Starliner Propulsion System Anomalies during the Crewed Flight Test - Investigation Report

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Rebecca J. Wingfield
Chair, Investigation Team

Original signed on 2/5/2026

Ben Papineau
Deputy, Investigation Team

Concurred by:

Original signed on 2/9/2026

Ken Bowersox
Associate Administrator, Space Operations Mission Directorate

Executive Summary

The Boeing CST-100 Starliner Crewed Flight Test (CFT), launched on June 5, 2024, under NASA's Commercial Crew Program (CCP), was a pivotal mission in certifying this U.S. commercial vehicle for transporting astronauts to the International Space Station (ISS). Originally planned as an 8-to-14-day mission, CFT was extended to 93 days due to significant propulsion system anomalies. The Starliner capsule ultimately returned uncrewed, while astronauts Barry "Butch" Wilmore and Sunita "Suni" Williams returned aboard SpaceX's Crew-9 Dragon in March 2025.

In February 2025, NASA chartered the Program Investigation Team (PIT) to investigate the technical, organizational, and cultural contributors to the anomalies occurring during CFT. The team's findings reveal a complex interplay of hardware failures, qualification gaps, leadership missteps, and cultural breakdowns that collectively posed unacceptable risks to crew safety.

This report was compiled and completed in November 2025, while technical cause investigation continues. This report does not reflect any new learning or iteration of the fault tree or proximate cause through ongoing testing, analysis and discovery post-report compilation. Iteration in proximate cause is expected.

The key technical anomalies investigated in this report can be broken down into four distinct hardware anomalies, outlined below:

<u>**Key Technical Anomalies**</u>

1. **Service Module (SM) RCS Thruster Anomaly**
   a. Five thrusters triggered fail off FDIR during ISS rendezvous resulting in a temporary loss of 6 Degrees of Freedom (6DOF) control.
   b. In-situ troubleshooting recovered four of five jets, enabling docking.
   c. Manual piloting did not specifically contribute to thrusters triggering their fail-off FDIR.
   d. <u>Most probable proximate (direct) causes and contributing factors:</u>
      i. Two-phase oxidizer flow (vaporization and cavitation)
      ii. Teflon poppet extrusion in oxidizer valves, restricting flow
      iii. Mechanical demand from GNC firing requests
2. **Crew Module (CM) RCS Jet Failure**
   a. A thruster failed to fire during descent, reducing the system to zero fault tolerance.
   b. <u>Leading theory:</u>
      i. Corrosion from carbazic acid formed by residual propellant and CO_2
3. **Helium Manifold Leaks**
   a. Seven of eight SM helium manifolds leaked during the mission.
   b. <u>Most probable proximate (direct) cause and contributing factor:</u>
      i. Material incompatibility of seals with oxidizer, leading to degradation and leaks
      ii. O-ring sizing and poor gland fill/squeeze tolerances
4. **Deorbit Capability Fault Tolerance**
   a. The propulsion system lacked required two-fault tolerance for deorbit burns, which was a design flaw present since early development but not identified until CFT pre-launch.

The investigation revealed multiple common findings and observations that led to the key technical anomalies experienced during CFT. These causes are outlined below:

<u>**Key Findings and Observations (Truncated Summary)**</u>

- **Inadequate Qualification Testing**: The propulsion system lacked enveloping, mission-representative testing, and NASA accepted insufficient verification data in lieu of qualification.
- **Insufficient Flight Data**: Low telemetry sample rates and lack of onboard data storage limited the ability to assess thruster performance and contributed to misdiagnosis of anomalies on Orbital Flight Test (OFT) 1 and OFT2.
- **Anomaly Resolution Discipline**: Acceptance of unexplained anomalies (UAs) without root cause resolution allowed systemic issues to persist from OFT1 and OFT2 into CFT.
- **Oversight and Insight Limitations**: NASA's insight into subcontractor-level data was restricted, limiting its ability to independently verify system readiness.
- **Schedule Pressure**: Persistent proximity to launch over several years created a high-stress environment, dictated a restrictive risk reduction initiative, and contributed to degraded trust with the workforce and overall fatigue.
- **Cultural and Contractual Misalignment**: The shared accountability model was poorly understood and inconsistently applied, leading to muddling of roles, responsibilities, and risk ownership.
- **Hardware Longevity and Sparing Concerns**: Starliner's limited hardware spares and the impending retirement of the Atlas V launch vehicle raise concerns about the program's long-term viability.

The PIT also identified cultural and leadership challenges that undermined technical rigor and exacerbated technical risks. These organizational findings are outlined below:

<u>**Near-Real Time Cultural and Organizational Findings**</u>

1. **Decision Authority**
   - Overlapping roles between NASA's CCP, ISSP, and Boeing led to unclear governance.
2. **Erosion of Trust**
   - Mistrust between NASA and Boeing was intensified by selective data sharing, perceived favoritism, and inconsistent transparency.
   - NASA teams outside CCP felt excluded from critical decisions, while CCP felt overwhelmed by external input.
3. **Leadership Approach**
   - CCP and Boeing leadership were perceived as overly risk-tolerant and dismissive of dissenting views.
   - A risk-acceptance posture created division and undermined confidence in the decision-making process.
4. **Team Dynamics and Communication**
   - The mission was marked by chaotic meeting schedules, unclear roles, and communication breakdowns.
   - Survey data shows low effectiveness ratings in team dynamics and organizational structure.
5. **Cultural Divergence**
   - NASA's traditional culture of technical rigor clashed with the commercial model's emphasis on provider autonomy.

All of the findings explained in this report led the team to determining the following as root causes for the anomalies that occurred over the CFT:

<u>**Root Causes (Organizational)**</u>

While these root causes are specifically separated out to bulletize each, it is nearly impossible to consider one without the others. It is important to keep in mind, **NASA created and implemented the contract structure; Boeing built the vehicle. Together the organizations agreed to fly.**

- **NASA's hands-off contract approach limited insight into the Starliner's development.**

- **Boeing's inadequate systems engineering and reliance on subcontractors without sufficient oversight created gaps in hardware qualification.**
- **NASA CCP's culture prioritized provider success over technical rigor.**

Mishap Classification

The PIT determined that the loss of 6DOF control during ISS rendezvous meets the criteria for a Type A mishap under NASA Procedural Requirements (NPR 8621.1D) for a loss of controlled flight on the docking axis due to thruster failures. An alternative argument could be made to classify as a High Visibility Close Call, since control was regained through in-situ troubleshooting which concluded in a safe docking of the Starliner spacecraft to the ISS.

The PIT recommends that the event be retroactively classified as a Type A mishap and that this report serve as the final mishap investigation report.

Lessons for Future Programs and Development Vehicles

The CFT mission offers critical insights for future commercial and government-led human spaceflight programs. These lessons are broadly applicable to new vehicles, architectures, and contracting models.

1. **Design and Qualification**
   a. **Lesson:** Qualification testing must reflect all mission-representative environments including but not limited to duty cycles, thermal environments, integrated system behavior, re-use, launch pad config, dynamic and quiescent operations, etc.
2. **Data and Telemetry**
   a. **Lesson:** Inadequate telemetry sample rates hindered anomaly detection and resolution.
3. **Fault Tolerance and Hazard Analysis**
   a. **Lesson:** A critical fault tolerance gap in the deorbit system went undetected for years.
4. **Organizational Integration**
   a. **Lesson:** Fragmented roles and responsibilities delayed decision-making and eroded confidence.
5. **Shared Accountability and Insight**
   a. **Lesson:** The commercial model's shared accountability was inconsistently understood and applied.
6. **Anomaly Resolution Discipline**
   a. **Lesson:** Repeated acceptance of unexplained anomalies (UAs) without root cause led to recurrence.
7. **Cultural Alignment**
   a. **Lesson:** Divergent risk assessments between NASA and providers created friction.

Conclusion and Path Forward

The CFT mission, while ultimately successful in preserving crew safety, revealed critical vulnerabilities in the Starliner's propulsion system, NASA's oversight model, and the broader culture of commercial human spaceflight. The PIT issued 61 formal recommendations across technical, organizational, and cultural domains to address these issues before the next crewed Starliner mission.

The report underscores that technical excellence, transparent communication, and clear roles and responsibilities are not just best practices, they are essential to the success of any future commercial spaceflight missions. The lessons from CFT must be institutionalized to ensure that safety is never compromised in pursuit of schedule or cost.

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1 Scope of Investigation

1.1 Mission Background

The Boeing Starliner Crewed Flight Test (CFT) represents a critical milestone in NASA's Commercial Crew Program (CCP) certification of Starliner as a U.S. commercial spacecraft to transport astronauts to and from the International Space Station (ISS). Starliner was launched on June 5, 2024, from Cape Canaveral Space Force Station, carrying NASA astronauts Barry "Butch" Wilmore (CDR) and Sunita "Suni" Williams (PLT) to the ISS. Initially planned as an 8- to 14-day mission, the flight was extended to 93 days due to technical anomalies. These anomalies ultimately culminated in an uncrewed return of the Starliner capsule to White Sands Space Harbor (WSSH) on September 7, 2024. Wilmore and Williams remained aboard the ISS as part of Expedition 71/72 and returned to Earth on March 18, 2025, aboard SpaceX's Crew-9 Dragon.

The CFT mission encountered challenges that tested both the spacecraft and operations team. Anomalies included a **loss of 6 degree of freedom control** due to reduced thrust from service module reaction control system jets, leaks from the helium lines used to pressurize the propulsion system and pneumatically operate valves, and a crew module thruster that did not operate during descent.

Acquiring vehicle operational knowledge, testing new systems, and working through anomalies are expected on test flights of a new spacecraft. However, the propulsion system anomalies on the Starliner during CFT were more significant than anticipated. **The unknown likelihood associated with the reliability of using the SM RCS for departure, from ISS, posed a risk to human life that could not be bounded with agreed to margins, during the mission.**

The anomalies experienced during CFT require attention and rigor in resolution. This report provides an in-depth evaluation of technical details regarding the anomalies prompting this investigation, as they are known at the time of writing this report. **It is important to understand that while much can be learned from this investigation, the testing and analysis that supports the proximate causes of these anomalies is ongoing.** This investigation also conducts an evaluation of the team dynamics that created friction throughout the decision-making process to return Starliner uncrewed.

Despite the anomalies, the extended CFT mission provided valuable data on Starliner's on-orbit performance and offered an opportunity for the Starliner crew to contribute to ISS operations and research. **While the CFT mission can be remembered as arduous and ripe with lessons to learn, the decisions made in flight ultimately prioritized the safety of the crew and can be seen in hindsight as a successful use of NASA's overarching governance model.** The CFT mission underscored both the promise and the complexity of integrating commercial systems into human spaceflight. Most importantly, it has highlighted the importance of rigorous systems engineering and validation for all future missions.

1.2 Unique Position in Human Spaceflight History

It is necessary to establish context for the time period of the CFT mission. This mission was conducted in a unique period of Human Spaceflight (HSF) history. The current era is marked by a transition within NASA and its many partners and providers, from predominantly government-owned and -led projects to programs and objectives increasingly driven by contracted services and provider-led operations. While there is clear momentum and strategic intent to leverage commercial capabilities, this shift is still in its early stages, and many foundational elements are being refined.

A unique aspect of the CFT mission is the crew's access to options, which is quite unique in the history of human spaceflight. Chief among these was the availability of a stable and highly capable safe-haven in Low Earth Orbit (LEO), the ISS. The ISS can support multiple crew members for extended durations and provides an environment that allows for problem-solving and contingency planning. This capability proved invaluable during the CFT mission. Additionally, the ISS is regularly serviced by a fleet of vehicles, including two spacecraft specifically designed for human transportation. **The combination of a reliable safe-haven and multiple crew transport options created operational flexibility that had not been exercised to this extent.**

In some ways, CFT was the first crewed test flight in the fully commercial model. Although the SpaceX Dragon vehicle completed a crewed test flight in 2020, that flight was preceded by nearly a decade of cargo Dragon operations, contracted by NASA as part of the Commercial ReSupply (CRS) service to ISS. During this preceding contracted service, the initial design of Dragon was tested and flown. Many similar lessons were learned and the Dragon design evolved and improved. In contrast, CFT was just the third flight of Starliner, a new design spacecraft. The success of a design is not specifically driven by the number of flight tests. Integrated test and supplemental analysis rooted in test are also keys to success, whether in-flight or on the ground. **While CCP contracted with 2 companies for the development of 2 transportation services, the companies, their approach to fulfilling the need and the vehicles themselves are different.** Attempting direct comparisons, especially in a given timeline where the development cycles are in different phases, results in unbalanced conclusions.

Additionally, SpaceX is a vertically integrated company, manufacturing many components and systems in-house. Boeing uses a multitude of capable subcontractors to acquire hardware, much of it with heritage design and successful track records. Neither approach is specifically right or wrong, but worth noting that they are different and thus not a one-for-one comparison.

1.3 Establishing the Investigation

In February 2025, the Starliner CFT Program Investigation Team (PIT) was charted by NASA's Associate Administrator, Space Operations Mission Directorate (SOMD), with details contained in distributed memo "Transition to Program Investigation Team for Starliner Propulsion Anomalies in International Space Station Proximity." This direction established a team to investigate the propulsion system anomalies experienced during the CFT mission. The investigation team has evaluated all events from the initial launch attempt through the currently available post-flight data review.

The team's primary objective is to identify the causes and factors behind the anomalies experienced during the Starliner CFT. The team was also instructed to leverage existing data from other investigating initiatives, such as the Starliner Tests and Anomalies Review (STAR) Investigation Team and the Starliner Data Review Team (SDRT), to avoid duplication of effort.

The PIT was tasked with evaluating four specific aspects of the CFT mission:

1. Root cause of helium manifold leaks in the Service Module (SM) propulsion system.
2. Root cause of Service Module (SM) thruster fail-offs leading to a loss of 6-DOF control.
3. Root cause of Crew Module (CM) thruster failure during entry, descent and landing phase of flight.
4. Review the culture and team dynamics associated with the near real-time decision-making team and process.

The objectives of the PIT are as follows:

- Identify the causes and factors that led to the propulsion system in-flight anomalies, including issues from previous flights, programmatic culture, programmatic resources, pre-flight processes, analysis, and test plans that led to a "Go" for launch with reduced system capability.
- Develop recommendations for change to future missions, including certification, processes, procedures, testing, analytical methods, and in-flight operations.
- Develop a fault tree for the following propulsion system anomalies:
    - Helium manifold leaks
    - Service Module (SM) Reaction Control System (RCS) Thruster fail offs
    - Crew Module (CM) RCS fail off
        - Each fault tree is to include proximate cause(s), intermediate cause(s), contributing factors, organization factors, observations and recommendations.
- Assess meeting/team/organization structure, contractor and contractual relationships, effectiveness in team decision making, and any potential cultural barriers or organizational factors that contributed to the findings.
- Produce a findings reports that includes all fault trees evaluating propulsion system anomalies with identified proximate, intermediate, and contributing causes, organizational factors, observations, and recommendations.

The full chartering memo, titled, "Transition to Program Investigation Team for Starliner Propulsion Anomalies in International Space Station Proximity," can be found as **Appendix F** of this report.

1.3.1 Team Membership

The Investigation Team includes representatives from a variety of disciplines. It is important to note that multiple members of this team were a part of the CFT mission. While this could introduce a bias into the findings, the team worked diligently to acknowledge their own experience and solely use evidence-based reporting and/or the opinions of interviewees as source data when determining the overall findings and observations included in this report.

