Public Release Summary of the Geostationary Operational Environmental Satellite-17 (GOES-17) Advanced Baseline Imager (ABI) Loop Heat Pipe (LHP) Mishap Investigation Board Report

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Overview of the Geostationary Operational Environmental Satellite-17 (GOES-17) Advanced Baseline Imager (ABI) Loop Heat Pipe (LHP) Mishap Investigation Board Report

For Public Release

Mishap Summary

The National Oceanic and Atmospheric Administration (NOAA) operates a system of environmental satellites in geostationary orbits to provide continuous weather imagery and monitoring of meteorological data for the United States, Latin America, much of Canada, and most of the Atlantic and Pacific Ocean basins. The Geostationary Operational Environmental Satellite (GOES) system provides atmospheric, oceanic, climatic, and solar products supporting weather forecasting and warnings, climatologic analysis and prediction, ecosystems management, and safe and efficient public and private transportation. The GOES system also provides a platform for space environmental observations, and auxiliary communications services that provide for GOES data rebroadcast, data collection platform relay, low-resolution imagery, emergency weather communications, and satellite-aided search and rescue.

The GOES-R Series Program is a collaborative effort between NOAA and the National Aeronautics and Space Administration (NASA) to extend the availability of the operational GOES system through 2036. The GOES-R Series includes development and acquisition of spacecraft, instruments, launch services, and all associated ground system elements and operations for four satellites. These satellites are designated GOES-R/S/T/U until they reach orbit, at which time they are renamed GOES-16/17/18/19. GOES-16 (formerly called GOES-R) serves as the operational geostationary weather satellite over the U.S. east coast. GOES-17 (formerly called GOES-S) became the operational GOES West satellite on February 12, 2019. The remaining GOES-R Series satellites, GOES-T and GOES-U, are currently in development.

The Geostationary Operational Environmental Satellite-S (GOES-S) spacecraft was launched on March 1, 2018, and achieved geostationary orbit on March 12, 2018. GOES-S was officially re-designated GOES-17 upon reaching geostationary orbit. The spacecraft was powered on and the outgassing phase began on March 19, 2018. The GOES-17 Advanced Baseline Imager's (ABI's) Optical Port Cover (OPC) was opened April 13, 2018. The ABI is the primary instrument on the GOES-R Series of satellites for imaging Earth's weather, oceans and environment. ABI views the Earth with 16 different spectral bands (compared to five on the previous generation of GOES), including two visible channels, four near-infrared (IR) channels, and ten IR channels. These different channels (wavelengths) are used by models and tools to indicate various elements on the Earth's surface or in the atmosphere, such as trees, water, clouds, moisture or smoke. ABI is a mission-critical payload for the GOES-R Series, providing more than 65 percent of all mission data products currently defined.

Following the opening of the ABI's OPC, the two loop heat pipes (LHPs) in the ABI's radiator/loop heat pipe (R/LHP) cooling system began to self-start every day when entering the hot phase of the orbit (approximately 6:30 Coordinated Universal Time [UTC]), where light from the Sun entered the optical port. The LHPs (designated LHP1 and LHP2) would run for approximately three hours and would then shut down after the Sun's light no longer entered the optical port. These self-starts were not planned; however, self-starts were considered normal in LHP operations.

At 22:19 (UTC) on April 28, 2018, flight controllers commanded the LHP start-up heaters to activate for the first controlled start of the GOES-17 ABI LHPs. Both LHPs started at approximately 22:52; however, telemetered temperatures indicated the LHPs were underperforming. The evaporator temperatures (an indicator of how well LHPs carry heat load) fell from 292K to only about 286K (versus an expected ~270K) over 15 minutes before beginning to rise. This situation was indicative of the LHP's entering a "laggard" mode in which heat could not be effectively transferred to the radiator. LHP2 shut down at 0:05 (UTC) April 29, 2019. The flight controller commanded a shutdown of both LHPs at 2:03 (UTC).

The following day, April 29, 2018 flight controllers attempted to test the two loop heat pipes independently. During these tests LHP2 did not initialize but LHP1 did. However, it was noted that LHP1 was not able to carry the full thermal load from the cryocoolers without exceeding preset limits on temperature. Data logs show both LHPs self-starting around 6:45 (UTC), and running until ~9:40. Flight controllers began to attempt to re-start LHP2 at 22:20 on April 29, 2018. Telemetered data indicated a start-up of LHP2 at 23:05. However, LHP2 was transferring relatively little heat. At ~23:45, flight controllers shut down the cryocoolers and LHP2. A similar attempt was made with LHP1 starting an hour later (0:40, April 30, 2018 UTC). Although LHP1 was carrying more heat load than LHP2, the heat load was still short of the expected amount. LHP1 was allowed to continue running until 14:53 (UTC) on May 1.

