shown to the right of the propellant in Fig. 3) suggested that for a ceria rod originally at a 28-cm (11-in.) radius, only 34% of the mass merged with the local ground deposits, about 22% sprayed downstream onto the ground and the board, and the remaining 44% was not recovered. At least part of the unrecovered ceria may have become airborne indefinitely. The post-test materials analysis provided important insight into the behavior of RTG materials subjected to a solid propellant fire and their thermal, chemical, and physical interactions with the combustion products of the fire and the sand and concrete ground materials.

In March 2006, APL participated in a Joint Army/Navy/NASA/Air Force workshop on Ambient Atmosphere Solid Propellant Combustion. Participants included national experts from government, universities, and industry. APL gave several invited keynote presentations on the solid propellant fire modeling, solid propellant fire tests, optical diagnostics overview and implementation, and calorimetrics. These were well received by the workshop participants, who noted in the workshop report that the Laboratory's work provided a valuable contribution in that the bottom-burning environment, which is the most severe environment for an object, had not been considered before.

NUCLEAR RISK ASSESSMENTS

As discussed in the boxed insert, DoE provides the NRAs as input to a mission's EIS. Tetra Tech NUS, Inc., under subcontract to APL, provided the NRAs in 2002 for the NASA MER missions, in 2005 for the New Horizons mission, and in 2006 for the MSL mission. In 2005, ASCA, Inc., also under subcontract to APL, provided the EIS databook for the New Horizons mission, which consisted mainly of accident conditions and probabilities. In 2002, Tetra Tech NUS also provided the FSAR for the MER missions.[9] (Each MER rover carried eight radioisotope heater units [RHUs] and no RTGs. The RHUs provide heat to the rovers' electronics to allow their survival during the cold Martian nights. Each RHU contains approximately 2.7 g [about 0.1 oz] of PuO_2 fuel, with an activity of 32.4 Ci, enclosed in a protective clad and graphitics. The cylindrically shaped RHU is 2.6 cm [1.0 in.] in diameter and 3.2 cm [1.3 in.] long, with a total unit weight of about 40 g [1.4 oz].[9])