The team divided into two sub-teams known as the "Root Cause" and "Decision-Making" teams. The Root Cause team focused on the technical issues, employing a traditional fault tree investigation of the Helium and SM RCS (loss of 6DOF Control) issues seen during CFT. The Decision-Making team focused on the "near real-time" decision making process and assessed the cultural issues witnessed during the mission execution timeframe.

Investigation Team and Regular Participants	
Position	Name
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
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[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
	[redacted]
[redacted]	[redacted]

Table 1: PIT Team Membership

Technical Experts who provided direct feedback or participated in fault tree reviews

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	

Table 2: Technical Experts in Fault Tree Reviews

2 Additional Investigations

During the CFT mission a substantial amount of analysis, technical discussion, and testing occurred. This work has been built upon in the time since landing. Additionally, several teams were created to investigate portions of the concerns that lead to the CFT mission result and propulsion system anomalies.

Post-Landing Investigation Efforts:

- Starliner Tests and Anomalies Review (STAR) Investigation Team – NASA CCP
- Starliner Data Review Team (SDRT) – NASA CCP
- Root Cause/Corrective Action (RCCA) Teams for prop issues – Boeing led, NASA participation
- Enterprise Root Cause/Corrective Action (eRCCA) – Boeing

A small workforce of capable engineers was needed to support both the Boeing/NASA Root Cause/Corrective Action (RCCA) process and the Program Investigation Team (PIT) process. The PIT received information through the NASA oversight and insight process to create independent fault trees and verify data for fault tree box closures because the RCCA activities for Helium and SM RCS (loss of 6DOF control) were in progress at the time of the creation of the PIT. For Helium and SM RCS (loss of 6DOF Control), the RCCA team continues through the testing path and campaign while the PIT focused on definition of root cause and forward recommendations.

The CM RCS RCCA investigation was earlier in its investigative state when the PIT was formed. The PIT took an observational role to the RCCA team through development of a fault tree for this anomaly. This RCCA effort remains unfinished at the time of the writing of this report. All RCCA efforts must be completed prior to the next flight of Starliner.

2.1 STAR Report Summary and Findings

The Starliner Tests and Anomalies Review (STAR) Investigation Team was established as an internal CCP investigation to identify lessons learned regarding initial certification approaches that could have prevented propulsion system anomalies experienced during CFT. This team looked back at the CCP history, developed Design, Development, Test, and Evaluation (DDT&E)/Certification timelines, collected historical data, and interviewed personnel with both CCP heritage and current experience. The findings of this investigation, along with any recommendations and lessons learned, can be found attached as Appendix G.

The Starliner PIT concurs with many findings from the STAR Report. The STAR contains significant organizational factors and relevant evidence that are applicable to observed failures and serves as a good internal look into CCP and the early days of NASA adoption of commercial services for human transportation. The review and findings of the STAR are specific to the NASA CCP and do not specifically reflect additional contributing factors from Boeing or other NASA entities (ISSP, technical organizations, FOD, etc).

A thorough review of the STAR report is advised. The PIT endeavoured to supplement the STAR report and not repeat its findings. A sampling of significant findings from the report is included below:

- Critical designs were set prior to CCtCap, with limited government interaction. Supplier contracts put in place early CCtCap for lot/lifetime buys of hardware design resulted in hardware propagation across numerous vehicles and increased impacts for change implementation.

- Resources and skills could have been more adequately addressed during key design activities prior to contract award.
- Rigor in resolving issues identified by NASA during early design reviews could have been increased.
- Shared accountability was applied inconsistently, and NASA incorrectly assumed commercial provider would effectively levy requirements and testing onto suppliers.
- CCP Requirements were adequate, but there was no spacecraft propulsion standard to provide guidance on qualification testing.
- CCP developed a good set of requirements, including design and construction standards. The CCP 1100 series of requirements were deliberately written at a higher-level, leaving room for provider innovation but there was also room for incorrect/inadequate interpretation by the providers.
- There was no specific design and construction standard(s) levied on this complex system which encompasses propulsion qualification and testing at system or subsystem levels.
- The Commercial Provider focused on meeting contractual requirement language resulting in insufficient demonstration across the components/system and ground/flight.
- RCS Thruster testing configuration was not flight like as it did not reflect actual duty cycles predicted for CFT, also it did not include insulative properties of the doghouse and included active cooling to reduce time between tests.
- Qualification tests had shortcomings.
- Suppliers' build quality/variability issues can be hard to exonerate for service modules, which is hardware that is disposed of during re-entry.
- The AR thermal model included the effects of jet firings, but these effects were not validated by ground testing. Boeing thermal model did not include the effects of jet firings before CFT.
- The thruster performance from OFT1 & OFT2 experienced greater than expected temperatures and continuing to operate lead to a false sense of security of the thruster capability/performance.
- Flight instrumentation locations for thermal sensors were limited and in different locations than the locations for RCS Thruster ground firings.
- OFT1 & OFT2 investigations did not include RCS/OMAC thruster firings and fault trees were not validated through subsequent ground testing.
- Limitations of flight measurements and data rates made troubleshooting RCS difficult.
- For OFT2, NASA/Boeing did not have tools to measure thruster degradation, simply treated the thruster as failed/operational.

2.2 Boeing's Enterprise Root Cause/Corrective Actions (eRCCA)

After CFT, Boeing performed an internal enterprise root cause/corrective action investigation. The eRCCA methodology is used to prevent recurrence of high severity or complex recurring problems by identifying more actual and potential causes. While the Technical RCCA teams focused on technical causes for the spacecraft anomalies, the enterprise RCCA focused on culture, people, processes and tools. This process investigated system programmatic and technical issues present during system design, verification and flight test that were not fully known, understood or resolved prior to CFT. The result concluded that issues encountered/discovered during CFT resulted in increased mission risk. During this investigation process, the systems engineering "V" was used as a structured tool to integrate the spacecrafts lifecycle, in order to identify root causes. A summary of the resulting causes and recommendations can be found in the appendix.[1]

[1] Labelled in the RCCA report as Root cause, as previously noted, the Boeing RCCA team does not utilize the same terminology as the NASA team for fault tree analysis.

3 Commercial Crew Program (CCP) Background

NASA's own words regarding the genesis of the Commercial Crew Program, via NASA.gov:

> "The Commercial Crew Program represents a revolutionary approach to government and commercial collaborations for the advancement of space exploration.
>
> **NASA's Prior Approach for Obtaining Crew Transportation Systems**
>
> Since the Mercury program in the early 1960s, NASA has used an almost identical operating model to achieve its goals of human spaceflight. This includes the Space Shuttle Program and the American portions of the space station. NASA identified a need for a crew transportation system and then the agency's engineers and specialists oversaw every development aspect of the spacecraft, support systems, and operations plans. A commercial aerospace contractor was chosen to build the system, ensuring that it meets the specifications spelled out by NASA. Personnel from NASA were heavily involved and oversee the processing, testing, launching, and operation of the crew system to ensure safety and reliability. All the hardware and infrastructure was owned by NASA.
>
> **Commercial Crew's Approach for Obtaining Crew Transportation Systems**
>
> NASA identified a need for a crew transportation system and a broad set of requirements that would be necessary to ensure crew safety. In the case of commercial crew, the need centered on safe, reliable, and cost-effective means of getting humans to low-Earth orbit, including the space station, and return safely to Earth. Interested companies are free to design in a way they think is best and are encouraged to apply their most efficient and effective manufacturing and business operating techniques. The companies own and operate their hardware and infrastructure. NASA's engineers and aerospace specialists work closely with the commercial companies, allowing for substantial insight into the development process and offering up expertise and available resources.
>
> **The Commercial Crew Program is the first time this model has been implemented.**
>
> NASA's Commercial Crew Program (CCP) was formed to facilitate the development of a U.S. commercial crew space transportation capability with the goal of achieving safe, reliable, and cost-effective access to and from the International Space Station and low-Earth orbit.
>
> CCP has invested in multiple American companies that are designing and developing transportation capabilities to and from low-Earth orbit and the International Space Station. By supporting the development of human spaceflight capabilities, NASA is laying the foundation for future commercial transportation capabilities.
>
> Ultimately, the goal is to establish safe, reliable, and cost-effective access to space. Once a transportation capability is certified to meet NASA requirements, the agency will fly missions to meet its space station crew rotation and emergency return obligations.
>
> Throughout the process, both NASA and industry have invested time, money and resources in the development of their systems. NASA also is spurring economic growth through this program as potential new space markets are created.

To accelerate the program's efforts and reduce the gap in American human spaceflight capabilities, NASA awarded more than $8.2 billion in Space Act Agreements (SAAs) and contracts under two Commercial Crew Development (CCDev) phases, the Commercial Crew

Integrated Capability (CCiCap) initiative, Certification Products Contract (CPC) and Commercial Crew Transportation Capability (CCtCap).

Additionally, to best facilitate the cost-effective shift to commercialization, NASA utilized a firm fixed price contracting type for CCtCap. This was a significant shift from the cost-plus contracting for traditional NASA builds of developmental vehicles. **These shifts signified that CCP was not only positioned to be an innovative, first-of-its kind program for NASA, but how it interacted with new and traditional space flight industry providers was setup to be significantly distinct and different.**

3.1 Orbital Flight Test (OFT) Summary

The following summary is directly quoted from the **DCC1-00709-15 OFT Final Test Report**:

> The Boeing CST-100 Orbital Flight Test (OFT) was completed in December 2019 and was the first orbital mission of the CST-100 Starliner spacecraft for the NASA commercial crew program. The mission was planned to be an eight-day test flight of the spacecraft, with primary test objectives to validate the integration and launch of the new vehicle on an Atlas V rocket, ascent, orbit operations, ISS rendezvous operations, docking, docked operations, undocking, descent, landing, and recovery.
>
> The mission launched successfully on December 20, 2019, at 6:36:43 am EST. Following nominal ascent and launch vehicle separation, an issue with the spacecraft's mission elapsed time (MET) clock caused the spacecraft to miss the nominal insertion burn. The spacecraft was then put in a stable/circular orbit at 187x222 km, but the required target orbit to allow docking with the ISS was not achieved. The flight plan was revised to reduce the mission duration from eight days to approximately 2 days which resulted in missing some of the planned test objectives (ISS rendezvous and docking/docked/undocking operations).
>
> On December 22, 2019, Starliner was cleared for de-orbit burn. After deorbiting, Starliner re-entered the Earth's atmosphere before successfully deploying all sets of parachutes. Starliner deployed airbags and successfully touched down at White Sands Missile Range at 7:58 AM ET.
>
> Although Starliner did not reach its planned orbit and dock to the International Space Station as planned, it was able to complete a number of test objectives during the flight, including:
>
> - Successful launch of the first human-rated United Launch Alliance (ULA) Atlas V rocket
> - Check out of the Starliner propulsion systems
> - Test of space-to-space communications
> - Confirmation of Starliner tracker alignments using its navigation system
> - Test of Starliner's NASA Docking System
> - Validation of all environmental control and life support systems
> - Completion of a positive command uplink between the International Space Station and Starliner
>
> **An OFT Independent Review Team (IRT) was chartered to determine root cause for the software/HSI anomalies discovered during the OFT mission**, including but not limited to:
>
> - Timing error that resulted in the inability to reach rendezvous orbit
> - FMC to IPC command translation errors that were discovered prior to de-orbit.
>
> **IRT Summary Takeaways**
>
> - **Competent Team working hard, but spread thin**
>   - Two critical software defects escaped into flight even in presence of multiple safeguards
>   - Ground intervention prevented loss of vehicle in both cases

    - Breakdown in design and code phase inserted defects (including peer reviews)
- **Breakdown in test and verification phase failed to identify defects preflight despite their detectability**
- **Due to the issues found in design, code and test, there is risk of latent defects that require systemic corrective actions**
    - Forward link comm & track anomaly still under investigation
    - Potential overdrive of SC3 [redacted] during CM-130 (new potential finding)
    - Comm signal [redacted] required to mitigate out of band interference
    - Signal path analysis and test will inform next steps
- **IRT Observations: Schedule and resource challenges**

3.2 Orbital Flight Test 2 (OFT-2) Summary

The following summary is directly quoted from **DCC1-00709-85 OFT2 Final Test Report**:

> The Boeing CST-100 Orbital Flight Test -2 was completed in May 2022. This flight was a repeat attempt of the original orbital mission of the CST-100 Starliner spacecraft for the NASA Commercial Crew Program. The mission was a six-day test flight of the spacecraft, with primary test objectives to validate the integration and launch of the new vehicle on an Atlas V rocket, ascent, orbit operations, ISS rendezvous operations, docking/undocking, descent, landing, and recovery.
>
> The mission launched successfully on May 19, 2022, at 6:54:43 pm EDT. Following nominal ascent and launch vehicle separation, the CST-100 vehicle completed the orbit insertion burn successfully.
>
> On May 25, 2022, Starliner was cleared to re-enter the Earth's atmosphere. After deorbiting, Starliner re-entered the Earth's atmosphere before successfully deploying all sets of parachutes. Starliner deployed airbags and successfully touched down at White Sands Space Harbour at 145/22:49 GMT.
>
> OFT-2 completed the planned ISS rendezvous. Starliner has evaluated all and **met a majority of the planned flight objectives.**

DCC1-00709-85 OFT2 Final Report details the following specifically regarding the SM RCS:

> In the hours prior to docking, 2 RCS thrusters (B1A3 and S2A2) failed off and a third (S1A1) was identified as failed off [redacted] but the S1A1 failure had insufficient [redacted] to mark it as failed off. The FDIR/FSW deselected the 2 thrusters marked as failed [redacted] and moved on to the next available thrusters with no loss of control performance. S1A1 continued to be commanded and successfully fired many times following its initial failure identification. **The [redacted] RCS Pc telemetry is insufficient to determine whether the enunciated failure was caused by a thruster valve issue or is a false failure indication.** Dedicated hot-fire testing of each failed SM RCS thruster as well as some additional thrusters that had exhibited periods of lower Pc in pre-dock telemetry were performed post-undock. All SM RCS thrusters that received this special test were shown by GN&C accelerometers to be delivering full thrust, so they were re-selected and used for the remainder of the mission. Following deorbit burn but before CM/SM Separation, S1A1 was identified by FDIR/FSW to have failed off; unfortunately, at the time of S1A1's fail-off, no other SM Thruster data was available as the vehicle had already changed to the entry telemetry format.

3.3 Comparing SM RCS Thrusters Triggering Fail-Off FDIR on OFT1/OFT2

As noted in Figure 1: Failed Thruster Across All Flights in comparison to temperature, OFT-1, ten SM RCS thrusters failed off during the brief, unsuccessful test flight. The ten failed thrusters included six of the eight aft-facing thrusters. The extremely rapid SM RCS jet firings which occurred early in OFT-1 led to the number of jet firings being far in excess of the qualification levels and resulted in RCS failure annunciations by Fault Detection, Isolation, and Recovery (FDIR). These rapid jet firings also led to thruster heating far in excess of qualification test levels. Of the ten thrusters that failed off in flight, nine were shown to be due to transducer failures triggering FDIR and one thruster had a transducer failure and another hard failure that caused the thruster to remain inoperative after the other thrusters were re-enabled. The hard failure was believed to be due to the valve [redacted] overheating. The limited RCS "hard" failures experienced during OFT-1 led to a false belief that the thruster hardware was very robust for exposure to high temperatures, except for the [redacted] (PCB-20-404). This belief persisted until the ground testing results were available during CFT.

