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NUCLEAR SAFETY LAUNCH APPROVAL: MULTI-MISSION LESSONS LEARNED

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Launching a NASA radioisotope power system (RPS) mission requires compliance with two Federal mandates: the National Environmental Policy Act of 1969 (NEPA) and launch approval (LA), as directed by Presidential Directive/National Security Council Memorandum 25. Nuclear safety launch approval lessons learned from multiple NASA RPS missions, one Russian RPS mission, two non-RPS launch accidents, and several solid propellant fire test campaigns since 1996 are shown to have contributed to an ever-growing body of knowledge. The launch accidents can be viewed as "unplanned experiments" that provided real-world data. Lessons learned from the nuclear safety launch approval effort of each mission or launch accident, and how they were applied to improve the NEPA/LA processes and nuclear safety of subsequent RPS missions, are presented. The current emphasis on cost improvements to future NEPA/LA processes are placed into context of these historical nuclear safety improvements, with a caution that certain cost improvements may have the short-term effect of lowering NEPA/LA costs but at the expense of curtailing potential nuclear safety improvements. The reader should note that changes are not made lightly, and a benefit is sought through the change. These improvements may be in other areas besides cost.

These missions and launch accidents are, in chronological order of launch date: Mars 96 (Russian), Mars Pathfinder (MPF), Delta II 241 (GPS IIR-1), Cassini-Huygens, Mars Exploration Rovers (MER-A Spirit and MER-B Opportunity), Pluto New Horizons (PNH or NH), Mars Science Laboratory (MSL), Antares Orb-3, and Mars 2020 (M2020). The Mars 96 spacecraft reached but failed to go beyond Earth park orbit. The spacecraft and its Russian radioisotope thermoelectric generators (RTGs) then reentered Earth's atmosphere and landed in the ocean and on land. This prompted launch contingency efforts for accidental suborbital and orbital reentries and the development of debris Earth impact footprint prediction capabilities for subsequent NASA RPS missions. During the NEPA/LA process for the MPF mission, a previously unrecognized and undefined accident environment, the bottom-burning solid propellant fire, was identified. The Delta II 241 accident, although it did not carry an RPS, still demonstrated the devastating effects of an in-air launch vehicle explosion over Cape Canaveral. The Cassini-Huygens mission trajectory to Saturn used a Venus-Venus-Earth-Jupiter Gravity Assist (VVEJGA) maneuver, where the Earth Gravity Assist (EGA) flyby was the primary nuclear safety focus of NASA, the U.S. Department of Energy (DOE), the Cassini Interagency Nuclear Safety Review Panel (INSRP), and the public alike. A solid propellant fire test campaign addressed the MPF finding and led in part to the retrofit solid propellant breakup systems (BUSs) designed and carried by MER-A and MER-B spacecraft and the deployment of plutonium detectors in the launch area for PNH. The PNH mission decreased the calendar length of the NEPA/LA processes to less than 4 years by incorporating lessons learned from previous missions and tests in its spacecraft and mission designs and their NEPA/LA processes. Analyses of the MSL mission near-pad trajectories showed that coincident impacts of solid propellant fragments and RPS components following launch vehicle breakups were more likely to occur on steel surfaces than on the more geographically prevalent sand surfaces. The Antares Orb-3 accident revealed a previously unrealized accident scenario of lofted concrete fragments. Finally, two more solid propellant fire test campaigns responded to the MSL lessons learned.

I. INTRODUCTION

Various nuclear-powered space missions since 1996 will be described in chronological order of launch date. Other events such as launch accidents are also described. Lessons learned from the NEPA/LA processes for each mission, and how those lessons learned improved the safety of subsequent missions, are described. The formal NEPA/LA processes for each mission have distinct milestone products. Briefly, the products for NEPA compliance include the Environmental Impact Statement (EIS) Databook, nuclear risk assessment (NRA), Draft EIS, risk communications activities, Final EIS, Supplemental EIS (if needed), and Record of Decision. Briefly, the products for launch approval are the Safety Analysis Report (SAR) Databook (and revisions); Preliminary SAR, Draft SAR, and Final SAR (FSAR); Safety Evaluation Report (SER); and Presidential launch approval decision [1]. Background descriptions for each mission, launch, or event are not explicitly provided here, but most are readily available online. For example, an asterisk (*) indicates subjects that are hyperlinked to the eponymous Wikipedia article.

