National Aeronautics and Space Administration

NASA Independent Review Team

Orb–3 Accident Investigation Report

Executive Summary

Date of Event: October 28, 2014

Date of Report: October 9, 2015

NASA Independent Review Team
Orb–3 Accident Investigation Report

Executive Summary

Commercial Services and the International Space Station

In the past few years, as NASA has focused on developing capabilities to further human and robotic exploration beyond low Earth orbit, the Agency has incubated new commercial capabilities to provide access to and support the International Space Station (ISS). NASA's Commercial Crew and Cargo Program Office and the ISS Program Office have successfully developed and implemented two novel models for using commercial rather than government sources to deliver cargo to ISS. Implementation of the Commercial Orbital Transportation Services (COTS) and Commercial Resupply Services (CRS) approach required a significant change in culture throughout the Agency and in how NASA interacts with the aerospace industry. COTS and CRS established a new approach for sharing financial and technical risks with industry to develop and operate new space transportation systems in support of human exploration endeavors. Within a few short years at a reasonable financial investment from NASA, this new approach resulted in the development of the following:

- Two commercial companies (i.e., Orbital ATK and SpaceX) capable of providing cargo delivery services to and from the ISS

- Two new and different launch vehicles (i.e., Antares and Falcon 9) capable of not only supporting ISS missions, but also other commercial and government missions

- Two new and different spacecraft vehicles (i.e., Cygnus and Dragon) capable of not only transporting cargo to and from the ISS, but also providing a baseline capability that can support other commercial and government missions; these spacecraft also have the capability of being launched on different launch vehicles, increasing availability to space should launch vehicle issues arise

- Two new and different spacecraft vehicles (i.e., Cygnus and Dragon) capable of complex rendezvous and proximity operations with a human occupied spacecraft that must safely maneuver to a precise capture box for capture by the ISS crew and must fully meet the human requirements associated with the ISS

- Two new launch pads and supporting facilities (Pad 0A at Wallops Flight Facility and Launch Complex 40 at Cape Canaveral) capable of launching medium-class Liquid Oxygen /Liquid Kerosene launch vehicles in support of the ISS Program and other commercial customers

- Four successful launches and missions to demonstrate the design and operational capability of the new launch vehicles, spacecraft, and support facilities; specifically single test missions for Antares and Falcon 9, and separate cargo demonstration missions to the ISS demonstrating the complete Orbital ATK and SpaceX cargo delivery systems

This effort established the framework to allow commercial companies to execute six consecutive and successful cargo transportation missions to the ISS using these new systems under the CRS contract prior to the first loss of mission event. The NASA Independent Review Team (IRT) recognizes the incredible achievement of these efforts, and believes these are accomplishments for which NASA and its COTS and CRS contractors should be extremely proud.

Orb-3 Accident

On October 28, 2014, at approximately 6:22 p.m. Eastern Daylight Time, Orbital ATK launched its Orb-3 cargo resupply mission bound for the ISS from the Mid-Atlantic Regional Spaceport, which is located on the eastern shore of NASA's Wallops Flight Facility in Virginia. The Orb-3 mission consisted of an Orbital ATK Antares-130 launch vehicle and a standard Cygnus spacecraft loaded with approximately 2296 kg (5057 lbs) of pressurized cargo[1]. Orb-3 was Orbital ATK's third cargo delivery mission under their ISS CRS contract.

Just over 15 seconds into flight, as shown in Figure 1, an explosion in the Antares Main Engine System (MES) occurred, causing the vehicle to lose thrust and fall back toward the ground. Just prior to Antares impacting the ground, range safety personnel issued a destruct command to the Flight Termination System to minimize the potential damage from the expected ground impact and ensuing explosion of the vehicle. The launch vehicle impacted near the launch pad resulting in loss of the vehicle and cargo. Although there was damage to the launch pad and adjacent facilities and buildings, there were no injuries to members of the public or workers involved in the launch. Figure 2 shows the condition of the launch pad on the day following the accident.