The GOES-R Flight Project continued troubleshooting the LHP issue for the next several months. On May 16, 2018 a yaw flip was executed in an attempt to test LHP performance with no direct solar loading from the radiator; however, this maneuver did not improve LHP performance. On May 23, 2018 NOAA publicly announced that there was an anomaly, and on May 29 a GOES-R Program-convened Independent Review Team (IRT) had its first meeting at the Advanced Baseline Imager (ABI) Contractor facilities in Fort Wayne, Indiana. The IRT was staffed by LHP experts from within and external to NASA and was focused on the physical hardware in developing a set of most likely proximate causes. An Optimization Team (consisting of members from the GOES-R Project team, the ABI Contractor, Spacecraft Contractor, and the user community) was also established to develop procedures to obtain as much data as possible out of the satellite. This team held its first meeting in Fort Wayne, Indiana the following week. The Optimization Team has been able to define alternate operations, procedures and hardware operating limits which have resulted in a 97 percent data availability for the GOES-17 ABI. With 97 percent data availability restored, GOES-17 became the operational GOES West satellite on February 12, 2019.

The lack of adequate cooling results in periodic loss of IR data on 13 of the 16 ABI spectral channels. The instrument's infrared detectors cannot be maintained at their required operating temperatures under certain seasonal and orbital conditions, resulting in a loss of approximately three percent of the instrument's availability over the course of a year[1]. A key performance parameter is that the ABI cannot experience data outages of more than six hours per year. Although the Optimization Team has provided 97 percent data availability, the inability to meet the limit of six hours or less of data outage per year resulted in NASA and NOAA declaring a mishap and jointly convening the GOES-17 ABI LHP Anomaly Mishap Investigation Board (MIB) on September 28, 2018. For the purpose of classifying the mishap, the estimated direct cost of the mishap was calculated as 3% of the $100M cost of the GOES-S ABI instrument. The $3M direct cost resulted in the mishap being entered as a Type-A mishap into the NASA Mishap Information System (NMIS).

GOES-17 MIB Investigation Process and Results

The MIB was tasked with gathering information; analyzing the facts; identifying the proximate causes, root causes, and contributing factors related to the ABI LHP performance issues; and recommending actions to prevent a similar mishap from occurring. The MIB conducted its investigation according to NPR 8621.1C, NASA Procedural Requirements for Mishap and Close Call Reporting, Investigating, and Recordkeeping[2] The MIB gathered evidence from over 30 one on one interviews and discussions, visits to the ABI Contractor and LHP Subcontractor sites, a large amount of project documentation, telemetered flight data, and pre-launch and post-anomaly test data and used this information to generate timelines, a Fault Tree and an Event and Casual Factor Tree (ECFT). The MIB based its Fault Tree and the resulting event and causal analysis on an undesired outcome related to the loss of mission data resulting from the inadequate cooling of the ABI detectors. Although the loss of data to support the NOAA mission is a critical aspect of the undesired outcome, the MIB also included, for consistency, a reference to the direct cost used to classify the mishap in the following undesired outcome: *The GOES-17 ABI Experienced a $3M Loss of Mission Data due to Inadequate Cooling of the ABI Detectors*.

The MIB developed a fault tree with the undesired outcome as the top-level failure event and populated the tree by incorporating additional elements that could potentially lead to the undesired outcome. Upon completion of the fault tree, the MIB evaluated each element to determine whether it could be closed (i.e., to prove it could not have occurred) so that it could be "ruled out" as a causal factor. The MIB had at its disposal a significant amount of data and analysis provided by the IRT, the ABI Contractor and LHP Subcontractor that examined the potential physical or "hardware" causes of the anomaly. The MIB thoroughly analyzed and carefully considered this data as it assessed the independently developed Fault Tree elements to support the causal analysis.

NASA has completed the Agency's assessment of the GOES-17 MIB report. The report is NASA sensitive, but unclassified (SBU), because it contains company proprietary information. The report also contains information restricted by the International Traffic in Arms Regulations (ITAR) and/or the Export Administration Regulations (EAR). This summary report provides an overview of publicly releasable information contained in the full report.

Proximate Cause and Highest-Level Intermediate Cause

Through its causal analysis, the MIB identified the following proximate cause and highest-level intermediate cause:

GOES-17 MIB-determined Proximate Cause:
ECFT-3: *The ABI R/LHP System Failed to Reject the Necessary Heat to Cool the ABI Detectors as Designed*

The R/LHP may not have been able to dissipate all of the heat routed to it due to a design or operational limitation or an on-orbit condition. This event assumes that the amount of heat routed to the LHP was within the design limit. Analysis of the LHP performance on orbit shows that LHPs initially were only carrying 60 W of heat load, and that load soon after dropped to 10 W to 20 W. The on-orbit requirement is 390 W. This indicates that there was either a design issue or failure on-orbit.

GOES-17 MIB-determined highest-level Intermediate Cause:
ECFT-6: *The ABI LHPs had Insufficient Working-Fluid Flow to Carry the Required Heat Load*

This intermediate cause indicates that the movement of the working fluid was inadequate to dissipate the heat load being provided to the LHP.