I.A. Mars 96 (Russian) *

The following description is excerpted from [2]: 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, the U.S. Space Command informed President Clinton, who then warned the Australian Prime Minister, that the spacecraft would crash near Canberra, Australia. But local Australian officials had already alerted emergency teams 2 hours earlier. Furthermore, spacecraft debris had fallen 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 rather than after), and accurate location prediction (where Earth impact would occur). These capabilities for a contingency effort ahead of the October 1997 Cassini launch were provided by The Johns Hopkins University Applied Physics Laboratory (JHU/APL). The NASA Cassini spacecraft carried three general purpose heat source (GPHS)-RTGs, a type of RPS that uses 10.9 kg of plutonium dioxide (plutonia) each to supply heat and electrical power to the spacecraft, and 117 light-weight radioisotope heater units (LWRHUs or RHUs). Before launch day, JHU/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.) JHU/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 the Jet Propulsion Laboratory (JPL), the spacecraft manager. JHU/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 JHU/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. At this point, the launch and interplanetary injection were successful, and no contingency activities were needed [3].

Similar suborbital/orbital reentry launch contingency efforts were conducted for MER-A and MER-B [4], PNH [5], and MSL missions. Top-level applications of lessons learned described in this paper on subsequent missions are listed in Table 1. For the Mars 96 launch, applications of lessons learned are for the Cassini-Huygens, MER, NH, MSL, and M2020 missions.

I.B. Mars Pathfinder *

The 1996 NASA MPF spacecraft carried the Sojourner rover. Embedded inside Sojourner were three LWRHUs, each delivering about 1 thermal watt, sufficient to prevent the Sojourner electronics from freezing in the Martian night. As part of the NEPA/LA process, DOE's Mound Laboratory was tasked with the NRA and the FSAR. MPF was launched on a Delta II 7925 rocket with a Star 48B third-stage. The Star 48B motor contains 4430 lb of solid propellant and is nearly spherical with a diameter of about 48 inches. During the nuclear safety analysis, one accident scenario involved solid propellant fragments burning on the ground in open-air conditions near LWRHUs. To assess the LWRHU response to this scenario, Mound Laboratory sought accident data, but the only available accident environment description was of a solid propellant fragment burning on its top surface. For this description to be used in the assessment, the LWRHU would need to be physically on top of the burning propellant. This was deemed non-credible in the FSAR, which

TABLE I. Top-level applications of lessons learned described in this paper on subsequent missions

Applications of Lessons Learned	**Year**																								
Launch or Activity	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Mars 96 (Russian)	11/16	🟦						🟦			🟦					🟦									▥
Mars Pathfinder (MPF)	12/4					🟦		🟦			🟦					🟦									▥
GPS IIR-1 (Delta II 241)		1/17						🟦			🟦					🟦									▥
Cassini-Huygens		10/15									🟦					🟦									▥
JHU/APL solid propellant fire tests						🟩		🟦			🟦					🟦	🟩				🟩				▥
GPHS Module redesign							🟩				🟦					🟦									▥
NRAs for MER, NH, MSL, and Mars 2020							🟩			🟩	🟩								🟩						▥
Mars Exploration Rovers (MER)								6/10			🟦														
New Horizons (NH)											1/19					🟦									▥
Mars Science Laboratory (MSL)																11/26	🟦				🟦				▥
Antares-Cygnus CRS Orb-3 accident																			10/28						▥
Mars 2020 (M2020)																									☰

Color Code	
🟩	Activity
M/D	Launch (Month/Date)
🟦	Lessons Learned application
☰	Launch (planned)
▥	Lessons Learned application (planned)