During OFT-2, two of the eight aft-facing SM RCS thrusters (B1A3 and S2A2) failed off during the approach to the ISS. These two thrusters were reselected and performed during the de-orbit burn. One RCS thruster (S1A1) experienced a single FDIR failure during ISS approach and subsequently failed during the de-orbit burn. Telemetry showed that two of the three failed jets had [redacted] temperatures observed at or above [redacted] and S1A1, S2A2, B1A3 and the four thrusters with the highest [redacted] temperatures were all aft facing. The heating related fault tree block (3.1.7 Hot Valve/[redacted]) was identified as a contributing factor for the B1A3 and S1A1 failures, but not the S2A2 failures because that [redacted] temperature never exceeded [redacted]. "[redacted] swelling was considered (reducing propellant flow) but since flow is controlled by [redacted] swell contribution to resistance change would be negligible" but the high [redacted] temperature was theorized to result in NTO bubble formation (OFT2 SMRCS Thruster Failure Investigation Kickoff, Slide 127, 3.1.7 Hot [redacted] Valve). The corrective action identified to mitigate the risk of further failures on CFT was a Mission Data Load (MDL) change to the [redacted] to reduce the potential for "false" failures due to the limitations of the thruster chamber pressure sensor sample rate (OFT-2 SM RCS Jet Fail-off, Non-conformance #NCR015432W, 15 December 2022).

RCS Thruster Failures Across All Flights

[redacted]

OFT
- 10 thrusters failed
- 9 were recovered
  B2A2, P2F2, P2U1, T1U3, P2D2, T2F2, T1F1, P1F3, S2D3, and S1R1
- 1 was not recovered
  B2R3

Note: Mission elapsed time software error led to excessive SM RCS firings outside of qualification space.

OFT-2
- 3 thrusters failed
  B1A3, S1A1, and S2A2
- 3 were recovered

CFT
- 5 thrusters failed
- 4 were recovered
  B2A2, S1A1, S2A2, and T2A2
- 1 was not recovered
  B1A3

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Figure 1: Failed Thruster Across All Flights

RCCA investigations were conducted for the SM RCS jet fail offs after both OFT and OFT2. However, both instances failed to find the proximate cause that was realized again on CFT. This was a missed opportunity. In reality, OFT served to provide a false confidence in the robustness of the thrusters that continued to perform, above their qualification temperature. More exploration on this is detailed in the STAR/SDRT report and in the analysis below.

4 Technical Root Cause Analysis (RCA) and Findings

4.1 Objectives and Approach

A Root Cause Analysis (RCA) is a structured evaluation method used to identify the root causes of an undesired outcome and determine the actions adequate to prevent recurrence.

An RCA should continue until organizational factors have been identified or until data is exhausted. The goal of RCA is to discover systemic problems that affected the organization involved in the undesired outcome. Root causes are often organizational factors that contribute to or create the proximate and intermediate causes and subsequent undesired outcome.

The investigation team completed an RCA to uncover as many relevant organizational factors as possible in order to recommend actionable steps to prevent repeating issues.

4.2 Definitions

The PIT Team used the following definitions for findings and recommendations. These definitions are an amalgamation of OA-WI-007 Program Investigation Team Work Instruction and NPR 8621.1D NASA Procedural Requirements for Mishap and Close Call Reporting, Investigating and Recordkeeping. Considerable consideration should be given in the future to specifically align the terminology of these two instructional investigation documents.

PROXIMATE/DIRECT CAUSE: The event that occurred, including any conditions existing immediately before the undesired outcome, directly resulted in its occurrence, and if eliminated or modified, would have prevented it. Also, known as direct cause.

INTERMEDIATE CAUSE: An event or condition that existed before the proximate cause, directly resulted in its occurrence, and if eliminated or modified, would have prevented the proximate cause from occurring.

CONTRIBUTING FACTORS: An event or condition that may have contributed to the occurrence of an undesired outcome, but if eliminated or modified, would not on its own have prevented the occurrence.

ORGANIZATIONAL FACTORS: Any operational or management structural entity that exerts control over the system at any stage in its life cycle including, but not limited to, the system's concept development, design, fabrication, test, maintenance, operation, and disposal—for example, resource management (budget, staff, training); policy (content, implementation, verification); and management decisions

OBSERVATIONS: A factor, event, or circumstance identified during an investigation that did not contribute to the mishap or close call, but if left uncorrected, has the potential to cause a mishap or increase the severity of a mishap; or a positive factor, event, or circumstance that should be noted.

ROOT CAUSE: An event or condition, primarily associated with organizational factors, which existed before the intermediate cause and directly resulted in its occurrence (indirectly caused or contributed to the proximate cause and subsequent undesired outcome) and, if eliminated or modified, would have prevented the intermediate cause from occurring and the undesired outcome. Typically, multiple causes contribute to an undesired outcome. In the absence of a prevalent organizational factor, the root cause may be identified as undetermined.

RECOMMENDATIONS: An action developed by the investigating authority to correct the cause, or a finding identified during the investigation.

4.3 Fault Tree

The team developed independent fault trees using design schematics, mission data and early versions of the Boeing-led Root Cause/Corrective Action (RCCA) team's fault trees. The fault trees were updated as new data was presented due to the simultaneous work being conducted by the RCCA technical teams. The design of the fault trees for root cause analysis in this report focuses first on the initial undesired outcome and expanded outwards to probe the design and environmental parameters. Each section's fault tree uses three specific categories: software, hardware, and environment.

The software tree details sensor, computer, and software failures to determine their impact on the event. The hardware tree identifies component level areas of concern and any possible associated failure mechanism. The environment tree outlines potential factors outside of the mechanical or software design that can induce, contribute, or exacerbate the failure mode or undesired outcome.

To further support evaluation and analysis, the Starliner PIT team consulted expertise from NASA engineers specializing in propulsion systems, thermal systems, and GNC systems with in-depth knowledge of the Starliner and the associated anomalies experienced during the CFT. Over the course of multiple months, the team deliberated on the data presented by the NASA experts and evaluated fault tree nodes using the criteria outlined in Figure 1: Rating Criteria. This rating helped establish probable proximate cause, intermediate causes, and contributing factors.

These independent fault trees were built specifically for the Loss of 6DoF/SM RCS and Helium Leak failures. The PIT did not build an independent fault tree for CM RCS and instead worked with the RCCA to monitor the build of that fault tree. This is due to where the RCCA teams were in their investigations at the formation of the PIT. At the time of charter, little information was available for the CM RCS, and the RCCA team had not yet built a fault tree. At the time of final report writing, the PIT has been an observer on the RCCA build for the CM RCS fault tree. The tree is built but not fully closed for proximate cause. More details are available in the below sections for analysis.

Color coding for rating criteria is as follows:

Rating Criteria	Color	Definition
Not Credible		Proximate Cause candidate does not support failure sequence of events. Refuting Evidence directly exonerating this cause is deemed stronger than any association with evidence.
Unlikely		Proximate Cause candidate does not easily fit failure sequence of events. Refuting evidence indirectly exonerating this cause is deemed stronger than supporting evidence
Credible		Proximate Cause candidate supports some of the failure sequence of events. Supporting evidence indirectly incriminating this cause is deemed stronger than refuting evidence.
Most Probable		Proximate Cause supports majority of failure sequence of events. Supporting evidence directly incriminating this cause is deemed stronger than any associated refuting evidence.
Not Yet Assessed		Awaiting further evidence of disposition by board.

Figure 2: Rating Criteria

The following sections provide an overview of the analysis for each of the areas scoped throughout this investigation. The propulsion system technical sections delve into detail of what may have caused each undesired outcome. Each section includes relevant proximate causes, intermediate causes, and some organizational and contributing factors.

After the analysis of each technical area is a common observations and organizational factors section. This section consolidates the intermediate causes and organizational factors and observations that are common from the technical investigations.

The technical sections are followed by a Culture and Decision-Making Process in Near-Real-Time section that specifically discusses culture and decision-making challenges faced during the mission. This section provides observations and recommendations to address observed challenges from CFT specifically.

The final Root Cause section covers the underlying organizational root causes that, if eliminated or modified, could have eliminated the intermediate and proximate causes that created the undesired outcome. These root causes directly map to the proceeding causes and factors.

4.4 Analysis: CM RCS Jet Failure

The proximate cause for the CM RCS Thruster Failure has not yet been determined. At the time of this report, Boeing is leading an RCCA team that is working through the fault tree.

The leading theory for the proximate cause of the CM RCS failure during the CFT is the formulation of carbazic acid, which corrodes stainless steel. The reaction between carbazic acid and stainless steel creates corrosion particulates in the thruster propellant valve, preventing it from opening. This corrosion can cause the mechanism within the thruster to get stuck or blocked and keep it from firing. To reiterate, this is a leading theory. Proximate cause has not been determined, as the process is still in work**.** Concluding that valve failure due to corrosion caused by the presence of carbazic acid, would be pre-mature for this PIT to determine, and risks a repeat of the lessons learned from the CCP Starliner Data Review Team (SDRT). The SDRT concluded that the investigation into SM RCS thrusters on both OFT and OFT2 could have found the systemic issue of jet fail offs had a more thorough fault tree and investigation been conducted instead of prematurely coming to a conclusion.

The CM RCS jet failure is specifically important to resolve. The CM RCS is required to control the capsule during return. The system is required to be two fault tolerant by design. For Starliner, Variance 1 (CCTS-VR-0001) was accepted and signed to approve the system at one fault tolerance, for all flights**.** This jet failure on CFT took the system to zero fault tolerance. **Loss of the single remaining redundant thruster, for this control axis, would have resulted in a loss of crew.**

While the validation of proximate cause and mitigation plans are still open work, the underlying root causes are the same as the other technical areas and are included in the root cause section below.

4.5 Analysis: Loss of 6DOF Control - SM RCS Jet Failures

The RCCA investigation into the Loss of 6DOF Control in-flight anomaly remains open and ongoing. The SM RCS Jets triggering their fail-off FDIR (five total) ultimately resulted in a loss of control in the +X direction, on the docking axis. Through troubleshooting, four of the five jets regained enough thrust to regain control and dock to the ISS. The information below is an independent review of the technical data and a detailed analysis down to organizational root causes.

As a starting summary, the most probable proximate causes and their intermediate (contributor) causes for the SM RCS Jets triggering fail off FDIR is a combination of:

1. Two phase flow of oxidizer reaching the combustion chamber, resulting in reduced chamber pressure
    a. Heat due to RCS Thermal Soakback
    b. Heat production due to pulse/firing demand
    c. Heating by OMAC firing
    d. Heat from OMAC Plume recirculation
2. Teflon poppet extrusion within the thruster valve causing an obstruction in oxidizer flow
    a. Teflon swell due to exposure to NTO
    b. Inadequate poppet retention
    c. Heat
    d. Pressure behind the poppet seat

Additionally, the way in which the GNC requests the use of a thruster (referred to as Pulse Train in the fault tree) has been flagged as a significant contributing factor for interactions with the Teflon poppet extrusion.

At the time of writing this report, the failure mechanism and its potential recovery path have not been recreated on the ground as part of the investigation. Therefore, all legs of the fault tree that remain open need to be fully dispositioned as a part of the RCCA investigation and In-Flight Anomaly (IFA) closure prior to the next flight of the Starliner.

Current computational fluid dynamics (CFD) analysis has shown that based on modeling of the thermal environment (Therm11a) of the RCS thruster valve, both vaporization/cavitation at elevated temperatures and a deformed poppet seal are credible reduced flow mechanisms. However, vaporization/cavitation alone does not explain the long-term degraded thruster performance after thruster temperatures decreased. The undesired outcome is likely the result of several contributing factors.

During Starliner approach on CFT, three of the five thrusters triggered their jet fail-off FDIR after the crew took manual control of the vehicle. The crew took manual control for troubleshooting purposes for the initial two thrusters. Per the post-flight analysis (included in the analysis below), the GNC and Propulsion teams have determined there is no difference in the control logic compared to automated pointing and translation modes; therefore, manual piloting did not significantly contribute to these additional thrusters triggering their FDIR.

In the detailed analysis below, you will find:

1. Description of the System
2. Description of Events and Timeline
3. B1A3 Thruster
4. Starliner Engine Testing at WSTF
5. Fault Tree

6. Causes and Organizational Factors

4.5.1 Description of the System

The service module (SM) reaction control system (RCS), depicted below in Figure 3, is comprised of two thruster types: RCS and Orbital Manoeuvring and Attitude Control (OMAC). Both types use the same fuel (MMH) and oxidizer (NTO) from the same supply tanks. The OMAC thrusters are used for large translation burns such as orbit insertion, rendezvous orbit adjusts, and the deorbit burn. The RCS thrusters are used for small translation burns and for attitude control. There are 28 RCS thrusters, with seven per doghouse and three to four per manifold, with two manifolds per doghouse.

RCS thrusters provide 6DOF attitude control for all mission operations. Each thruster has a nominal chamber pressure of [redacted] and produces roughly 85 lbf. Thruster health is monitored via chamber pressure and the fuel/oxidizer injector temperatures. At the end of the mission, the service module is separated from the crew module and does not return. Therefore, there is no recovered hardware to inform the investigative process.

Six DOF is the ability to independently control motion in the three translational and three rotational degrees of freedom. Starliner lost 6DOF control on the docking access to ISS during CFT, when enough aft facing jets triggered their fail off FDIR and were removed from the control algorithm, leaving the vehicle unable to proceed in the +X direction, towards ISS. This was a temporary loss of 6DOF control.

[redacted]

Figure 3: Starliner SM Propulsion Subsystem

Nominal SM RCS Thruster Firing

To evaluate the anomalies experienced during the CFT, it is important to understand nominal SM RCS thruster firing. During nominal SM RCS thruster firing, the guidance navigation control (GNC) algorithms within the flight management computer (FMC) determine the changes needed in velocity or attitude and which thrusters will be required to affect the desired change. The [redacted] then command the desired SM RCS thrusters to fire via the [redacted]. The [redacted]. The solenoid valves when opened permit helium to open dual poppet valves, one for NTO and one for MMH which fires the thruster. When [redacted] is removed from the solenoid valves, they cut off the helium supply and vent the downstream helium resulting in normally closed [redacted] to return the poppet valves to the closed position.

SM RCS thrusters are commanded at [redacted] For certain mission phases, there is a cutout band [redacted].

SM RCS Thruster Fail-Off Fault Detection, Isolation, and Recovery (FDIR)

Understanding SM RCS Fail-Off FDIR is important to understanding the loss of 6 DOF control that occurred during CFT's rendezvous with the ISS. Knowledge of what occurred during rendezvous to the SM RCS thrusters is limited by a few factors: the service module is disposed of prior to entry (SM not available for post-flight inspection), low thruster chamber pressure sample rate makes real-time and postflight analysis difficult, and the possibility that the issue affecting the thrusters heals with time and/or temperature. However, it is certain that the SM RCS FDIR commanded the thrusters to be removed from the control algorithm based pressure transducer readings. Therefore, a detailed understanding of jet fail-off FDIR as part of the reconstruction of the loss of 6DOF control is necessary.

[redacted]

[redacted]

Note: OFT2 IPCs were supposed to set a fail-off flag [redacted] This was not fixed for CFT. Instead, the FMC [redacted] was changed [redacted]

Note: [T]he time from [the FMC] command[ing] ON to Pc reaching [redacted] (See Slide 51 "1.4.5 – Delayed response/Calibration shift" Figure 5: Slide 197 – [redacted] – Backup -)

Note: Chamber pressure rise time is known to be longer for certain operational environments (e.g., higher inlet valve temps, higher fuel/ox temps, low prop/ox line pressures, two-phase flow, poppet extrusion, etc. – as well as the interacting effects).