With the limited set of available telemetry data and without the ability to evaluate the in-flight hardware, the R/LHP failure could not conclusively be isolated to a specific part or failure. These circumstances prevented the MIB from developing causal linkages below the intermediate level. However, after reviewing all of the data available, the MIB concludes that the most likely technical explanation for the failure of the GOES-17 LHPs to transport and reject their expected heat load is physical blockage of the LHP assembly by particulates contained in the working fluid.

In its causal analysis, the MIB examined objective evidence for causal elements in six categories (quality, requirements, design, testing, contamination, and structures) to assess the impact of each element as a potential contributor to the mishap. The MIB determined the engineering, process, and organizational issues related to those elements and have provided recommendations to address the issues identified.

Overview of GOES-17 MIB Recommendations:

An overview of the intent of key recommendations from the MIB report is provided below. NASA/NOAA will determine how these recommendations apply to the GOES-R program as well more generally to other programs in both agencies.

- When presented with evidence that requirements are driving significant design changes or unique design solutions, a requirements vs. design trade should be performed to assess the rationale for the higher level requirements and decomposition of these requirements to reduce design risk. This assessment should be conducted as part of the convening authorities' evaluation during milestone design reviews.

- Contractors' deliverables should be evaluated to ensure that failure modes and effects analyses (FMEAs) include failure modes, criticality, and mitigation plans down to the component level for all instrument subsystems including subcontractor hardware.

- The use of Technology Readiness Assessments on ALL new flight builds should be used during formulation to ensure an adequate risk posture is identified (as discussed in the Final Report of the NASA Technology Readiness Assessment [TRA] Study Team [2016][3], located at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170005794.pdf

- Data delivery requirements should be levied on prime contractors to enable the required TRA to be performed by NASA on the contractors' designs. An evaluation of the technology readiness level (TRL) of new technologies should be required at the preliminary design review (PDR).

- The roles and responsibilities of program and project leadership down to the instrument level should be included in program/project documentation to clarify decision-making authority, ownership, and accountability. These roles and responsibilities should be reviewed with the team, Program Management and institutional engineering to facilitate understanding and ensure personnel with the required skills are assigned.

- NASA/NOAA project team members should be encouraged to ask questions and initiate requests for action (RFAs) during the Lifecycle Design Reviews.

- Any actions and issues identified during a Lifecycle Review dry run that are still open at the time of the lifecycle review should be required to be submitted as RFAs for evaluation by the board.

- Requirements that are derived for fluid system cleanliness should be compatible with the smallest expected flow path dimensions and the system sensitivity to particulates.
- Cleaning procedures should be in place (including procedures for subsystems and components) to verify through testing that the final particulate levels of working fluids in closed systems meet the contamination requirements of the system designs.
- A process for how NASA participates and establishes a technical position at contractor Failure Review Boards (FRBs) should be documented.
- Training to re-inform personnel supporting projects about pathways to voice concerns and the roles and responsibilities of technical authorities (TAs) should be provided. This training should re-emphasize the importance of expressing alternate viewpoints and dissenting opinions.
- All TA representatives should be directed to actively seek out issues and alternate viewpoints from discipline engineering leads, subject matter experts (SMEs), and safety and mission assurance (S&MA) personnel (quality assurance providers, mission assurance personnel, safety experts, etc.) at all levels within projects. To encourage these discussions, the program should develop a process or institute a forum to document and discuss alternate viewpoints to ensure they are appropriately heard, considered and addressed.
- All performance data from systems of the same design (i.e., the same series of instruments, including other systems tested for other customers) should be required to be evaluated as part of the FRB process and that all possible differences in hardware (e.g. different lots or manufacturers) are assessed thoroughly as contributing factors internal and external to the system.
- The documented NASA FRB position should be reviewed for increased risk level or new risks, especially when no definitive root cause for an issue is identified; document a formal conclusion on whether there is a new or increased risk level; and elevate areas of increased risk to the Program Risk Board.
- Independent problem resolution teams including technical experts outside the project (reaching across the Agency) should be used when an FRB finds no definitive root cause and project risk is increased. The use of an independent problem resolution team should be discussed and evaluated as part of developing a NASA/NOAA technical position.
- The components of a flight system that are capable of shedding particles that might affect the system performance should be identified and design requirements should be developed to enable the system to perform as intended.

- When proprietary data concerns result in a contractor presenting high-level summary statements and general conclusions without supporting detailed data, NASA should question and scrutinize such summary statements and conclusions.
- NASA should identify and implement flight instrumentation to more easily enable forensics or diagnostic capabilities.

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[1] GOES-R Series website: https://www.goes-r.gov/users/GOES-17-ABI-Performance.html

[2] NPR 8621.1C, NASA Procedural Requirements for Mishap and Close Call Reporting, Investigating, and Recordkeeping

[3] HQ-E-DAA-TN43005, Final Report of the NASA Technology Readiness Assessment (TRA) Study Team (March 2016).