Example:
Lessons learned from the Mars 96 (Russian) were or will be applied to the Cassini-Huygens, MER, NH, MSL, and M2020 missions

stated "propellant fires which could be encountered during the launch of the Delta II 7925 vehicle are not expected to result in a measurable plutonium release to the environment except in the virtually impossible case where an LWRHU would somehow become perched atop a block of the [top] burning solid fuel [propellant]" [6]. The more likely configuration would be an LWRHU on the ground, with a block of solid propellant burning on its bottom surface positioned over it or in proximity to it. However, no tests existed for this configuration, nor test data of that environment; only tests and test data of the environment caused by a block of top-burning solid propellant. Therefore, although the configuration of an LWRHU on the ground with burning solid propellant over it was more likely, no environmental data were available to evaluate the LWRHU's response and possible consequences. Based on this lack of data, it is not surprising that the earlier Environmental Assessment for the MPF mission produced a Finding Of No Significant Impact [7]. DOE thus requested that tests of bottom-burning solid propellant be conducted, and the measured environments be provided in the launch vehicle databooks for subsequent missions.

I.C. GPS IIR-1 (Delta II 241) *

The Delta II 241 accident occurred on January 17, 1997. Although the Delta II 241 mission did not carry RPS materials, it is notable because the rocket exploded about 13 seconds after liftoff and rained debris over the launch complex, including burning propellant.

In 2001, the Research Triangle Institute (RTI) was tasked to analyze the secondary fragment distribution of a Star 48 ground impact for the MER mission. RTI used the U.S. Air Force FRAG program to predict the distribution based on a log normal curve fit with the largest fragment size as anchor. One source of data on observed secondary fragments was the Delta II 241 accident. The Air Force 45th Space Wing and RTI reported results after examining available video, film, debris, and reports for useful data to reconstruct the accident. One video showed fallback of the mission's Star 37 third stage on land and ejection of secondary fragments from the impact. The largest secondary fragment was termed "Alpha." Using luminescent range data from the January 2001 JHU/APL solid propellant fire tests, the Alpha diameter was estimated at approximately 22 inches, which equates to an approximately 350-lb fragment mass [8]. The Alpha impact point was located approximately 1000 feet northeast of the crater. A large amount of slag, or aluminum oxide (alumina) deposits from a burning solid propellant fragment on the ground, was found in the southwest area of the third-stage impact crater. Based on the ratio of alumina deposit mass to fragment mass from the JHU/APL tests, the Delta II 241 propellant fragment that produced those deposits was estimated to be roughly 620 lb [8]. These estimates were used in the secondary fragment distribution in the MER FSAR Databook [9] and subsequent databooks. A lesson learned was that forensic reconstruction of an accident should be pursued in a timely and systematic manner; this would in fact be done for the 2014 Antares Orb-3 accident.

I.D. Cassini-Huygens *

The prominent nuclear safety concern of the Cassini mission was the EGA maneuver portion of the overall VVEJGA mission trajectory to Saturn. The EGA itself was characterized by its designed flyby speed—the initial velocity is 63,812 ft/s (19.5 km/s). If there were an accidental Earth atmospheric reentry during the EGA maneuver (although the probability of that occurring was less than 10^{-6}) [10], analyses predicted atmospheric release of the on-board plutonium. The primary concern of the GPHS module response to inadvertent reentry during the EGA maneuver was the high energy of the reentry velocity and the module's structural design itself. Indeed, new methods were developed to evaluate this scenario [11], [12]. The Cassini INSRP wrote in the SER: "Special consideration has been given to the radiological health effects resulting from inadvertent reentry during the EGA maneuver. This high-velocity reentry is a complex issue, and its potential effects are quite controversial. If one assumes the complete burn-up of the space vehicle and RTGs upon inadvertent reentry, it is possible, using the linear non-threshold dose hypothesis, to postulate up to several tens of thousands of latent cancer fatalities worldwide over the next 50 years. In the view of the Cassini INSRP, such health effects estimates must be viewed with caution. While such effects can be calculated, it is most probable, given the total vaporization of the plutonium, that the average dose to a single individual would likely be on the order of 10 microsieverts (1 millirem), a dose clearly insufficient to adversely affect all but the most sensitive individuals. Additionally, land impact of RTG components would cause minor localized health and environmental effects." [13].