Figure 1. Antares Failure during Orb-3 Launch

[1] An overview of the Orb-3 mission and cargo contents is available on the NASA website at http://www.nasa.gov/sites/default/files/files/Orbital_CRS_mission_overview.pdf.

Figure 2. Antares Launch Pad Damage Following the Orb-3 Accident

Immediately following the accident, Orbital ATK established an Accident Investigation Board (AIB). Consistent with the NASA Contingency Action Plan, which had been approved by NASA and the Federal Aviation Administration, which approved the commercial license for the Orb-3 mission. Representatives from the ISS Program were invited to participate as representatives on the AIB.

In November 2014, the NASA Associate Administrator for Human Exploration and Operations established the IRT to independently investigate the Orb-3 failure for NASA. The IRT was given the following charter:

- Independently determine the technical root cause of the Orb-3 failure;
- Independently develop a detailed fault tree and provide independent assessment of telemetry data and physical evidence from the accident;
- Validate the Orbital ATK AIB efforts;
- Inform the Agency's risk posture in support of Orbital ATK's return-to-flight activities; and,
- Make recommendations on how to develop, operate, and acquire more reliable systems.

The IRT performed detailed analysis and review of Antares telemetry collected prior to and during the launch, as well as photographic and video media capturing the launch and failure. Based on this analysis, the IRT determined that the proximate cause of the Antares launch vehicle failure was an explosion within the AJ26[2] rocket engine installed in the Main Engine 1 position. Specifically, there was an explosion in the E15 Liquid Oxygen (LO2) turbopump, which then damaged the AJ26 rocket engine designated E16 installed in the Main Engine 2 position. The explosion caused the engines to lose thrust, and the launch vehicle fell back to Earth and impacted the ground, resulting in total destruction of the vehicle and its cargo. Figure 3 shows a single AJ26 engine stored on its transportation and processing skid. Figure 4 shows the aft end of a typical Antares launch vehicle with both AJ26 engines installed.

The IRT also developed a detailed system-level fault tree, timeline of events, and failure scenarios, and performed analysis and forensic investigation of the hardware recovered from the accident. The IRT concluded that the cause of the explosion on launch was loss of rotor radial positioning resulting in contact and frictional rubbing between rotating and stationary components within the Engine LO2 turbopump Hydraulic Balance Assembly (HBA) seal package. This frictional rubbing led to ignition and fire involving LO2 within the turbopump HBA. This conclusion is consistent with the proximate cause determination made by the Orbital ATK AIB investigation findings. Figure 3 highlights the general location of the HBA within the turbopump, but further detail about the turbopump and HBA design is not provided due to proprietary restrictions.