With the combination of [redacted] a jet needs to fire for greater than [redacted] for it to be possible to even have a fail-off condition declared by an FMC. Many thruster firings are less than [redacted].

[redacted]

Figure 5: Slide 197 – IPC Fail-Off/On Logic – Backup - "OFT2 SMRCS Thruster Failure Investigation Kickoff"

Sensor Sampling Limitations and Data Retention

Accurate assessment of SM RCS thruster performance during flight depends heavily on system sampling rates and data retention capabilities via telemetry. This section outlines the system capabilities and limitations during CFT.

Flight data for the propulsion system is primarily obtained from telemetry downlinked in near real time. Propulsion data from CFT was not recorded at rates faster than telemetry could manage and downloaded later. Instead, data was downlinked near real time and recorded on the ground. Table 3, below, lists a few of the critical parameters captured via telemetry on Starliner that were used to diagnose the SM RCS thruster firing issues during and after flight.

Sensor Parameter	**Units**	**Sample Frequency**
Chamber Pressure	PSI	[redacted]
NTO (Oxidizer) Injector Temp for each SM RCS Jet	Fahrenheit	[redacted]
MMH (Fuel) Injector Temp for each SM RCS Jet	Fahrenheit	[redacted]
NTO Pressure	PSI	[redacted]
MMH Pressure	PSI	[redacted]
Helium Pressure	PSI	[redacted]
Thruster On Time	Cumulative Seconds	[redacted]
Doghouse Temperature Sensors	Fahrenheit	[redacted]

Thruster Pulse Count (labelled Duty Cycle in Boeing docs)	Cumulative Integer	[redacted]	
Thruster Inlet Valve Position	Binary		
SM RCS FAIL OFF	Binary		

Table 3: Propulsion System Data

SM RCS thrusters are commanded in [redacted]

> **Note**: Commanded pulse lengths are neither recorded nor downlinked near real time with telemetry. The investigation teams were able to reconstruct a statistical best guess of the commanded pulse sizes using available telemetry from the thrusts and inertial data. This complicates efforts to understand what went wrong with SM RCS jets when data suggests that pulse length is correlated to observed soakback temperatures.

Many thruster pulses are less [redacted] FDIR in the [redacted] The FMCs see chamber pressure over a data bus from the [redacted] but the chamber pressure is only sent to the ground with a sample rate for recording every [redacted] limiting insight into thruster performance. This does not meet Nyquist Criterion for capturing the chamber pressure signal. As a result, aliasing effects may occur for pulses shorter than [redacted] where high-frequency components of the pressure signal are misrepresented or lost, further complicating accurate reconstruction of thruster behavior.

The flight data rate/telemetry sampling rate, which is available to ground teams, is the only means to receive thruster data as the vehicle does not store or retain data for later downlink or physical return. This means that the vehicle can fire the thrusters between [redacted], but as a result of data rate [redacted] only a subset of those will capture the exact peak and ramp on rates, along with associated aftereffects of the thruster.

Starliner's inertial measurement unit (IMU) data for both rotational and translational accelerations was used both real time and post-flight to assess and analyse thruster performance. While IMU data was helpful, propulsion focused sensors with sample rates paired with the frequency of the expected signal would have contributed to better real time and post flight diagnosis of thruster behavior.

4.5.2 Description of Events and Timeline

While on approach to ISS, two aft-facing jets triggered the jet fail-off FDIR which removes that jet from the control algorithm. With the loss of these two jets, Starliner became single fault tolerant to loss of 6DOF control: S2A2 failed at 9050 m (GMT 14:00) and B1A3 failed at 526m (GMT 14:57). This created the condition that required a delay before entry into the ISS Keep Out Sphere (KOS), per Flight Rule J2-31 JOINT CST-100/ISS Go/No-Go matrix rendezvous, approach, and docking. A delay at this point in the rendezvous is an intentional position to stop and troubleshoot a given system prior to getting within close proximity to ISS.

Below, Figures 6 and 7 demonstrate the CFT relative motion to ISS during the loss of 6 DOF. Figure 6 shows relative motion, the other is a general visual of the loss of 6 DOF. These graphics are important to visually understand the events outlined in this section and the decisions made by the Flight Control Team (FCT).

[redacted]

Figure 6: CFT relative motion to ISS during Loss of 6DoF

[redacted]

Figure 7: Loss of 6DoF Visual

Flight Rules are written pre-flight to provide agreements between the flight operations team and the program(s) and to define acceptable operating risk. The FCT evaluates real-time events and determines the critical path forward, using the guidance of the pre-agreed to flight rules. The FCT weighs risk to Starliner Crew, ISS Crew, the Starliner and the ISS in real-time. During the CFT rendezvous scenario, a Starliner Abort was a conservative approach to protect the ISS, but an abort would have placed Starliner in a re-rendezvous trajectory with the possibility of deorbiting with suspect/degraded thrusters.

It cannot be definitively stated, but there is heightened probability that a re-rendezvous or deorbit operation could have exacerbated the on-going thruster issues. This would have put the safety of the CFT Crew at higher risk to loss of life. **It was the right course of action, to troubleshoot and continue with the rendezvous and docking to ISS.**

While in a manual hold at 260m, two additional jets triggered fail-off FDIR. Thrusters B2A2 (GMT 15:28), were removed from the the control algorithm resulting in 0FT for 6DOF control, and S1A1 (GMT 15:31), resulting in loss of X-axis translation and degraded pitch and yaw capability. **The loss of X-axis translation resulted in a loss of movement in the forward direction and the Starliner vehicle was no longer capable of docking to the ISS, until a subset of thrusters could be recovered.**

The crew was able to station-keep with degraded control while the ground team performed hot-fires to troubleshoot and recover jets. Starliner goes free drift (coast) during hot fires. The crew had to manually point Starliner to keep relative navigation sensors tracking so they could be used later for returning to auto control for final approach and docking.

With the spacecraft in manual piloting mode, troubleshooting was performed by commanding an individual jet to hotfire. The hotfire test was performed, without any other jets firing and then thrust/output was evaluated in real-time

At the conclusion of the hotfire, when thruster is demonstrated, a jet is reenabled with jet-fail FDIR inhibited. Through this sequence, four of five jets were recovered. Spacecraft 6DOF control was reestablished in all axes. The spacecraft was moded back to auto and the rendezvous/dock was completed.

While the flight rules allow an SM RCS thruster to be used with jet-fail off FDIR inhibited, doing so removes a hazard control. CCTS-16.01Failure to Provide SM Propulsive Capability for Nominal Operations, Cause 4 Failure to Operate (Mechanically) a SM RCS Thruster, Control 12a states, "For all SM RCS thrusters, the [redacted] detects failed operation of an SM RCS thruster by comparing its chamber pressure transducer measurements to threshold pressure levels provided by the [redacted] and annunciates RCS Jet[x] Failed Off [redacted]" for generation of Fuel Oxidizer Reaction Propellant (FORP). In turn, this can cause a spontaneous combustion of a small amount of fuel in the throat of a thruster nozzle (ZOT).

The time elapsed to perform troubleshooting, in combination with flowing cold prop through the thruster for a hotfire, may have allowed the thrusters to cool, which may have aided in their recovery enough to proceed. None of the thrusters that triggered jet-fail off FDIR were recovered to 100% during this sequence. However, each generated some thrust and each thruster was deemed capable by the operations team to be utilized to finish the rendezvous. This action taken by the ops team, was in accordance with Flight Rule I6-35 SM RCS THRUSTER FAILURE RESPONSE.
The flight control team and crew demonstrated tremendous capability and understanding of the system to facilitate the recovery of four thruster failures. Without the precise actions of the crew and flight control team, this event could have resulted in a loss of the Starliner crew. A timeline of events is included in Figure 8.

2024	158:13:38:12	OMAC burn (T3A3, B3A3, P3A1, and S3A1)
2024	158:13:38:14.240	S1A1 - 1st strike
2024	158:14:00:34.200	S2A2 - failed
2024	158:14:02:31.040	TPI
2024	158:14:47:21.540	IF1
2024	158:14:57:38.840	B1A3 - 1st strike
2024	158:14:57:38.937	B1A3 - failed
2024	158:15:07:22.040	IF2
2024	158:15:24:03.920	Manual piloting for hotfire
2024	158:15:28:22.140	B2A2 - 1st strike
2024	158:15:28:22.976	B2A2 - failed
2024	158:15:31:47.257	S1A1- failed
2024	158:15:36:02.500	Hotfire - S2A2 ([redacted] 51% from GNC)
2024	158:15:37:22.120	Hotfire - B1A3 ([redacted] 11% from GNC)
2024	158:15:38:34.700	Hotfire - B2A2 ([redacted] 91% from GNC)
2024	158:15:39:45.720	Hotfire - S1A1 ([redacted] 29% from GNC)
2024	158:15:43:08.360	B2A2 - enabled
2024	158:15:43:57.740	T2A2 - 1st strike
2024	158:15:44:51.360	S1A2 - enabled
2024	158:16:04:07.420	B1A3 - enabled
2024	158:16:12:15.500	T2A2 - failed
2024	158:16:12:17.640	Back to auto piloting
2024	158:16:26:50.540	Manual piloting for second hotfire
2024	158:16:28:17.437	Hotfire - T2A2 [redacted], 45% from GNC)
2024	158:16:33:54.597	Hotfire - S1A1 ([redacted], 55% from GNC)
2024	158:16:37:05.839	Hotfire - B1A3 [redacted] 0% from GNC)
2024	158:16:43:13.937	S1A1 - enabled
2024	158:16:44:26.058	T2A2 - enabled
2024	158:16:45:19.777	B1A3 - disabled
2024	158:16:41:40.257	Back to auto piloting
2024	158:16:52:09	T1F1 - 1st stke
2024	158:17:34	Docking to ISS

Figure 8: Timeline of Loss of 6 DoF Event

4.5.3 B1A3 Thruster Failure

The B1A3 thruster was the only thruster not recovered to some reduced capability during the rendezvous. B1A3 was commanded to fire 138 times totaling 8.3 seconds for the IF1 burn (See Figure 6 CFT relative motion during Loss of 6DoF on page 27). Post-IF1, the thermal soakback peaked at approximately [redacted], from the initially observed approximately [redacted]. The thruster was not requested to fire for over 10 minutes, then during its first set of firings following the IF1 burn the thruster was removed from the control algorithm when the jet fail-off FDIR was triggered. At the time of the FDIR trigger, the thruster had a temperature reading of approximately [redacted] and Pc less than [redacted]

B1A3 was hotfired approximately 45 min after the FDIR removed the thruster from control. The injector temperature sensors, fuel injector sensor VPRTB001T and oxidizer injector sensor VPRTB002T, had dropped to approximately [redacted]. This Pc measurement is based on telemetry observable by the ground teams with a sample rate of [redacted] The thruster is capable of firing at a faster rate, so a telemetry sample at [redacted] is not a conclusive picture of the overall observable health of the thruster. (More information regarding sample rate can be found in the Description of the System section.)

During the real-time evaluation, the vehicle rate assessment suggested jet provided approximately 39% thrust, however reanalysis of the data in the post-docking timeframe suggested B1A3 only achieved approximately 11% thrust. The FCT selected B1A3 to fire again based on the 39% thrust determination, B1A3 was re-selected and commanded to fire 271 times for a total of 21.26 sec.

[redacted]

Figure 9: B1A3 Temperature and Pressure Chamber Firing During Docking

The temperature signatures from the thruster valve showed successful valve opening, but not the expected heating, meaning little, if any, combustion occurred. The recorded pressure chamber reading from B1A3 during this time was less than 10% of the normal Pc, which indicated that there was no NTO flowing into the thruster.

As a result, B1A3 was deemed too risky to hotfire again or to be used during the CFT descent as there was a potential risk to the ISS. As B1A3 was never fired again following CFT docking, it is difficult to determine and/or verify the nature of its failure in comparison to the other thrusters or its ability to recover over time. It is highly probable that the B1A3 thruster failed in the same way as the other four thrusters; however, the data is not fully conclusive.

This failure signature was unique to B1A3 because the four other thrusters were capable of firing again, even in a degraded state. This singles out B1A3 as a permanent failure. The other thrusters were considered transient in nature. B1A3 had a unique firing pattern which could have played a role in how it failed. Testing has not been performed to confirm whether this unique firing pattern played a role in the thruster's failure. B1A3 appears to have one flow path mostly blocked, as a result the fault tree highlights the potential for [redacted] line, which is not the expected failure of the other thrusters.

[redacted]

Figure 10: B1A3 Chart Demonstrating Fuel Flow Across the Injector

While it is highly probable that the B1A3 thruster failed in the same way as the other four thrusters, testing has yet to demonstrate entire blockage of the NTO line from the extrusion of the Teflon poppet in the thruster valve. There remains a possibility that B1A3 is standalone in nature.

4.5.4 Starliner Engine Testing at White Sands Test Facility (WSTF) during CFT

Due to the FDIR declared failures early in the CFT mission, troubleshooting was performed on the RCS thrusters after ISS docking in order to augment data collected during free-flight. Docked hotfires were conducted on multiple thrusters, including all previously failed/recovered units (excluding B1A3) and degraded performance was still observed. This testing demonstrated the issue was not purely transient. The testing demonstrated that some long-lasting reduction in peak performance had occurred. Figure 11 summarizes results from free-flight and docked testing.

[redacted]

This observation during the on-orbit hotfire, was a driving force in team performing additional ground testing at the White Sands Test Facility (WSTF) during the summer of 2024. Testing was necessary to provide further understanding of the issue and inform a risk reduction path for a crewed CFT return. This testing recreated an RCS stressing downhill mission profile on an engine with observed degraded performance from the uphill mission phase. Per Figure 11: Docked Hotfires, the most affected recovered thruster was T2A2, and therefore its mission profile was selected for testing. The profile was broken down into five 120 min segments: WSTF Uphill Profile [1] OI→NC, [2] OCC's Part 1, [3] OCC's Part 2, [4] NHPC1→IF1, and [5] Docking.

These initial uphill profiles were followed by a series of five simulated downhill profiles to predict the potential behavior of the degraded thrusters during undock and return. Due to the nature of the setup for testing, artificial heat sources were employed to simulate (to the understood degree, at the time) the impacts of adjacent OMAC thrusters and other environmental factors. **In addition to demonstrating transient degradation during high heating, the test program demonstrated an unrecoverable cumulative degradation that was potentially indicative of the observed performance of CFT.**

[redacted]

Figure 12: WSTF Testing Cavitation Detected

As shown in Figure 12: WSTF Testing Cavitation Detected, cavitation signatures were detected during the WSTF test runs. In subsequent runs, a decrease in the overall performance of the thruster was observed. **The final test run of the thruster resulted in a degraded performance down to approximately 71% of the expected pressure** and thrust during 3 second trim burns. The impact on short operational length pulses would have been more severe due to slower startup of the degraded thruster. The successive degradation during standardized trim burns between test profiles is captured in Figure 13: WSTF Testing Cavitation in NTO.

[redacted]

Figure 13: WSTF Testing Cavitation in NTO

Following testing, borescope inspection of the thruster valve was performed. This showed that the Teflon poppet on the oxidizer section of the thruster valve extruded. Blockage like this would disrupt and reduce the flow of oxidizer to the combustion chamber.

[redacted]

Figure 14: Borescope Inspection of Teflon Poppet from WSTF

CT scans of the thruster valve and full thruster tear-down occurred following testing. As shown in Figure 15: Void behind Teflon poppet of the NTO side of the thruster, the CT scans showed a void was generated behind the Teflon poppet on the oxidizer side of the thruster valve. The fuel side valve was not affected similarly.