A number of other activities affected the Cassini launch approval process:

1. Disagreement between the project and the Reentry Subpanel of the INSRP on the thermophysics associated with these severe reentry environments
2. Need for the EIS [14] to be supplemented [15]
3. Timeliness of the databook [16]
4. In-air releases of nuclear fuel allowed by predicted recession of the GPHS modules and graphite impact shells (GISs) from EGA reentry
5. Need for a laser illumination system to provide vehicle attitude imaging during nighttime launches

After the Cassini launch, JHU/APL further investigated the science of Earth atmospheric reentry physics at 19.5 km/s. This investigation included engaging several prominent national researchers, but they disagreed on the level of uncertainty in radiation heating, the surface energy balance, and the wall boundary condition. The unique and extreme nature of the aerothermal analyses and the lack of supporting data or research in this regime made it difficult to substantiate the theories for the Cassini mission [17].

I.E. JHU/APL Solid Propellant Fire Tests (2001 Campaign)

Following the MPF findings, JHU/APL began a solid propellant fire testing campaign at the former Thiokol facility in Elkton, MD, in 1999. After a series of small-scale tests, a larger scale test was performed on a sand substrate with witness materials in 2001. It was found that the iridium half-shells melted [melting point (MP) = 2739 K], a heretofore unexpected result given previous fire specifications in the databooks peaked at 2400 °C = 2673 K, below the MP of the iridium clad of the plutonium fuel pellets. Melting of molybdenum at MP = 2896 K ≅ 2900 K also occurred. Maximum object temperatures of 2900 K and maximum heat fluxes of 2 MW/m^2 under the propellant were reported [18]. A longwave infrared camera measured flame T > 3000 K.

Other findings of the JHU/APL solid propellant fire tests (2001 campaign) include the following:

- Results were used to size propellant fragments from the Delta II 241 accident [8].
- Concentrations and locations of plutonia surrogates (yttrium oxide (yttria) (Y_2O_3), and cerium oxide (ceria) (CeO_2)) depositions were mapped.
- Maximum measured temperatures anchored the solid propellant fire specification in the MER databook [9].
- Temperatures, heat fluxes, and burn rates were determined at ambient 1.0 atm pressure [18].
- Solid propellant fire specifications were provided for the PNH [19] and MSL [20] databooks.

In 2014, JPL and Sandia National Laboratories (SNL) conducted an additional and independent bottom-burning solid propellant fire test campaign in Albuquerque, NM, at 6350 ft elevation (0.8 atm ambient pressure) and measured the fire environment. JPL reported maximum object temperatures of 2900 K and maximum heat fluxes of 2 MW/m^2 under the propellant [21].

I.F. GPHS Module Redesign

Part of the concern for the thermostructural response of the GPHS module to Cassini's EGA maneuver came from the structural design of the GPHS module itself. Thus, "DOE made a commitment to [the Office of Science and Technology Policy] in 1994 that the GPHS module would be improved after Cassini" [22].

After the Cassini launch, the original GPHS module (now called the "Step 0" module) was redesigned based on EGA loads, but in two "steps." For the Step 1 module, an internal web of 0.10-inch thickness was added between the two internal GISs, thereby increasing the module's total outer width by 0.10 inch. Note that the Step 1 modules were the same height as the Step 0 modules; thus, 18 Step 1 modules could fit into the GPHS-RTG. For the Step 2 module, in addition to the internal web, the two broadfaces were each increased in thickness from 0.185 to 0.285 inch (increasing the total outer height by 0.200 inch). As a result of these two simple but important modifications, the resistance of the GPHS module to thermostructural stresses and recession from EGA loads increased dramatically [22]. The Step 1 GPHS module was used in the GPHS-RTG for the NH mission, and the Step 2 GPHS module was incorporated into the multi-mission RTG (MMRTG) for the MSL mission. Neither mission called for an EGA.

An additional study in 2004 examined possible alternate materials for the GPHS and GIS. Several candidate materials, including the incumbent fine-weaved pierced fabric (FWPF), were assessed. Evaluation criteria included availability, cost, performance, and qualification needs. The overriding consensus of the GPHS Aeroshell Materials Working Group was: (1) a reestablished FWPF represents the best choice of an aeroshell material for future missions, (2) the current FWPF inventory at DOE and contractor facilities that will be used for near-term hardware/system qualifications and flights further solidifies FWPF as the "proven" material for RPS applications, and (3) measures should be considered to immediately support start-up efforts to assure the earliest possible availability of new FWPF billets [23].