LAUNCH CONTINGENCY EFFORTS

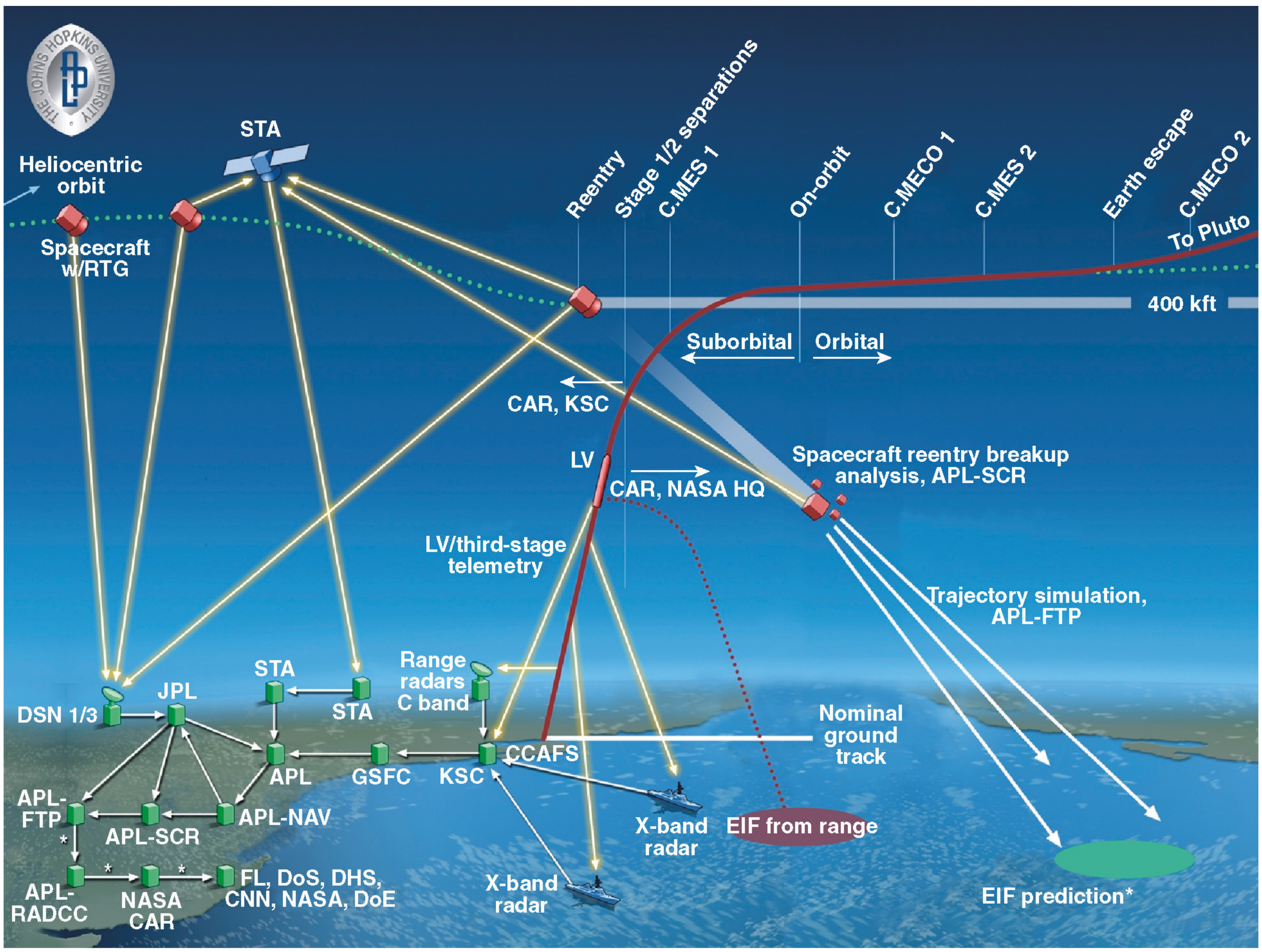
The failure of the fourth stage carrying the Russian Mars 96 spacecraft with four Russian RTGs, each containing 200 g (7 oz) of Pu-238, resulted in Earth reentry in November 1996. According to the *Washington Post*,[10] the U.S. Space Command informed President Bill Clinton, who then warned the Australian Prime Minister that the spacecraft would impact Australia near Canberra. But local Australian officials had already alerted emergency teams 2 h earlier. Furthermore, the spacecraft debris had already landed a day earlier, not in Australia but near the coast of Chile.

This series of events demonstrated the need for real-time proactive monitoring of a nuclear space launch and on-orbit trajectory until Earth escape. Specifically, this experience illustrated the need, after a reentry accident, for accurate timing (when to expect Earth impact), timeliness (warning before, not after), and accurate location prediction (where Earth impact would occur). These capabilities were provided by APL's Cassini launch contingency effort[11] for the October 1997 launch. The Cassini spacecraft carried three GPHS-RTGs and 117 RHUs. Before launch day, APL distributed to the community a set of ballistic coefficients of the GPHS and RHU modules so that the same information was used by all parties. (The ballistic coefficient of a body is a measure of its ability to overcome air resistance in flight.) APL provided the capability to predict the time of spacecraft reentry from an orbital decay based on orbital parameters from U.S. space tracking assets. In the event of a suborbital or out-of-orbit reentry, U.S. space tracking assets would also provide the reentry conditions of the spacecraft. The breakup conditions of the spacecraft and RTG would be provided by JPL, the spacecraft manager. APL would then predict the trajectory of the GPHS modules and RHUs released from the spacecraft as well as their Earth impact footprints via a three-degree-of-freedom trajectory propagation code that used the ballistic coefficients of the GPHS modules and the RHUs, all within an hour of reentry. These predictions would be used for notification and recovery purposes. The contingency function was stood up at APL, and the capabilities for predicting the reentry time and impact footprints were brought online and staffed for launch, through ascension to park orbit, to final Earth escape. The launch and interplanetary injection were successful, and no contingency activities were needed.