[redacted]

The full physical blockage of the valve seat is not necessary to significantly disrupt thrust. A sufficiently reduced gap promotes cavitation at less extreme conditions than normal. CFD analysis was used to estimate the extrusion and temperature necessary to block/reduce flow of NTO, as shown in Figure 16: CFD assessment of poppet extrusion. This helped to explain why cavitation was observed during ground testing and potentially on orbit during CFT.

[redacted]

4.5.5 Fault Tree

The fault tree provides an in-depth analysis of the Starliner PIT's investigation and analysis related to the SM RCS thruster failures and the loss of 6 DOF control. Each section examines specific branches of the fault tree: software, hardware, and environment. Graphical representation of the fault tree is included, following the color coding established in the Root Cause Analysis (RCA) section of this document. The branch analysis is then followed by an explanation of the most probable proximate causes. The entire fault tree is available at the end of the report.

Software
As shown in Figure 17: Software, the main nodes in the software section of the fault tree are Sensors Failures, Computer Failures, and Software Design flaws that could contribute to or cause the RCS fail-offs during the CFT mission.

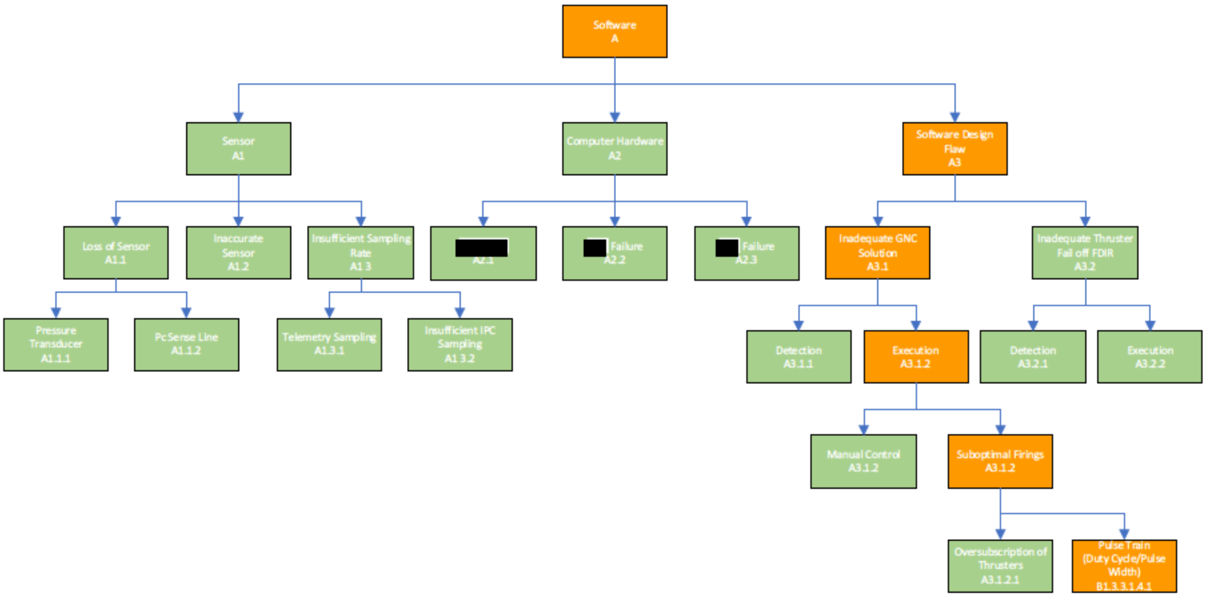

Figure 17: Software Section of Fault Tree

A1 Sensor

The sensor section of the fault tree was investigated to determine if the **A1.1 loss of sensor(s), A1.2 inaccurate sensor(s)**, or **A1.3 insufficient sample rate** could produce, contribute to, or cause the SM RCS failure. Suspect thrusters were removed from the firings solution as a result of the jet fail-off FDIR registering insufficient Pc from the combustion chamber. In this consideration there were no sensors lost. The sensors were deemed healthy and capable of relaying accurate sample data. However, there is insufficient IPC sampling occurring for the IPCs to address the physics within the RCS thruster. There is insufficient telemetry sampling to provide sufficient insight to thruster operations. This is due to the thruster firing for 5ms pulse, the shortest duration allowed. The sampling rate of the IPC is [redacted], which is a sampling rate of every [redacted] The IPC may not capture all pulses below [redacted] instead it relies on pulse aftereffects and modelling to identify the follow-on effects. This sampling rate did not directly cause the thruster fail offs during CFT as the vehicle was able to safely operate without capturing all possible thruster pulses. **A1.1 loss of sensor(s), A1.2 inaccurate sensor(s)**, or **A1.3 insufficient sample rate** were deemed not credible.

Insufficient sampling rate contributed to the misdiagnosis of thruster fail-offs during OFT1 and OFT2, as most thruster firings and operations are not able to be viewed by the ground for real time operations, troubleshooting, or vehicle qualification/human rating certifications. The insufficient sampling rate is tracked in the common findings under **Organizational Factor 8: Insufficient Verification and Validation** and the misdiagnosis of the thruster fail-offs contributed to the **Organizational Factor: Insufficient Anomaly** resolution process.

A2 Computer Hardware

The computer hardware section outlines the investigation to determining whether an **A2.1 IPC Failure**, **A2.2 SMC Failure**, or **A2.3 FMC failure** contributed or caused the undesired outcome. There were no computer failures/anomalies of the [redacted] that occurred during the CFT and contributed to this undesired outcome.

A3 Software Design Flaw

The design flaw branch investigated whether software related to thruster firings caused or contributed to the undesired outcome. The design flaw branch was divided into **inadequate GNC solution** or **inadequate thruster fail-off FDIR**.

A3.1 Inadequate GNC Solution is divided into detection and execution fault tree branches. The description of failure for the **A3.1.1 Detection** branch is whether the vehicle can detect its current position accurately. The Starliner vehicle was able to select burns to reach the ISS, indicating accurate detection of spacecraft position. The **A3.1.2 Execution** branch is defined as the ability for the Starliner vehicle to select and engage in the burns necessary to reach its next destination. The potential faults identified for execution are **A3.1.2 Manual Piloting** and/or **A3.1.2 Suboptimal Thruster Firings**. **A3.1.2 Suboptimal Thruster Firings** are divided into **A3.1.2.1 Oversubscription of Thrusters** and the **A3.1.2.2 Pulse Train (Duty Cycle/Pulse Width/Duration)**.

A3.1.2 Manual Piloting examines the three of five jet fail-offs that occurred after Starliner transitioned to manual control for thruster troubleshooting and hotfires. Per NASA GNC, there is no difference in the control logic compared to automated pointing and translation modes; therefore, manual piloting did not contribute to these failures.

A3.1.2.1 Oversubscription of Thrusters means that the undesired outcome could be induced by the software aggressively pulsing the thrusters beyond their capability. This would result in a cascading failure if jets in the same regime were to be selected repeatedly until failure. The Starliner vehicle has software to prevent this from occurring called the thruster firing counter. [redacted] Discussions with NASA GNC experts determined the thruster firing counter was working effectively prior to the thruster fail-offs, proving oversubscription of thrusters was not a cause or contributor.

A3.1.2.2 Pulse Train (Duty Cycle/Pulse Width/Duration) could contribute and/or cause the failure of a thruster by firing at a particular duty cycle and duration. This can result in excessive generation of heat degrading the structure and/or build of the thruster or may result in other failure cases if operated outside of planned qualification space. Duty cycle is the percentage and/or rate of on-time for a given thruster during a burn. Pulse Width and/or Duration is the length of time that the thruster is activated to produce thrust. **As detailed further below, there is insufficient data at the time of writing this report to determine the overall impact of Pulse Train.**

The thermal model (Therm11-a) that was generated for the RCS thrusters [redacted] This simplified model did not capture the heating from the OMAC thrusters or an overall doghouse thermal model. The model did not adequately correlate to observed inflight data. This model was used in the initial verification of the RCS thrusters, to capture the overall impact of the pulse train on RCS Soakback.

The structure of the RCS thruster retains heat and is unable to be dissipated from the firings of the thrusters. This causes the propellants to heat rapidly. Rapidly heated propellants combined with RCS thruster fires results in an increase in heat soakback from the thruster chamber. The correlation is the amount the thruster is fired and the rate at which its fired then contributes to the overall heating of the of the RCS Structure.

The heating of a thruster must be precisely controlled to prevent heating of the propellants and thruster softgoods beyond the planned qualification space. Overheating propellants and thruster softgoods may result in poor thruster operation and/or failure of the thruster. Due to the thruster model not being anchored in test, it is unknown the extent to which RCS Soakback contributed to the potential failures. This will be unknown until a new model is generated and is anchored in test. Upon evaluation of the evidence, **Pulse Train (Duty Cycle/Pulse Width) has been labelled as a credible cause.**

A3.2 Inadequate Thruster Fail-Off FDIR identifies the possibility that the FDIR used to determine thruster health may have caused or contributed to the observed thruster fail-offs. **A3.2.1 Detection** identifies the possibility that the FDIR may have falsely detected a thruster failure. **A3.2.2 Execution** identifies that FDIR may have improperly executed and removed an incorrect thruster or unable to remove a failed thruster.

The purpose of the Thruster Fail-off FDIR is to monitor the pressure in the combustion chamber and determine if a thruster is considered healthy. The threshold for determining if a thruster is healthy is if the chamber pressure is higher than [redacted]. This is to prevent a build-up of Fuel Oxidizer Residual Propellant (FORP) and potential detonation of associated FORP if the thruster is operated below healthy threshold. The thruster fail-off FDIR inhibited the unhealthy jets, which resulted in loss of 6DOF. It takes a minimum of 3 RCS thruster failures in the same direction in order to cause a loss of 6DOF. The failed-off RCS jets not producing adequate thrust, in conjunction with low Pc, demonstrates that the failures were real and FDIR responded appropriately. The thruster fail-off FDIR was determined not to be a cause or contributor to the thruster fail offs.

Hardware

The hardware section is addressed in multiple parts including Ox Flow, Fuel Flow, Combustion Chamber, Thruster Throat, Thruster Nozzle, and the mechanisms in which those components or systems could contribute to or cause the failures.

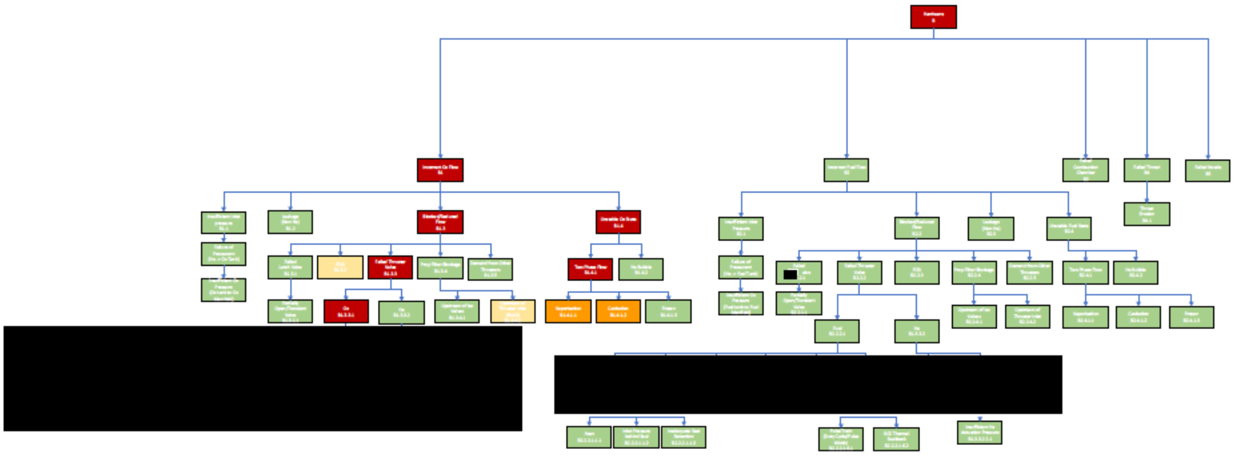

Figure 18: Hardware Section of Fault Tree – ([larger version linked here])

B1 Incorrect Ox Flow

The incorrect oxygen flow branch of the fault tree addresses the insufficient fuel flow reaching the combustion chamber. This is caused by insufficient pressure, leakage, or an unstable Ox state causing an interruption to the reaction occurring within the combustion chamber. The fault tree branch is divided into four branches: **B1.1 Insufficient Inlet pressure**, **B1.2 Leakage (Non-He)**, **B1.3 Blocked/Reduced Flow**, and **B1.4 Unstable Ox State**.

B1.1 Insufficient inlet pressure addresses whether there was the necessary pressure for the propellant to reach the thruster. Data demonstrates there was sufficient helium to reach the oxygen tank and sufficient commodity from the oxygen tank to reach the Ox thruster manifold.

B1.2 Leakage (Non-He) explains that the vehicle had too much leakage present for the thrusters to fire correctly. There was no significant pressure differential in the Oxidizer manifolds or upstream lines indicating no gross leakage of commodity.

B1.3 Blocked/Reduced Flow branch of the fault tree is broken down further into **B1.3.1 Failed [redacted] Valve, B1.3.2 FOD, B1.3.3 Failed Thruster Valve, B1.3.4 Prop Filter Blockage**, and **B1.3.5 Demand from Other Thrusters**.

B1.3.1 Failed [redacted] Valve investigates how this failure would result in the thruster being unable to receive propellant. There is no indication of a failed [redacted] valve such that it was partially open/transient, and the vehicle could not have completed the necessary burns to reach the docking access with this type of failure and this type of failure had manifested.

B1.3.5 Demand from Other Thrusters, that there was insufficient pressure from all of the thrusters firing at the same time, causing a reduction in flow that may impact one or more thrusters. The doghouse manifold pressure shows full pressure of [redacted] was maintained during firings which means was sufficient commodity to provide for all available thrusters.

B1.3.2 Foreign Object Debris (FOD) addresses that significant amounts of FOD may result in a bad mixture ratio. While reduced thrust data consistent with a mixture ratio shift could result from FOD, other thrusters on manifold did not see performance reduction and/or failures. Filter upstream of the manifold Iso protects the relatively small downstream manifold. Any FOD in the manifold should have affected the thruster much earlier compared to the time of failure. Importantly, final hot fire results at the ISS refutes the presence of FOD.