I.G. Mars Exploration Rover (MER-A Spirit and MER-B Opportunity) *

The results of the JHU/APL solid propellant fire tests (2001 campaign), influenced the design of the MER missions, which called for use of the Star 48 motor. Large solid propellant fragments were not desired because they posed a crushing threat, explosives threat, and solid propellant fire threat. The command destruct or automatic destruct of the Star 48 motor involved two 19-g small conical shaped charges (CSCs) that would detach the aft end of the motor and thus its pressure integrity, thereby rendering it non-propulsive. However, large fragments could still remain. The engineering solution was to create a BUS by adding two additional CSCs of 500 g of C-4 explosives each to the forward payload attach fitting (PAF) to break up the large propellant dome of the Star 48 motor. The BUS was tested at the NASA Johnson White Sands Test Facility (WSTF) in New Mexico and worked as designed [24]. The two MER missions each launched with a BUS as flight hardware, although neither had to be deployed for the two successful launches.

I.H. Nuclear Risk Assessments for MER, PNH, MSL, and M2020

Tetra Tech NUS, Inc. (TtNUS; now Tetra Tech, Inc.), under subcontract to JHU/APL, produced the NRA for the MER mission [25]. The MER NRA followed the traditional methodology of calculating radiological consequences of accident scenarios and mission risks from pertinent mission reference design information related to the launch vehicle, spacecraft, mission profile, and radioactive materials, considering accident scenarios, their probabilities, and source term estimates for the LWRHUs and small quantity sources. TtNUS produced the FSAR for the MER mission as well [26].

TtNUS also produced the NRA for the PNH mission [27]. The PNH NRA followed a different methodology of calculating radiological consequences of accident scenarios and mission risks than that of the MER NRA. Pertinent mission reference design information was still considered, but the derivation of the radiological consequences of accident scenarios and mission risks were derived from scaling the results for past missions [e.g., Cassini, Outer Planets (early safety work, missions canceled), and MER] on a per curie inventory basis for specific accident environments and scenarios, coupled with additional supplemental analyses where considered appropriate. Considering that the PNH design differed from the baseline designs in some notable areas (e.g., GPHS-RTG versus LWRHUs and Atlas V 551 versus Titan IV Solid Rocket Motor Upgrade and Delta II 7925), scaling has its limitations.

TtNUS also produced the NRA for the MSL mission [28] using the same scaling methodology, but based on consideration of the PNH NRA and additional MSL mission-specific analyses where considered appropriate. Note that the MSL NRA is thus based on scaling from the PNH NRA, which was itself based on scaling from the Cassini and MER missions and other safety work. Also, considering that the MSL design differed from the PNH design in some notable areas (e.g., MMRTG versus GPHS-RTG), scaling has these additional limitations as well.

Perhaps noting these limitations of the scaling methodology used to obtain the MSL NRA, SNL produced the NRA for the M2020 mission [29], using the traditional methodology of calculating radiological consequences of accident scenarios and mission risks from M2020 mission-specific information. This was done even though MSL and M2020 are similar in their mission designs: both carry MMRTGs on similar rovers in similar spacecraft, both NRAs were agnostic as to the launch vehicle (i.e., equal probability of each candidate), and MSL was launched in the fall, whereas M2020 is scheduled to launch in summer. Given these similarities and differences, it is instructive to compare the overall mission risks from the EISs of both missions, as predicted by their respective NRAs.