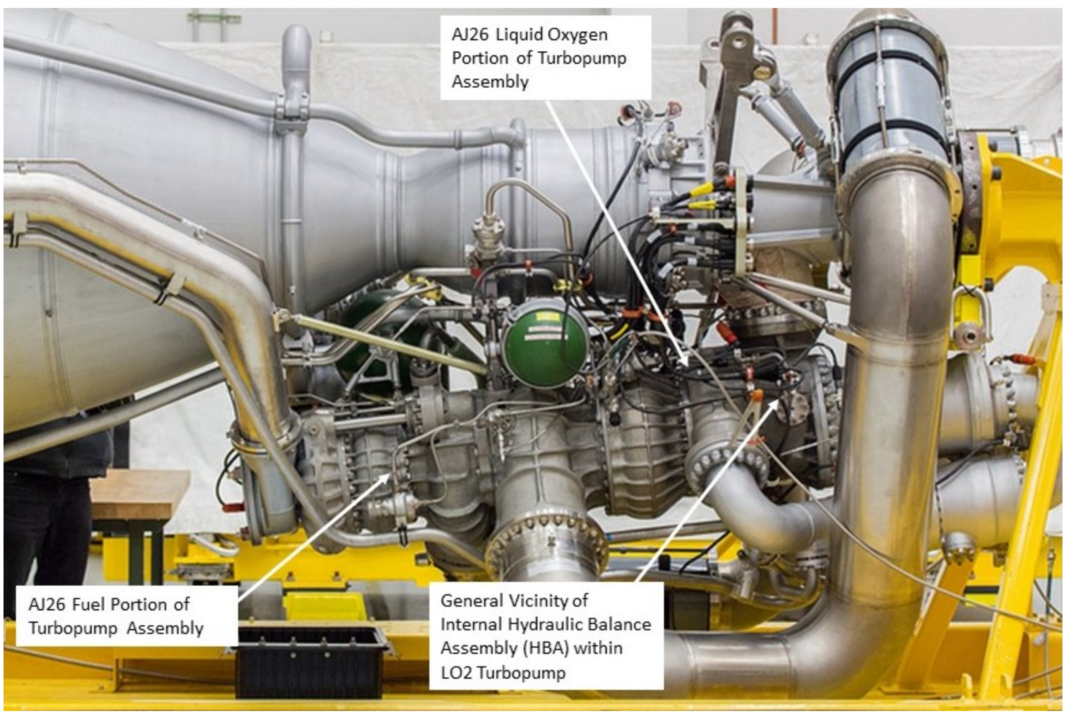

Figure 3. AJ26 Engine on Transportation and Processing Skid

[2] The AJ26 engine used for Antares is based on a core Russian NK-33 rocket engine designed and manufactured in the early 1970s in support of the Russian N-1 moon program. Aerojet-Rocketdyne modifies the NK-33 configuration for use on U.S. launch vehicles. For Antares, the AJ26 also includes several operational variations from the NK-33 operations originally intended for the N-1 program, such as but not limited to operation at a higher power level and engine gimballing.

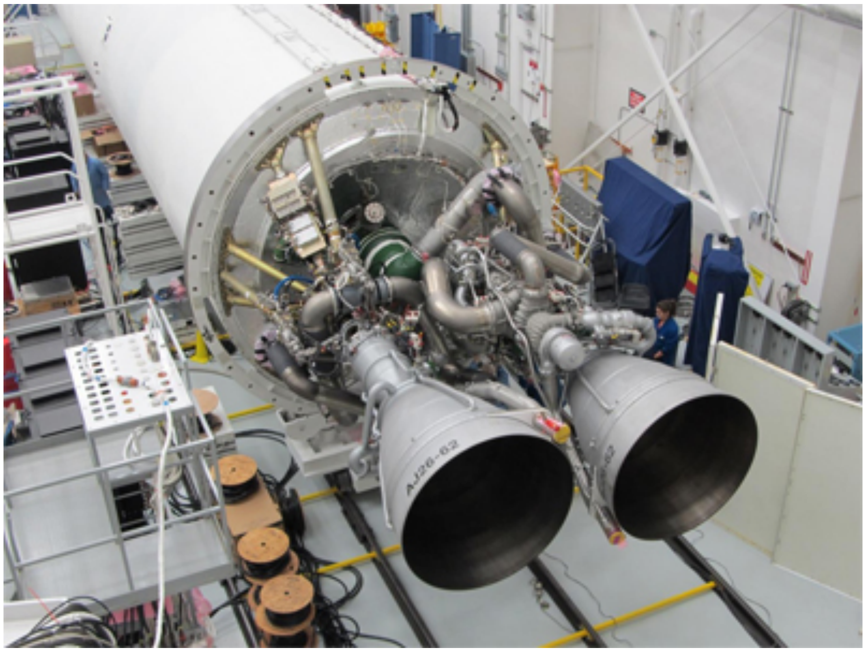

Figure 4. Antares First-Stage Core with Two AJ26 Engines Installed

Technical Root Causes

The IRT was not able to isolate a single technical root cause for the E15 fire and explosion. The IRT identified three credible technical root causes (TRCs), any one or a combination of which could have resulted in the E15 failure:

- **TRC-1: Inadequate design robustness of the AJ26 LO2 HBA and turbine-end bearing for Antares**. After performing extensive technical design evaluation and a number of sensitivity analyses of the LO2 turbopump, it became apparent to the IRT that the HBA and thrust bearing designs have several intricacies and sensitivities that make it difficult to reliably manage bearing loads. As a result, this area of the turbopump is vulnerable to oxygen fire and failures. The AJ26 engines were not subjected to a thorough delta-qualification program to demonstrate their operational capability and margin for use on Antares. Performing a thorough delta-qualification program for Antares would likely have revealed these issues. Furthermore, the Acceptance Test Program (ATP) established for the AJ26 engines was not sufficient to test and screen the engines for these design sensitivities and potential workmanship issues that could exacerbate those sensitivities.

- **TRC-2: Foreign Object Debris (FOD) introduction to the E15 LO2 turbopump**. Forensic investigation identified the presence of both titanium and silica FOD within E15 prior to its impact on the beach. However, no firm conclusions can be drawn with respect to the quantity of FOD introduced to or already present within the engine prior to or at the time of the explosion. The lack of significant particle impact damage to the recovered impeller and other components indicates that there were not gross-levels of FOD present within the system. In addition, there is no clear forensic evidence that FOD directly or indirectly led to the E15 failure.

- **TRC-3: Manufacturing or other workmanship defect in the E15 LO2 turbopump**. Forensic investigation performed by Orbital ATK and NASA discovered the presence of a defect on the turbine housing bearing bore that was not consistent with baseline design requirements[3]. The investigation determined that the defect was introduced during machining of the bearing bore housing and was therefore present prior to the engine ATP and Antares launch for Orb-3. Forensic investigation of Engine E17, which failed during ATP in May 2014, discovered the presence of a similar non-conforming defect in the housing bearing bore. A limited number of other engine turbine housings (i.e., Engine E16 and the 1998 test engine) previously and successfully subjected to extended ground tests and ATP, as well as an untested spare turbine housing, were inspected. Neither E16 nor the spare housing showed any evidence of a similar manufacturing defect. However, the 1998 test engine that had been subjected to extensive ground testing exhibited a similar defect to that observed in Engines E15 and E17, but it was not possible to conclude whether the defect was introduced during manufacturing or was the result of wear from extended operation of the engine. Sufficient information is not available without further engine inspections and tests to conclude that the presence of this manufacturing defect would always result in failure of the engine during operation.

The IRT determined that all three of these technical root causes would need to be addressed as part of any return to flight efforts for Antares. The IRT concluded that the failure could have been the result of any one of the identified root causes above; however, the presence of the machining defect and FOD could have increased the possibility of failure associated with the engine design and Antares operating conditions.

Technical Findings and Recommendations

The IRT developed six Technical Findings (TFs) associated with the technical root causes discussed above. Seven Technical Recommendations (TRs) were identified by the IRT that, if fully implemented, would likely resolve the technical root causes and prevent recurrence of a similar failure in the future.

In addition, since Orbital ATK was in the process of procuring and testing new engines to replace the AJ26 for future Antares flights while the investigation was ongoing, the IRT provided several additional technical recommendations for Orbital ATK and the ISS Program that were used to support those testing activities and to reduce overall risk for Antares return to flight and follow-on mission efforts. Given the technical nature of those recommendations, they are not provided here due to potential proprietary and export control restrictions.

[3] Further information about the turbine bearing bore housing design and the location and configuration of the defect is not provided due to proprietary restrictions.