B1.3.3 Failed Thruster Valve is divided into **B1.3.3.1 Ox** and **B1.3.3.2 Helium.** The Helium portion of the fault tree covers FOD in the **B1.3.3.2.1 FOD in He Line** and **B1.3.3.2.2** [redacted] **Valve Failure.**

The **B1.3.3.1 Ox** branch, of the **B1.3.3 Failed Thruster Valve,** is divided into:

- **B1.3.3.1.1 Main Seat Separation of the Poppet Teflon Seat**
- **B1.3.3.1.2** [redacted]
- **B1.3.3.1.3 Poppet Fracture**
- **B1.3.3.1.4 Hot Valve/Injector**
- **B1.3.3.1.5** [redacted] **Shift**
- **B1.3.3.1.6 Inadequate** [redacted] **Margin**

B1.3.3.1.1 Main Seat Separation (Extrusion of the Teflon Poppet) identifies the possibility that the oxidizer poppet of the thruster valve could extrude causing a blocked or reduced flow. Blocked or reduced flow means there is insufficient flow of propellant reaching the combustion chamber. Post-test tear down of the WSTF thruster showed significant deformation of the Teflon seal on the ox valve poppet. **Therefore, the evidence supports this being a contributor to the thruster fail-offs.**

B1.3.3.1.1 Main Seat Separation (Extrusion of the Teflon Poppet) of the **B1.3.3 Failed Thruster Valve,** is divided into:

- **B1.3.3.1.1.1 Heat**
- **B1.3.3.1.1.2 Pressure behind the Poppet**
- **B1.3.3.1.1.3 Traditional Teflon Swelling (NTO)**
- **B1.3.3.1.1.1 Inadequate Poppet Seat Retention**

B1.3.3.1.1.1 Heat identifies that excessive heating could cause the poppet to extrude, reducing flow. Poppet extrusion was observed in the post-test tear down of the WSTF thruster unit. The initial heating caused by the internal doghouse temperatures addressed later in **C4.1 Thermal** and the follow-on heating induced by **B1.3.3.1.4.2 RCS Thermal Soakback,** then caused excessive temperatures beyond the capability of the thruster softgoods causing the Teflon poppet to extrude. **The evidence supports this being a contributor to the thruster fail-offs.**

B1.3.3.1.1.2 Pressure behind the Poppet identifies the possibility that NTO could seep behind the poppet seal and that the trapped fluid could produce an upward force on the poppet seal when heated. This upward force upon the poppet would generate a void, allowing additional NTO to ingress behind the poppet thus repeating the process. This process likely requires excessive heating. The mechanism for this is not fully understood and there may be other elements that impact the generation of this "void." This "void" was identified via CT scan of the post-tear down of the WSTF thruster unit. **The evidence supports this being a contributor to the thruster fail-offs.**

B1.3.3.1.1.3 Traditional Teflon Swelling (NTO) identifies the possibility that NTO causes the Teflon to swell and impede the propellant from reaching the chamber. Teflon poppet swelling due to NTO exposure was observed during WSTF testing. The growth or swelling of Teflon when exposed to NTO is between eight and nine percent. It is unlikely that this effect alone generated the observed failures. The thruster is designed with a poppet stroke to account for this swelling. This effect did likely have an impact on an extruded Teflon poppet, allowing the volume of the poppet to expand slightly more. **The evidence supports this being a contributor to the thruster fail-offs.**

B1.3.3.1.1.1 Inadequate Poppet Seat Retention identifies the possibility of the design of the poppet being insufficient to prevent the Teflon seal from extruding/moving outward thus blocking/reducing the flow of propellant. Inadequate seat retention is a failure caused by inadequate engagement of the thruster valve poppet swage, which can also create a leak path to the backside of the poppet. Swage refers to the metal on the sides of the poppet that help to keep it in place. If there was more defined swage, this may have prevented some of the observed extrusion.

As a comparison, MOOG found a similar issue during an ATP of hardware bound for the Japanese experimental HOPE-X project in 2000. This hardware was identical to hardware used in the Shuttle APU upgrade, leading to a presentation regarding the issue presented at the STS-101 FRR showcasing separation between the concerned hardware and the hardware set to fly. In this instance, during an ATP test campaign at the manufacturer, poppet extrusion was noted after the poppet seat had only been exposed to water, not NTO, at ambient temperatures (not elevated temperatures). Teflon poppet seats of this geometry can demonstrate extrusion without propellant or high temperature exposure.

Another notable difference is that this comparison hardware utilizes teeth to keep the poppet in place, unlike the Starliner valve. The finding here was that the teeth had been filed down too far during the deburring process, allowing an improper engagement of the teflon to remain in position. While this is not a one-for-one hardware comparison, this corollary representation shows that extrusion can happen without adequate poppet seat retention.

[redacted]

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[redacted]

B1.3.3.1.2 [redacted] **Damage/Slip,** covers that the [redacted] to move the poppets on the ox/fuel lines could become damaged or disconnected/slipped leading to the valve not properly operating in opening the fuel/oxidizer poppets properly to allow sufficient flow into the RCS thruster combustion chamber. This would result in either diminished or no thrust. [redacted] damage/slip would be evident in the available data as the thruster valve would be unable to adequately move, there would be no flow to the combustion chamber, and significant damage would likely result in gross leakage. These effects were not observed.

B1.3.3.1.3 Poppet Fracture identifies that damage to the poppet from firing the thruster causes blocked/reduced flow. Poppet fracture would be permanent and could produce very low thrust level as seen repeatedly on B1A3 following reselection post-fail-off. Poppet fracture similarly to [redacted] would likely result in a gross leakage of commodity out of the thruster valve. There was no indication of gross leakage of commodity.

B1.3.3.1.4 Hot Valve/Injector identifies that the possibility that the propellants (especially NTO) in the thruster valve and/or injector were heated significantly to the point of boiling. This reduces the flow into the RCS thruster combustion chamber, leading to diminished combustion and reduced thrust. Excessive heat could cause injector warping which would cause loss of performance by reducing optimal propellant mixing; however, this would not explain the level of thrust observed in B1A3. The closest available temperature sensor indicated an initial valve temperature of [redacted] and flight valve temperatures at time of post-re-selection firings were reading below the boiling temperature of NTO. Both initial temperatures and post re-selection temperatures of the valve are based on Therm11a thermal model. The Therm11a model is a simplified model and does not accurately nor adequately correlate the potential effects of the surrounding temperatures. There is an undefined gradient between the Pc tube temperature and thermal sensors, based on available thruster verification data that is not incorporated into the modelling. It is possible that the valve and the associated softgoods of the thruster valve reached higher temperatures than the closest thermal sensor read. The evidence supports this being a contributor to the thruster fail-offs.

The effects of heating upon propellants are captured in **B1.4.1 Two Phase Flow** and sub nodes **B1.4.1.1 Vaporization** and **B1.4.1.2 Cavitation**. The heating caused by RCS Thruster firings is captured in **B1.3.3.1.4.2 RCS Thermal Soakback** and the potential effects external effects, such as thermal, is captured in the thermal sections of the **C Failure from the Environment.**

B1.3.3.1.4.2 RCS Thermal Soakback identifies the possibility that structure of the RCS thruster retains heat, and the heat is unable to be dissipated from the firings of the thrusters, causing the propellants to heat rapidly. Heat soakback for this node is defined as the heating from the thrust chamber. This heating is strongly dependent on **A3.1.2.2 Pulse Train (Duty Cycle/Pulse Width/Duration).** Due to insufficient qualification testing that does not adequately inform the associated RCS thermal model, it is not possible to fully quantify the effects of **A3.1.2.2 Pulse Train (Duty Cycle/Pulse Width/Duration)** on the thruster. **The evidence supports this being a contributor to the thruster fail-offs.**

B1.3.3.1.5 [redacted] somehow shifted in place, blocking or restricting the propellant flow into the RCS thruster combustion chamber. [redacted] would result in a permanent Pc pressure drop and observable in telemetry. However, there was no indication of permanent change in Pc pressure.

B1.3.3.1.6 [redacted] **Margin** identifies the possibility that the [redacted] margin within the RCS thruster [redacted] valve is insufficient. Therefore, the [redacted] valve did not properly operate and [redacted] poppets open properly to allow sufficient flow into the RCS thruster combustion chamber. There are long duration thruster firings indicating the valves were staying open for the full duration they were commanded open. There is no evidence of the pilot valves not opening/closing properly.

For **B1.3.3.2.1 FOD He Line** addresses that FOD could cause the pilot valve to be unable to move, preventing the thruster valve from moving. There is no data demonstrating blockage of the helium commodity. Firing commands show the valve opening and releasing flow for all thrusters, except for B1A3. For B1A3, the injector temperatures dropped demonstrating that the valve was opening and there was no blockage to the He Line.

The B1A3 thruster is unique in its failure signature which is consistent with a total blockage of one of the commodities; however, blockage would have to be sudden since thruster performance was nominal during last pulse before failure. As B1A3 was unable to be recovered, and on orbit data suggests a complete blockage of commodity. There is therefore insufficient data to definitively state that there was no blockage of the upstream thruster valve for the B1A3 thruster, as its failure signature was vastly different from the remaining thrusters. Solely for B1A3 is this delineated on the fault tree, which is reflected in the color of the associated causes of **B1.3.2 FOD** and **B1.3.4 Prop Filter Blockage** being labelled as unlikely. It is unlikely that the B1A3 thruster had an entirely different failure from the other thrusters.

B1.3.3.2.2 [redacted] addresses that the [redacted] valve becoming stuck and causing the [redacted] to not move, thus causing the thruster valve to not open. Similar to **B1.3.3.1.6 Inadequate** [redacted]**,** that all thrusters, with the exception of B1A3, being capable of firing before and after the event, demonstrating the [redacted] valve is capable of opening/closing properly. This has been deemed not credible.

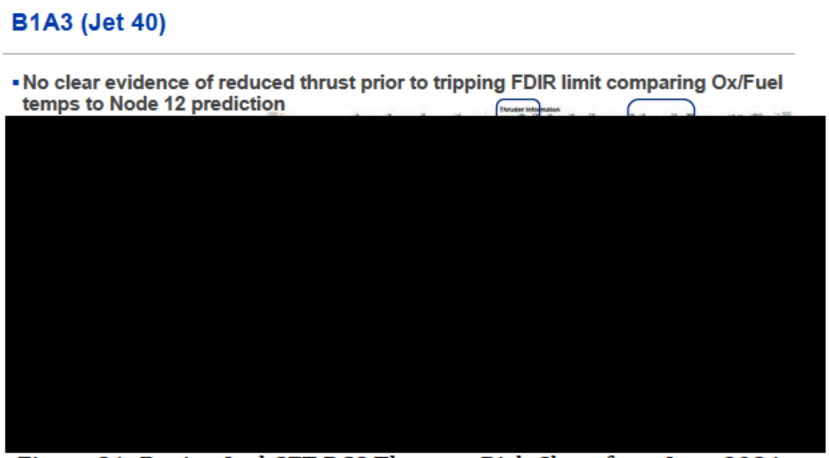
B1.3.3.2.2.1 Insufficient He Actuation Pressure addresses that the pilot valve opens via He, so there is a potential failure mode of inadequate helium to drive the pilot valve. Similarly to **B1.3.3.1.6 Inadequate** [redacted] **Margin,** this node has been deemed not credible as longer duration thruster firings that valves were opening/closing properly indicating that the valves were staying open for full duration commanded open. Preflight analysis shows adequate hold open force margin.

B1.3.4 Prop Filter Blockage addresses that significant amounts of FOD could reduce or block flow of oxidizer and clog the associated filters. It is unlikely that the thruster level filters would have been impacted. It is far more likely that the upstream manifold filters would have been affected by significant amounts of FOD. Degrading Pc/Thrust with continuing hotfire is consistent with the presence of a blockage; however, most thrusters were able to recover during docked hotfires, invalidating this as a potential cause.

B1.4 Unstable Ox State identifies the possibility that the oxidizer was not capable of providing a sufficient reaction. The oxidizer was not of the correct phase/density when reaching the combustion chamber. This branch is divided into **B1.4.1 Two Phase Flow** and **B1.4.2 He Bubble**.

B1.4.1 Two Phase Flow identifies the possibility that the state of the oxidizer from liquid to either gas or solid (frozen) impacted mass flow rate of NTO (oxidizer) to the combustion chamber. **B1.4.1 Two Phase Flow** is divided into **B1.4.1.1 Vaporization**, **B1.4.1.2 Cavitation**, and **B1.4.1.3 Frozen**.

B1.4.1.1 Vaporization identifies that NTO is heated above its boiling point for a given pressure, turning it from a liquid to a gas. This would reduce the mass flow rate of the oxidizer to the combustion chamber negatively affecting the chamber pressure and thrust. Valve body temperatures observed near the NTO/MMH inlet exceeded NTO boiling point at various times during the mission. This was observed via the node 12 temperature sensor on various thrusters, to is captured below in Figure 21: Boeing Led CFT RCS Thruster Risk Chart from June 2024.



[redacted]

Figure 21: Boeing Led CFT RCS Thruster Risk Chart from June 2024

Two phase NTO would increase flow resistance, resulting in a mixture ratio shift and reduced thrust. In addition, Temperatures downstream of valve seats, in the oxidizer flow path to the injector, are expected to be higher than those measured at valve in soakback conditions.

[redacted]

B1.4.1.2 Cavitation identifies the possibility that a choking of the flow rate occurred, causing insufficient oxidizer to reach the combustion chamber. Two phase flow has a lower density due to the presence of gas bubbles and chokes more quickly compared to an incompressible fluid. This limits the mass flow downstream of the chokepoint.

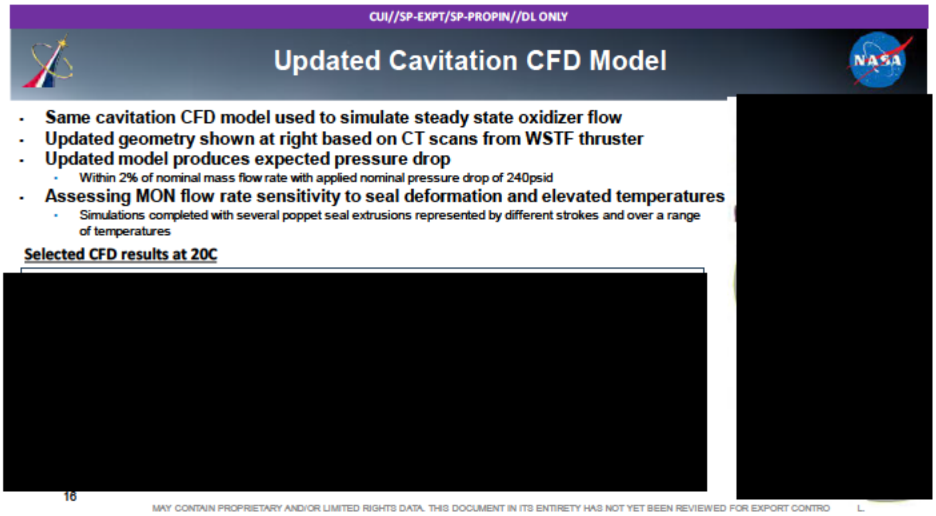


Figure 23: Cavitation Model of the RCS Thruster

Cavitation occurs when flow velocities are locally dropping static pressure below vapor pressure, causing cavitation pockets. This temporary effect was observed during WSTF testing during Truncated Profile 4. There was also a drop in performance observed in other downhill tests that were run, each resulting in RCS thrust becoming permanently degraded.

It is expected that B1.4.1.1 **Vaporization** would be transient in nature. After enough flow has occurred the thruster would cool and expected performance would return. If the reduction in flow were a result of **B1.4.1.2 Cavitation**, then it would be expected to be semi-permanent as the change in flow rate as a result in a change of the structure of the valve would likely remain in subsequent thruster firings. **The evidence supports this being a contributor to the thruster fail-offs.**

B1.4.1.3 Frozen identifies the possibility of a phase change in the oxidizer resulting in insufficient flow of the oxidizer to the combustion chamber. This would result in reduced thrust. There is no evidence of the oxidizer reaching temperatures below the freezing and causing this to potentially occur.

B1.4.2 He Bubble identifies the possibility that a change in temperature of the oxidizer could result in the helium coming out of solution. The He bubbles would cause a poor mixture and reduced thrust. Based on CFD analysis, it is not possible for a bubble to reach significant enough size or accumulation to explain the thruster failures and associated degraded performance.