I.I. New Horizons (NH or PNH) *

NH, as the first Principal Investigator (PI)-led and competed NASA RPS mission, obviously competed on schedule and cost as well as performance. To complete the NEPA/LA processes in 4 calendar years, the NH mission proactively took the following steps based on lessons learned from previous and concurrent missions: (1) an EGA was deliberately not included in the NH mission trajectory design to avoid the complexities caused by the EGA employed in the Cassini mission; (2) NH deliberately did not specify a nighttime launch because the laser illumination system was not available; and (3) the NH mission specified a BUS for its Star 48 motor, taking full advantage of the development effort for the MER missions. A notable difference of the NH spacecraft configuration from the MER spacecraft configuration was that NH positioned an RTG in proximity of the CSCs, separated by only the thin metal of the PAF, whereas the MER mission employed more intervening structure between the LWRHUs and CSCs, including the spacecraft and rover. JHU/APL predicted that the oblique angles of the CSC backside fragments striking the metal PAF and the metal housing of the RTG would prevent penetration of the fragments. Indeed, subsequent CSC testing revealed that “all three tests and all twelve capture pack samples of the fragment damage effects on the RTG simulant showed that fragments generated by detonation of the CSCs are not likely to damage the graphitics in the RTG” [19]. This and other NEPA/LA lessons learned for the NH mission are described in [1].

Based on the 2001 JHU/APL solid propellant fire tests data and solid propellant fire specifications, the FSAR predicted that near-pad exposure of RTG components to the fire environment could result in releases. During the 2006 NH launch, as a new technology, 11 Environmental Continuous Air Monitors (ECAMs), which can distinguish plutonium air concentrations at near-background levels via alpha spectrometry, were positioned at various geographical locations near the launch pad at Cape Canaveral Air Force Station (CCAFS), Florida, in the event of an accident and release [30]. ECAMs were also deployed for the 2011 MSL launch.

I.J. Mars Science Laboratory (MSL) *

The fire accident scenario consists of a solid propellant fragment, burning on its bottom surface, with RPS components underneath or nearby, resting on the ground or substrate. The ground around the CCAFS launch complex consists of mostly sand, then concrete surrounding the launch pad, then asphalt, and finally steel. The steel of the mobile launch platform is covered with an ablative coating called Flexfram. Previous assumptions were that sand would be the most prevalent substrate for this accident scenario because it is geographically the most common. However, the criteria should be for the most probable substrate for coincident impact of a solid propellant fragment and the RTG components. Given the launch vehicle trajectory, timing of destruct actions, solid propellant fragment generation and fallback, and RTG component disassembly and fallback, the most common substrate is Flexfram-covered steel, and the next is concrete. This finding was used in the 2012 JHU/APL solid propellant fire testing campaign, where the two tested substrates were concrete and Flexfram-covered steel. These findings were also included in the subsequent NRA for the M2020 mission [29].

The Power Systems Working Group (PSWG) of the MSL INSRP provided comments on the MSL FSAR, including the following: “The PSWG observes that the situations where large amounts of [plutonia] fuel are exposed to the solid propellant fire environment result in the largest biologically effective releases by far, and dominate the mean source terms, mean health effects, and mean mission risk more than any other single factor. Thus, the PSWG believes that the behavior of plutonia and MMRTG components in solid propellant fire environments should be the subject of a significant research and even experimental program prior to the next RTG launch in order to improve the accuracy of these release predictions and improve the accuracy and relevance of all related risk assessment results” [31]. The application of these lessons learned resulted in the 2012 and 2016 JHU/APL solid propellant fire testing campaigns.

I.K. Antares-Cygnus CRS Orb-3 Accident *

The Antares-Cygnus Orb-3 accident occurred on October 28, 2014 from launch pad 0A, Mid-Atlantic Regional Spaceport, Wallops Island, VA. Three items are of note: (1) the Antares Orb-3 did not carry any RPS; (2) the amount and quality of photos and videos, from the press and the public as well as Government and industry, was impressive; and (3) a new accident scenario was revealed. Several types of forensics data were used: building damage, video analysis, shock wave, crater formation, and plume rise, among others. Several months after the Antares Orb-3 accident, DOE, SNL, JHU/APL, and JPL personnel toured the M2020 planned launch site SLC-41 at CCAFS and noted that there were several similar large blocks of concrete. This accident scenario had never been analyzed before.