Technical Findings	
TF-1	The AJ26 LO2 turbopump thrust bearing and HBA have numerous intricacies and sensitivities that make it difficult to reliably manage the bearing loads and makes this area of the turbopump vulnerable to failure and oxygen fires.
TF-2	Given the non-linear rotordynamic behavior of the NK-33/AJ26 LO2 turbopump, life testing at the 2x Antares mission profile and duration was not sufficient to demonstrate bearing life margin.
TF-3	The instrumentation suite for the engines during flight and ATP was not sufficient to gain adequate insight into engine performance and to support anomaly investigation efforts.
TF-4	A comprehensive delta-qualification program for the AJ26 engine with the design changes and flight parameters planned for Antares missions was not performed.
TF-5	Although the IRT cannot definitively conclude that FOD was the cause or a contributor to the E15 failure, evidence suggests that FOD was present within E15 at the time of failure.
TF-6	Based on forensic inspection of E15 and E17, workmanship issues in E15 are credible contributors to the Orb-3 failure.

Technical Recommendations		Finding(s) Addressed by Recommendation
TR-1	NASA should not rely on the AJ26 for further missions without undertaking a more thorough inspection, qualification and acceptance test, and certification program.	TF-1, TF-2, TF-4, and TF-6
TR-2	For the new RD-181 engine that Orbital ATK has identified as a replacement to the AJ26 engine, Orbital ATK should ensure a thorough qualification program and acceptance test program is implemented specific to planned Antares operations.	TF-2 and TF-4 (Also, PF-7, PF-8)
TR-3	For future Antares missions, additional MES sensors and sensor filtering should be provided by Orbital ATK.	TF-3
TR-4	For future engine ATPs, sensors more suitable to the test environment should be utilized, and sensors should be better placed to understand and characterize engine performance.	TF-3
TR-5	Greater insight and verification activities should be implemented to ensure that cleanliness is consistent with engine (and other critical component) requirements.	TF-5
TR-6	To further reduce the likelihood of moisture intrusion into the engine, a more robust and verifiable moisture barrier approach should be utilized by Orbital ATK.	TF-5
TF-7	Orbital ATK and NASA should have greater insight into and understanding of engine design, certification, and operation.	TF-1, TF-2, TF-3, TF-4, TF-5, TF-6

Programmatic Findings and Recommendations

In addition to ascertaining the technical root cause of the Orb-3 failure, the IRT was tasked with informing the Agency's risk posture in order to support Orbital ATK's return to flight activities and to make recommendations on how to develop, operate, and acquire more reliable systems. To support evaluation of these "programmatic assessment" areas, the IRT developed a programmatic leg of the Orb-3 failure fault tree to determine how well the ISS Program and NASA understood the Antares launch vehicle risk.

The programmatic portion of the fault tree was divided into three distinct legs for further evaluation, focusing on three risk areas that could be potential contributing factors to the loss of the Orb-3 mission:

- NASA's definition of the risk policy and model for CRS missions, and how well the policy and model was understood and flowed within NASA and Orbital ATK.

- Communication of risk at a variety of levels and interfaces, such as between Orbital ATK and its vendors, between NASA and Orbital ATK, and internally within NASA.

- The level of insight to and understanding of technical risk at a variety of levels and interfaces, such as risk insight and understanding by Orbital ATK, risk insight and understanding by the Aerojet-Rocketdyne, risk insight at the system and subsystem level by NASA, and risk understanding and agreement between the ISS Program and its supporting organizations.

As part of its programmatic assessment efforts, the IRT concluded that the CRS model is generally working as intended:

- The management and risk model established for commercial services is well understood and embraced by and at all levels of the NASA team and community.

- Orbital ATK acknowledges and accepts primary responsibility for managing launch vehicle risk.

- Orbital ATK and NASA understand and agree on the need for sufficient technical insight by NASA to understand launch vehicle risk and to enable NASA to manage overall ISS risk.

- ISS Program Management believes that CRS is realizing a significant cost savings for cargo delivery to ISS, even in spite of schedule delays and mission failures.

- Good working relationships have been established between NASA and Orbital ATK, and these comfortable relationships seem to foster open and thorough communication.

- The ISS Program's approach to manifesting cargo based on launch vehicle risk, need for the cargo on-orbit, and overall cargo criticality ensures a balance of CRS mission risk (i.e., loss of cargo) against ISS risk (i.e., critical need for cargo, value of cargo).