The same launch contingency efforts were planned for the two MER launches in June and July 2003. The MER rovers, Spirit and Opportunity, each carried eight RHUs, as noted earlier. In preparation, APL improved the prediction capabilities by using a six-degree-of-freedom trajectory propagation code, incorporating winds, and validating the code to predict the time of spacecraft reentry from an orbital decay.[12] Again, two successful launches precluded the need for intervention by the APL contingency team.

To prepare for the New Horizons launch in January 2006, APL's launch contingency roles were expanded[13] as part of NASA/DoE Radiological Contingency Planning. In addition to the tasks of the Cassini and MER launch contingency efforts, APL also wrote the contingency plans for the debris impact footprint definition and heliocentric orbit, participated in the Radiological Control Center (RADCC) at the Kennedy Space Center as the APL Payload Representative, provided a hazardous elements picture book for first responders, developed capabilities for spacecraft and RTG breakup predictions,[5] coordinated with U.S. space tracking assets, and reviewed pre-positioned cables to U.S. embassies. The Laboratory distributed to the community a set of ballistic coefficients of third-stage and spacecraft individual components that could reenter so that the same information was used by all parties. APL also completed the database of full rotational aerodynamic coefficients of the GPHS module to cover the supersonic and transonic flight regimes by computational fluid dynamics analysis. These coefficients supplemented existing subsonic and hypersonic wind tunnel data.

The probability of a launch accident leading to a suborbital or orbital reentry was estimated at about 3% in the New Horizons FEIS,[3] with Earth impact possible anywhere worldwide between 28.8°N and 28.8°S. The concept of operations for the debris impact footprint prediction following a reentry is shown in Fig. 4, with a nominal launch shown by the solid red line. In case of a reentry accident, APL was to provide an Earth impact footprint prediction in less than an hour. The footprint predictions would be made by personnel at the Emergency Operations Center on the APL campus and forwarded to the APL Payload Representative in the RADCC at the



APL-FTP	= APL Footprint Prediction Representative	DoS	= U.S. Department of State
APL-NAV	= APL Navigation and Tracking Representative	DSN	= Deep Space Network
APL-RADCC	= APL Payload Representative in the RADCC	EIF	= Earth impact footprint
APL-SCR	= APL Spacecraft Reentry Breakup Representative	FL	= Florida state and local government officials
CAR	= Coordinating Agency Representative	GSFC	= Goddard Space Flight Center
CCAFS	= Cape Canaveral Air Force Station	JPL	= Jet Propulsion Laboratory
C.MECOx	= Centaur main engine cutoff 1 or 2	KSC	= Kennedy Space Center
C.MESx	= Centaur main engine start 1 or 2	LV	= Launch vehicle
CNN	= Cable News Network (proxy for all news media)	RADCC	= Radiological Control Center at KSC
DHS	= U.S. Department of Homeland Security	STA	= U.S. space tracking assets
DoE	= U.S. Department of Energy		

Figure 4. Debris impact footprint prediction concept of operations.[13]

launch site. APL's footprint predictions would then be passed on to NASA and DoE officials for notification and recovery purposes.

The actual launch went off flawlessly. Thirteen months later, in February 2007, the New Horizons spacecraft flew by Jupiter and gathered scientific data on that planet, its moons, rings, magnetosphere, and magnetotail. New Horizons is expected to fly by Pluto and Charon in July 2015, then past additional Kuiper Belt objects a few years after that, for our first close encounters with these bodies.

CONCLUSION

It has been said that more than 99% of our solar system is unexplorable without nuclear power. Past missions enabled by space nuclear power have revealed some of the secrets held by the planets, their moons, and the edge of the solar system. Future missions to bodies in the solar system and beyond to interstellar space could also use space nuclear power. APL has contributed to the aerospace nuclear safety of past missions and maintains the technical expertise to continue to do so in the future.

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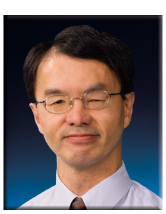

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