The following are lessons learned from review and analysis of the Antares Orb-3 accident [32]:

- Large blocks of concrete were lofted into the air by the force of the explosions and launch vehicle fallback and landed several feet from their starting locations.
- Nearby LO_2 and propellant tanks could be impacted by falling debris.
- Activation of the command destruct may be delayed.
- A destruct initiation may be blocked by plasma shielding.
- Blasts from large-scale volumetric liquid propellant explosions differ from trinitrotoluene (TNT) blasts.
- Large pieces of solid propellant could survive a fallback and burn on the ground for several minutes.
- Plume rise prediction is difficult and depends on meteorological conditions as well as empirically derived parameters.
- Care must be taken in estimating the “TNT equivalent” for such blasts.

I.L. JHU/APL Solid Propellant Fire Tests (2012 and 2016 Campaigns)

In 2012, JHU/APL tested bottom-burning blocks of Star 48 propellant on Flexfram-covered steel and on concrete substrates at the Orbital ATK facility in Elkton, MD. The intumescent Flexfram expanded, and the concrete spalled, as expected. Two surrogates of plutonia were tested: yttria, and ceria. Five major findings were as follows:

1. A trimodal alumina particle size distribution in the plume was determined by a laser transmissometer experiment, the predicted particle sizes were later validated by scanning electron microscopy of alumina deposits, and agglomeration of the particles was observed [33].
2. Propellant burn rates and temperatures at 1 atm ambient pressure were measured [34].
3. Total mass of alumina particles lofted in the plume was determined by a micro-pulse lidar experiment [35].
4. Concentrations of plutonia surrogates lofted in the plume were inferred by in-air filters and also separately by forensics of alumina deposits.

5. The tests proved that plutonia surrogates were lofted into the plume and that they condensed on respirable alumina smoke particles.

In 2016, JHU/APL tested these and several other surrogates of plutonia, including manganese oxide (Mn_3O_4), chromia (Cr_2O_3), yttria, and hafnia (HfO_2). These last four surrogates are also slated for future planned mass balance testing as representative of four mechanisms for plutonia lofting in bottom-burning solid propellant fires (namely, vaporization, chemical reaction, shear, and entrainment, respectively). For 2016, the plutonia surrogates in powder form were introduced with a powder injection system into the plume of top-burning propellant blocks [36], and optical instruments interrogating the plume detected lofted plutonia surrogates. Although in situ fluorescence [37] was not detected because of unfavorable testing conditions, fluorescence indicating substitution of chromium into alumina was detected in post-test analysis in the laboratory. Also, spectra indicating the formation of metal chlorides as well as oxides were observed in the field test data, corroborating thermochemical analyses predicting these previously unrecognized and undefined metal chloride gases (the chlorine source is the propellant's ammonium perchlorate oxidizer). Finally, solid propellant fire specifications from a refined model [38] were provided for use in development of the M2020 FSAR. This model was validated with data from the JHU/APL solid propellant fire tests, 2001, 2012, and 2016 testing campaigns.

II. CONCLUSIONS

Several missions' nuclear safety launch approval lessons learned were described. The applications of each mission's lessons learned carried forward to several subsequent missions.

- Lessons learned from past missions, tests, and analyses were exploited by the NH mission to complete its NEPA/LA processes in 4 years.
- Several unrecognized, undefined, unexpected, or unanticipated results were discovered during the course of the NEPA/LA processes of different missions. Three notable results are:
    - Bottom-burning solid propellant fragments were not tested nor their environments defined (1996).
    - Iridium melted in solid propellant fire tests (2001).
    - Metal chloride gases were detected in solid propellant fires (2016).
- Scaling consequence and risk results from previous missions and safety work have their limitations.
- New information, data, insights, and knowledge are constantly being acquired for each mission. If some previous missions' risk analyses were re-visited with new knowledge, risk results may change. In 2005, for example, DOE asserted that "if re-evaluated with today's knowledge, Cassini risks would increase" because of a better understanding of the solid propellant fire environments and more sophisticated mechanical impact modeling tools [39].

It has been shown that by undertaking the rigor of the formal NEPA/LA processes, lessons learned are realized and applied to subsequent missions. Reducing certain NEPA/LA efforts, for example by scaling of the design features between missions, could bypass the understanding gained through the formal NEPA/LA processes, and the potential safety improvements that they afford.

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