[redacted]

B2 Incorrect Fuel Flow

Incorrect fuel flow addresses the possibility that the fuel flow reaching the combustion chamber was insufficient**.** This could mean there was insufficient pressure, leakage, or unstable fuel state causing an interruption to the reaction occurring in the combustion chamber. Telemetry data across failed thrusters indicates that fuel was continuing to flow and that there was no interruption of fuel into the combustion chamber. It shows the fuel was cool enough and not at an excessively elevated temperature. This is evidenced below in the cooling that was occurring within the combustion chamber, as observed in Figure 10: B1A3 chart demonstrating fuel flow across the injector.

B3 Failed Combustion Chamber

A ZOT or other event that causes a degraded state of the chamber, can possibly cause a failed combustion chamber, affecting the overall capability of the thruster. On-orbit inspections did not show any damage, though image resolution is limited. The borescope images from the ground, during WSTF inspections, are of much higher fidelity than the images taken on orbit. The borescope images were positioned in the throat itself, while the cameras on orbit were hovering on the outside of the nozzle. The data from docked firings demonstrated that the thrusters had somewhat recovered, which would not have occurred in a failed and/or degraded thruster chamber. The combustion chamber is not considered to be a cause or contributor.

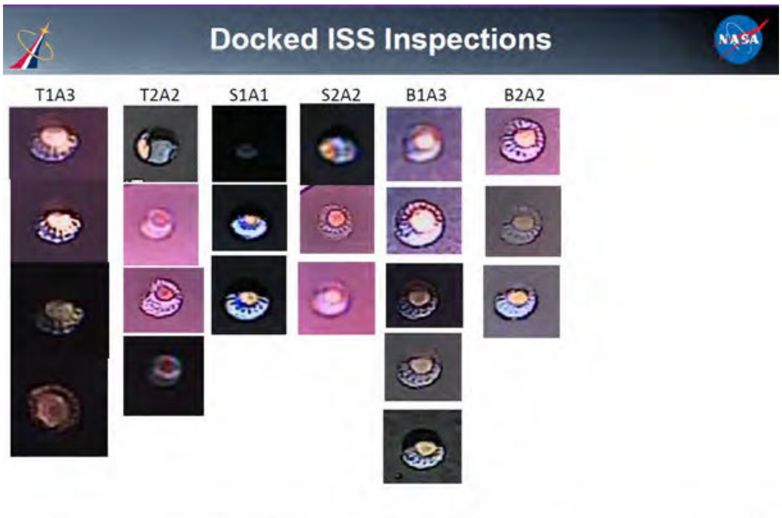


Figure 25: On-Orbit Inspections of Thruster Chambers

B4 Failed Throat

B4.1 Throat Erosion investigates whether the thruster throat may have become degraded and/or failed because of thruster operations. Similarly to the combustion chamber, on-orbit inspections did not indicate throat erosion. It is possible that some throat erosion may have been missed during the on-orbit inspections due to lower image quality and ability to get a close image. Collected flight data is not indicative of an impactful level of throat erosion However, minor throat erosion would result in a minor reduction to the Pc which could have dropped an already degraded thruster below the FDIR limit.

The docked hotfires demonstrated that chamber pressure recovered. This would not have been possible if the throat had significantly eroded or there was total loss of the throat causing the observed reduction in the Pc. It should be noted, that due to the smaller thruster firings of the Starliner Vehicle, in comparison to nominal ISS Thrusters, and the position of the thrusters in comparison to the ISS Space Integrated Global Positioning System/ Inertial Navigation System (SIGI), there is an error rate of approximately 14% which may hide minor throat erosion. The removal of the thruster via FDIR was not the failure, but the degradation of the thruster and its capability to produce thrust. It is possible that minor throat erosion, incapable of being viewed with the available imagery, did contribute to the degradation of the Pc. Thus, throat erosion is an unlikely contributor.

B5- Failed Nozzle

A failed nozzle, a damaged nozzle, or a cracked nozzle would potentially affect the thruster capability. There was no damage observed on the thruster nozzles during the on-orbit inspections.

Environment
Environment is divided into phases of flight across the mission: **C1 Failure from Pre-Launch Environment, C2 Failure from Launch Environment, C3 Failure from On-Orbit Environment**, and **C4 Failure from Vehicle Ops Environment.**

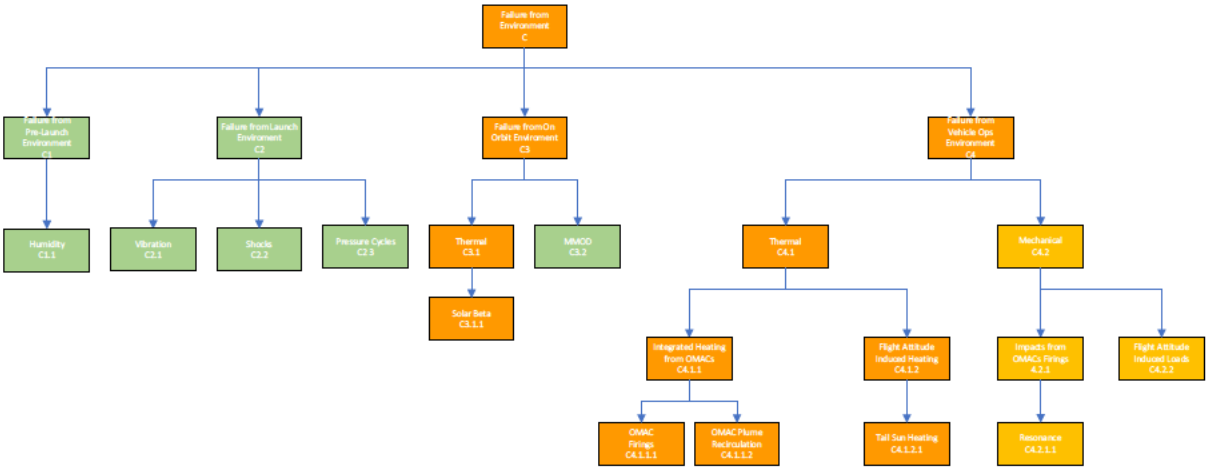


Figure 26: Environment Section of the Fault Tree

C1 Failure from Pre-Launch Environment identifies the possibility that the pre-launch environment may have had an impact on the thrusters that lead to the thruster fail-offs.

C2 Failure from Launch Environment identifies the possibility that the launch environment may have had an impact on the thrusters that lead to the thruster fail-offs.

Due to the timing of the failures, there has been no contributing causes or factors identified from the **C1 Failure from Pre-Launch Environment** or **C2 Failure from Launch Environment.** Any potential contributors would have been identifiable earlier within the flight.

C3 Failure from On-Orbit Environment identifies that there may have been impacts due to the on-orbit environment that may have had an impact upon the Starliner vehicle. **C3 Failure from On-Orbit Environment** is divided into **C3.1 Thermal** and **C3.2 MMOD**.

C3.1 Thermal identifies that there may have been impacts to the thruster failures from the on-orbit environment, specifically **C3.1.1 Solar Beta.** It is not possible for the contributions of heating from **C3.1.1 Solar Beta** alone to cause the thruster fail-offs. If it was to cause the fail-offs, the failures would have occurred far early in flight. It is possible that the **C3.1.1 Solar Beta** did provide an initial minor heating load that impacted the Starliner vehicle, though this would at most be a contributing factor and likely not having a significant impact on the observed failures.

C3.2 Micro-Metroid Orbital Debris (MMOD) identifies the possibility that MMOD could have had an impact upon the Starliner Vehicle and may have contributed to the thruster fail-offs. There is no evidence of MMOD contributed to these failures, and if it were to, it would be immediately identifiable.

C4 Failure from Vehicle Ops Environment identifies the possibility of Starliner hardware and operations, aside from the RCS Thrusters, may have contributed to the thruster fail-offs. The **C4**

Failure from Vehicle Ops Environment branch is divided into **C4.1 Thermal** and **C4.2 Mechanical**.

C4.1 Thermal identifies the possibility of the nominal heating to the RCS Thrusters contributed to the thruster fail-offs. **C4.1 Thermal** branch is divided into **C4.1.1 Integrated Heating from OMACs** and **C4.1.2 Flight Induced Attitude**.

C4.1.1 Integrated Heating from OMACs identifies the possibility of **C4.1.1.1 OMAC Firings** and **C4.1.1.2 OMAC Plume Recirculation** causing excessive heat in the doghouse structure and subsequently RCS Thrusters, contributing to the overall thermal environment and RCS Thruster fail-offs. According to OFT2 S1A1 RCCA, "Flight data shows some correlation between OMAC firing and S1A1 valve temperature gradient. Heat rate is drastically reduced when the OMAC firing ends ruling out heat coming directly from OMAC chamber/blanket." **C4.1.1.2 OMAC Plume Recirculation** identifies gapping in the Port and Starboard doghouses that possibly caused plumes from OMAC firings to heat and contribute to an elevated thermal environment. **Though the thermal models, prior to CFT do not capture the impacts of OMACs upon the RCS thrusters, the evidence supports this being a contributor to the thruster fail-offs.**

C4.1.2 Flight Induced Attitude identifies the possibility of the RCS Thrusters heating and contributing to the elevated thermal environment because of **C4.1.3 Tail Sun Heating** designed to provide power to the vehicle from the solar arrays. Data from OFT2 demonstrated that thruster S1A1 had increased temperatures, because the aft thruster nozzle extends outside the doghouse and is susceptible to solar heating. This is observed with an increased valve temperature on aft thruster of 10°F to 50°F compared to other thrusters. **The evidence supports this being a contributor to the thruster fail-offs.**

C4.2 Mechanical identifies the possibility of loading and/or vibrations from OMAC firings could contribute to the thruster fail-offs. **C4.2 Mechanical** is divided into **C4.2.1 Impacts from OMAC Firings** and its subnodes **C4.2.1.1 Resonance** and **C4.2.2 Flight Attitude Induced Loads.** The mechanical portion of the Vehicle Ops Environment is meant to encompass cycling, slam starting, vibrations, and other items that would have had an effect upon the prop system. Based on the available telemetry there is no indication that there was an effect upon the RCS thrusters from mechanical effects of firing the OMACs, but the telemetry rate may not be capable of capturing the minute effects. These items are unlikely contributors as it is not possible to entirely exonerate these factors.

4.5.6 Most Probable Proximate Cause

Based on the fault tree analysis conducted in the previous section, the most probable proximate causes of reducing the combustion chamber pressure, which triggers jet fail off FDIR (the undesired outcome), are two phase flow and mechanical deformation impeding oxidizer flow path. The fuel side of the RCS Thrusters was operating nominally. The potential failures that could cause a **Blocked/Reduced Flow** would likely cause a permanent disabling of the thruster capability to produce thrust, significant degradation of the Pc, and/or observable leakage from the thrusters. This led to the Starliner Engine Testing at WSTF in 2024. Teams at WSTF conducted testing to provide a risk reduction path for crewed CFT return by recreating an RCS stressing downhill mission profile on an engine with observed degraded performance from the uphill mission phase.

WSTF Summer 2024 testing identified a reduction in performance of the RCS engine following one of the uphill runs, which persisted. The RCS engine continued to degrade in subsequent runs. Post-testing tear down identified that the oxidizer poppet of the RCS thruster valve had extruded. As a result of decontamination, it is likely that this extrusion was less pronounced and/or retracted in comparison to the testing that was observed.

[redacted]

Figure 27: CT scan of Ox Poppet

This deformed/extruded poppet would have permitted **Cavitation** to occur. **Vaporization** would not have been present during the docked hotfires, conducted weeks after the thruster fail-offs. This extruded poppet provides an explanation for the continued thrust degradation observed in the post docking hotfires. NASA fluid experts performed CFD analysis at MSFC. Analysis shows the more a poppet extrudes, the less space the NTO can travel through, meaning a lower temperature of the NTO would be required to transition to vapor. See Figure 27: Cavitation CFD Model Results.

[redacted]

Incorrect Ox Flow to the Combustion Chamber was driven by **Blocked/Reduced Flow** and **Unstable Ox State**. **Blocked/Reduced Flow** was caused by a **Failed Thruster Valve** due to **Teflon Poppet Extrusion.**

Poppet seat swell/extrusion is a historically documented and known issue for this type of thruster. Many examples of Teflon poppet seat swelling were identified by the NASA propulsion team and reviewed by the SDRT. Examples include Gemini attitude control anomaly investigation from 1967, Shuttle Auxiliary Power Unit (HOPE-X Program) in 2000 ATP failure, Wideband Global Satcom (WGS) failure investigation, and the Mars 71 Anomaly investigation.

Teflon Poppet Extrusion was caused by **Heat and Pressure behind the Poppet** and driven by seeping NTO behind the poppet, occurring because of **Inadequate Poppet Seat Retention.** The NTO behind the poppet generated a void as result of the overall thermal environment (**Heat).** Based on information provided by Moog during Shuttle APU testing, for STS-101, and similar failures, as identified by the STAR,inadequate retention contributed to the observed failures. The Moog ATP data, from STS-101, references that the combination of the extrusion and high load conditions/rapid firing of the APU would have resulted in a failure/shutdown; therefore, **Pulse Train (Duty Cycle/Pulse Width/Duration)** is considered to be a potential contributor due to the mechanical loading upon the poppet from rapid firing**. Traditional Teflon Swelling (NTO)** contributed to the Teflon Poppet Extrusion by further expanding the poppet.

Heat was caused by **RCS Thermal Soakback** which is a result of **Pulse Train (Duty Cycle/Pulse Width/Duration).** Additional effects were a result of **OMAC Firings, OMAC Plume Recirculation,** and **Tail Sun Heating**, which lead to elevated temperatures in prop lines, manifold, and injectors.

The **Unstable Ox State** was a result of **Vaporization** and **Cavitation. Vaporization** was driven by **Heat** and **Cavitation** was a result of **Heat. Teflon Poppet Extrusion** likely contributed to the unstable ox state as well.

Due to the nature of the failure of SM RCS Thruster B1A3, it is possible that the thruster failed as a result of **Upstream of Thruster Inlet** due to **FOD**, [redacted], **Poppet Fracture**, or [redacted] **Shift**. It is highly unlikely that the B1A3 thruster would experience an entirely unique failure compared to the other four thrusters.

There is a residual risk of the failure mechanism being separate or not validated via testing as a result of the uniqueness of the B1A3 thruster having a separate failure mechanism or poppet extrusion occurring, resulting in the total and unrecoverable blockage.

As the thruster failures from CFT have not been recreated on the ground, the proximate cause cannot be confirmed and is considered the most probable, not definitive.

Proximate Cause 1: Two-Phase Flow of NTO: Vaporization/Cavitation

The NTO within the 5 aft thrusters was heated to the point of vaporization/cavitation, causing a subsequent drop in chamber pressure which triggered jet-fail FDIR and removed the thruster from control.

Proximate Cause 2: Flow path restriction: Poppet Extrusion

The thruster poppet extruded causing insufficient NTO to flow into the combustion chamber, causing a drop in chamber pressure which triggered the jet-fail off FDIR and removed the thruster from control.

Recommendation:
R.1 [Boeing] - SM RCS Thruster Fail-Offs IFA Closure

When testing is complete, formally disposition the SM RCS Thruster Fail-Offs IFA and address residual risk of poppet extrusion effecting a thruster valve. Show via test or analysis that the proximate cause of the failure is rectified, through hardware/GNC software modification, to complete necessary Starliner vehicle certification.

At the time of the writing of this report, recreation of the thruster mechanism that occurred during CFT has not been produced on the ground. Testing has yet to validate the proximate causes. The poppet recovery mechanism and the extent to which a poppet is expected to recover is not understood. The WSTF testing from Summer 2024 reached thrust degradation levels of ~71%, but the FDIR trigger threshold is below 33%. Additional testing, with poppet extrusion, was not performed in an integrated doghouse test setup environment.