The IRT identified opportunities for improvement in several general areas, which are captured in the eight Programmatic Findings (PFs) listed and the six Programmatic Recommendations (PRs) listed below. The IRT recognizes that these opportunities for programmatic improvement come with additional program cost but believes the reductions in risk and other benefits to be gained could be worth the additional costs.

Programmatic Findings	
PF-1	Overall, there is clear and consistent understanding and acceptance of the CRS risk approach throughout NASA and by the Service Providers.
PF-2	The perception of acceptable risk for any given CRS mission varied significantly within and between NASA organizations.
PF-3	The Launch Vehicle Assessment (LVA) as currently developed may provide a false sense of security in the overall risk associated with the launch vehicle design and a particular mission.
PF-4	The proprietary nature of launch vehicle information may be serving as an artificial barrier to communications and leading to communication shortfalls.
PF-5	Although the launch vehicle designs from the Service Providers continue to evolve under CRS, the Launch Vehicle Manager (LVM) does not have the benefit of a COTS development phase or funding to assess those changes.
PF-6	A variety of factors contributed to Orbital ATK accepting greater launch vehicle risk (and thus NASA accepting more risk of cargo loss) as time went on, and contributed to the lack of an integrated partnership between Orbital ATK and Aerojet-Rocketdyne as time went on.
PF-7	Aerojet-Rocketdyne and Orbital ATK lacked sufficient NK-33 design and operational knowledge, as well as failure history knowledge, for the NK-33 engine.
PF-8	A lack of design and operating insight into the AJ26 engines creates a low level of confidence in loss-of-mission predictions made by Orbital ATK and Aerojet-Rocketdyne.

Programmatic Recommendations		**Finding(s) Addressed by Recommendation**
PR-1	The ISS Program should reassign LVA management responsibility to a senior engineer at the Marshall Space Flight Center (MSFC) with significant launch vehicle development and assessment experience, as well as increase the number of individuals from MSFC engineering supporting development of the LVA.	PF-3, PF-5, and PF-8
PR-2	The ISS Program should establish a standing working group for parties with launch vehicle responsibilities (e.g., ISS, Engineering, Launch Services Program) to openly discuss and coordinate launch vehicle issues, status of risk assessment activities, etc.	PF-3, PF-4, and PF-5
PR-3	Within the constraints of the CRS contract, the ISS program should more fully disseminate launch vehicle design, anomaly, and other information to personnel supporting LVA activities.	PF-3 and PF-4
PR-4	The ISS Program should formally define and communicate a baseline level of acceptable risk, even if qualitative, to be considered for CRS missions, and in particular launch vehicle risk, to ensure personnel throughout the program are all assessing issues to a consistent risk level.	PF-2

Programmatic Recommendations		**Finding(s) Addressed by Recommendation**
PR-5	For future instances where NASA intends to share development costs and risks with commercial industry, NASA should apply the various risk reduction lessons learned from the COTS/CRS efforts associated with the Orb-3 failure. a. Allow time for system development and demonstration efforts to be fully complete prior to establishing milestone-based fixed-price contracts to purchase services using those systems. b. When providing financial investments to commercial industry to develop launch vehicles, perform a greater level of due diligence for major system components. This due diligence should not only include technical focus, but also contractual relationships and programmatic integration plans between the prime Service Providers and their contractors for major system components. c. When providing financial investments (contract) to commercial industry to develop launch vehicles that might be used later to provide services to NASA, include contract provisions to require/ensure an integrated partnership exists between service providers and engine providers (and with other critical/highly coupled system/component providers, like flight software and GN&C systems) given the criticality and complex integral role the engine plays in launch vehicle mission success.	PF-6 and PF-8
PR-6	The Service Providers and NASA should have sufficient technical expertise and insight into the design, development, test, and failure history of the engines (as well as all launch vehicle systems).	PF-3, PF-7, and PF-8