Without recreating the thruster signatures observed during CFT, there is likely to be residual risk for an unidentified failure mode. Additionally, it is probable that the B1A3 thruster hard-failed in the same way, but remains a possibility that B1A3 failure is standalone.

4.5.7 Intermediate Causes, Contributing Factors, Organizational Factors

Below is an exploration of the intermediate causes, contributing factors and organizational factors that contributed to each proximate cause. This section is structured such that each proximate cause is explored separately, but please note that because this is a multi-factor failure mode, overlap is expected.

Causes/Factors Contributing to Proximate Cause 1: Two Phase Flow of NTO

Intermediate Cause 1: RCS Thermal Soakback
The structure of the RCS thruster retains heat which is unable to be dissipated from the firings of the thrusters, causing the propellants to heat rapidly.

This cause was also identified by the RCCA Team and the STAR team. There is already a recommendation from the STAR: “Conduct ground testing of the SM doghouses in their flight configuration to validate the thermal models when the OMAC and RCS jets are firing.

The closure plan for the CCP Program for the associated action (A-6), is to conduct IDH testing. As already identified by the STAR, closure of this action is tied to the acceptance of the SM RCS IFA at PCB.

Intermediate Cause 2: Pulse Profile (Duty Cycle/Pulse Width/Duration) of the RCS Thruster Firings

NASA propulsion experience is that overall heating of the thruster is driven by duty cycle/pulse width along with other factors, including soakback and pulse sequence.

Until SEDQ and IDH testing and thermal models, are complete, it is not possible to determine the full extent to which the pulse profile contributed to the failure. Additional testing may need to be performed in order to more fully understand the effects of pulse profile on the environment.

Recommendation:
R.2 [CCP, ENG] - Pulse Profile (Duty Cycle/Pulse Width/Duration)

When Therm-11c is complete, perform analysis and evaluation to validate the impact of GNC changes made between OFT2 and CFT and verify they did/do not pose additional risk to CFT/Starliner.

An example of GNC changes made between OFT2 and CFT is [redacted], a change that was made to "Enable expanded [redacted] during translation burns to reduce thermal impact on thruster hardware."

Figure 29: SEDQ1 Pc Tube State Temp with Cutouts from [redacted]

"The theory being that pulses near that bottom of the zone were pushed down, and this could have resulted in a higher number of pulses in the 'red zone.' Especially since a lot of pulse-trains are in that 20-30% DC range. So, it could have shifted from green/yellow to orange/red," a NASA Prop Expert said.

The RCCA team and the STAR team also identified this cause. There is already a recommendation from the STAR: "Update the SM doghouse thermal environments as needed based on the updated thermal models and ground testing".

The CCP closure plan for the associated action (A-8), is "Use of test validated thermal models and GNC analysis of required jet firings to ensure that all required operational plans are enveloped in IDH testing. Includes use of the validated models mentioned in A-7."

Recommendation:
R.3 [Boeing] - Thruster Health

Validate threshold and associated logic for determining the health of a thruster.

Boeing and CCP should provide confirmation to the Thruster Fail-off FDIR threshold of 30% and verify that previous analysis is still valid based on new test data. This must be accurate to prevent hardware failure due to off-nominal mixture ratio.

Boeing and CCP should validate the threshold for thruster failure used in flight and update the associated flight rules and procedures.

The [redacted] FDIR was changed because of the OFT2-76, RCS thruster injector temperatures during soakback appear to have exceeded temps observed during qual, to "to minimize thruster fail-off due to slow chamber pressure ramp up caused by hot propellant." This change should be evaluated and verify whether a roll-back to the previous version of the FDIR is warranted.

Intermediate Cause 3: OMAC Firings

The OMAC firings were identified as a likely contributor to the thermal environment of the Starliner Vehicle. This was observable in the flight data correlation. Models prior to CFT did not include OMAC thruster firings. There was no integrated ground testing including OMAC firings prior to CFT.

Profile #1 – Injector Temps (Test vs. Flight vs. 3D Model)

[redacted]

Figure 30:CFT Flight Data Overlaid with Potential Impacts from OMACs

This cause was also identified by the RCCA Team and the STAR team. There is already a recommendation from the STAR:"Conduct ground testing of the SM doghouses in their flight configuration to validate the thermal models when the OMAC and RCS jets are firing."

The closure plan for the CCP Program for the associated action (A-6), is to conduct IDH testing. As already identified by the STAR, closure of this action is tied to the acceptance of the SM RCS IFA at PCB.

Intermediate Cause 4: OMAC Plume Recirculation

OMAC Plume Recirculation was identified as a likely contributor due to increased temperatures based on the observed differences in the flight data. This was significantly more apparent in the starboard doghouse when compared to others, which is believed to be a result of the SureSep bracket causing more recirculation to occur. This was not identified as a potential cause in the OFT2 high temp IFA, which then repeated on CFT.

If ground testing is unable to test plume recirculation in the ground IDH testing configuration, a plan should be developed to validate any changes to fix this problem, in flight. For additional information on this see ***Observation 1: No clear criteria for Starliner-1*** and **Recommendation: R.13 -Return to Crewed Flight.**

Intermediate Cause 5: Inadequate Thruster Thermal Models
Inadequate thermal modelling caused insufficient scrutiny for the thermal environment, leading to excessive heating from RCS thermal soakback and integrated heating from OMACs.

Thermal models lacked the right complexity, were not sufficiently anchored in test/fight data, had insufficient case runs, and had incorrect baseline assumptions.

This is captured in PCB-19-383, in September 2019. This PCB identified that the SM RCS did not meet the "standard for human rated engine qualification [which] includes flight representative mission duty cycle testing, including worst case thermal soak back/ratcheting and successful restart."

In May 2019, the PCB accepted the "SM doghouse thermal model (PROP-06) not in critical model Database" risk, which was generated in 2017. As identified by Passive Thermal Control System (PTCS), "there was a gap in Boeing thermal modeling. Specifically, the internal componentry within each of the doghouses isn't modeled in THERM-16. This area is modeled by Aerojet-Rocketdyne (AR) per contract with Boeing PROP. The contract only furnishes the results and not the model that produces the results. a.) AR model needs to undergoes accreditation. There is no NASA insight into the validity of the results and therefore verification effort is compromised."

The rationale closure states, "The Doghouse thermal model that Boeing has now agreed to incorporate into their SM vehicle thermal model, only accounts for [redacted] operation within the Doghouse. It does not model the thruster operation and thermal soakback. AR has performed their internal analysis of on-orbit thruster operation but that AR- model will not go through the Accreditation process."

In May 2019, Boeing accredited the Therm-11 model and included it in the library of specialty models. However, the library itself did not include anything about doghouse thruster operation. Following OFT1, the Therm-11a model was generated with a focus on doghouse RCS [redacted] due to the thruster failures observed and was deemed accredited by Boeing in November 2020. This was the first time a Boeing thermal model included something related to thruster operation."

The Therm-11a model did not incorporate OMAC firings, or initial heating that could occur from the doghouse environment, which is critical given that the aft thrusters have the longest feed line in comparison to every other thruster.

[redacted]

Figure 31: Therm11a Model Description – CFT Anomaly Investigation

There was no thermal model available to adequately understand the full impacts of the thermal environment upon the RCS thrusters, specifically the aft thrusters with the longest feed line tube, and very close proximity to the OMAC thrusters.

[redacted]

Figure 32: RCS Feedline Length OFT2 RCS Failure Investigation Slide 94

This cause was also identified by the RCCA Team and the STAR team. There is already a recommendation from the STAR: "Update AR and Boeing thermal models as needed based on the ground test results."

The closure plan for the CCP Program for the associated action (A-7) states, "Update Boeing thermal models as needed based on the ground test results." The initial closure plan is addressing the many thermal models have been created and are in the process of being validated. These include Therm-11a, -11b, -11c; Hi-Fi IDH models of all four doghouses, both the WSTF test stand and flight versions; Ultra Hi-Fi RCS Valve model; and NTO transport model.

Intermediate Cause 6: Insufficient Thruster Qualification

SM RCS Thruster Qualification did not cover the flight envelope for temperature and duty cycle (TLYF).

Thruster qualification efforts lacked comprehensive integrated testing. Key deficiencies included limited hot case coverage, inadequate consideration of hypergolic propellants during valve testing, and insufficient hot-fire qualification of the integrated service module. These gaps contributed to missed failure mode identification. Notable issues were later uncovered during WSTF Summer 2024 testing, including poppet extrusion, seepage behind the poppet, Teflon seal swelling, and poor engagement of the thruster valve poppet swage.

The quote below from the RCS Assembly Qualification Report, RD18-272 Rev. A, delivered in April of 2019, demonstrates that the RCS thruster was operated outside qualified/tested range.[2]

> **"4.2.5.2 Off-Nominal Propellant and Hardware Temperature Testing**
> Testing at increased and reduced propellant temperatures was conducted to verify thruster operation at the specified operating box in the Boeing specification. There were two different temperature requirements stated in the Boeing SCC1-00095 Rev E requirements document. In Section 3.7.3.1.1 states an operating box inlet temperature at [redacted] Section 3.2.7.2.8 states propulsion subsystem RCS thruster operating temperatures at [redacted] Due to the Redmond facility temperature conditioning limitations at [redacted] with qual margins, it was agreed to perform testing at [redacted] with qual margins. For the low temperature testing with qual margins, test temperature would be at 6.6 °F which is below the propellant freezing point for oxidizer at approximately 11.7 °F. Based on the oxidizer mixed oxides of nitrogen (MON) level variation, test temperature instrumentation accuracy, and test margin it was agreed to test at [redacted] F. Thrusters 1, 2, and 3 completed a series of steady-state and pulse mode tests at the following off-nominal temperatures during 1X life testing:
>
> - Cold Temperature = [redacted]
> - Hot Temperature = [redacted]

There is a vast difference for the actual inflight temperatures observed during OFT1, OFT2, and CFT, as observed in Figure 1: Failed Thruster Across All Flights, compared to the qualification temperatures/environment detailed in the section **4.2.5.2 Off-Nominal Propellant and Hardware Temperature Testing** of the RCS Assembly Qualification Report.

Multiple groups, prior to CTF, discussed the lack of mission representative operational duty cycle testing for SM RCS engines.. This concern is one that has been tracked since prior to OFT1 and is specifically reviewed in this intermediate cause because it is widely accepted that operational duty cycle is a primary driver of hardware temperature. NASA Engineering and the CCP Spacecraft Office have consistently identified this qualification gap and recommended additional testing, however it was not incorporated into the pursued plans for risk assessments between flights.

[2] This is a part of the DRD 111 delivery from the Ground Test1130 VCN

OFT1: The SM RCS Qual Gaps risk was accepted in September 2019 (PCB-19-383), Boeing RCS/OMAC (Engine) Qual Issues for OFT.

OFT2: During PCB-20-404 for SM RCS Jet Failure During OFT, the plan outlined the use SM RCS as is, noting that the OFT MET Anomaly demonstrated robustness of RCS thrusters design despite long duration of excessive usage. Design mods were evaluated to [redacted] which was the leading theory for B2R3 failing to fire. This is highlighted in the CCP SDRT report as a missed opportunity to further investigate the failure modes of the SM RCS thrusters and is discussed further in a later organizational factor regarding anomaly resolution.

CFT: The qualification gap risk was addressed in April 2023 during PCB-23-100 (CFT: Starliner Prop, OMAC/RCS Hot-Fire Qual Gaps). The program directive issued at that time resolved to accept the qualification gap for duty cycles for CFT only. This acceptance was encompassed within the previously approved elevated 2x5 risk level from PCB-23-053, which was documented during the IFA closure for OFT-2 related to valve/injector assembly temperature measurements exceeding qualification limits. These temperature exceedances were categorized as an Unexplained Anomaly (UA). The directive acknowledged that during OFT-2, several valve/injector assemblies experienced temperatures beyond their qualified thresholds, attributed to specific operational duty cycles. Consequently, the thermal risk associated with these duty cycles was accepted as a 2x5 risk for potential jet failure, despite the IFA being closed under the UA classification. Engineering teams reiterated the importance of addressing this issue and emphasized the recommendations from the Engineering Review Board (ERB), specifically ERB-23-0045-R2, which advocated for testing SM RCS thrusters using flight-like duty cycles.

While none of the directives in these PCBs, which are the formalized program document for accepting risk, specifically talk a reason for not pursuing additional qualification testing, it is largely considered to be a pursuit balanced by schedule and cost. This concept of the impact of an aggressive launch schedule is further explored in section **4.8.7 Schedule**.

This cause was also identified by the RCCA Team and the STAR team. There is already a recommendation from the STAR: "Conduct ground testing of the SM RCS thrusters in their flight configuration to re-qualify the propulsion system for the anticipated thruster usage and induced environments. Qualification testing campaign should be augmented, TLYF."

The closure plan for the CCP Program for the associated action (A-16), is which is "Ensure that the SM RCS delta qualification test plan is consistent with the findings, recommendations and lessons learned identified." Qualification testing campaign should be augmented, TLYF." As already identified by the STAR. Closure of this action is tied to the acceptance of the SM RCS IFA at PCB.

The PIT is not writing another recommendation for this issue as the STAR recommendation to conduct testing to re-qualify the propulsion system, is adequate. However, this should not be seen as downplaying this issue. Understanding the thruster qualification is, in fact, one of the most important outcomes requiring resolution, in this report.

Causes/Factors Contributing to Proximate Cause 2: Flow path restriction (Poppet Extrusion)

Intermediate Cause 1: Heat
Heating from RCS firing/integrated OMAC firings contributes to poppet extrusion.

This cause was also identified by the RCCA Team and the STAR team. There is already a recommendation from the STAR: "With many variables playing into thruster failures, and history showing failures as low as approximately 230°F, it is critical to ensure that thermal environment changes and improvements planned for the next mission demonstrate significant margin. There is uncertainty into where the actual failure temperature is, so margin is required to limit the chance of thruster failure."

The closure plan for the CCP Program for the associated action (A-5), is to conduct IDH testing. The closure plan for the CCP Program for the associated action (A-7), is to Update AR and Boeing thermal models as needed based on ground test results. As already identified by the STAR, closure of this action is tied to the acceptance of the SM RCS IFA at PCB.

Intermediate Cause 2: Pressure Behind the Poppet Seat
Liquid NTO seeps behind the poppet, as temperature increases and causes NTO to vaporize, it provides the force necessary to further extrude the poppet.

It is unclear at time of writing this report, all of the mechanisms that allow NTO to enter behind the poppet. It may be related to material variability of the poppet or tolerancing of the swage as detailed below; however, there are clearly additional elements that have yet to be identified as poppet extrusion has yet to be recreated and sufficiently understood. This variability may indicate why some thrusters have reached higher temperatures but did not degrade as observed during OFT1 and OFT2.

Recommendation:
R.4 [CCP, ISSP] - Remaining Residual Risk

When testing is complete, formally disposition the SM RCS Thruster Fail-Offs IFA and address residual risk of poppet extrusion effecting a thruster valve. Show via test, or analysis that the proximate cause of the failure is rectified, through hardware/GNC software modification, to complete necessary Starliner vehicle certification.

Intermediate Cause 3: Inadequate Poppet Seat Retention
Inadequate poppet seat retention may allow to the path for NTO behind the poppet, and when temperatures reach the vaporization for NTO, will create an expanding pocket, forcing the poppet to extrude into the seat. (See: Intermediate Cause 2)

With similarly designed hardware, inadequate seat retention can extrude a poppet through the mechanical pressure of repetitive actuation.

See details in Fault Tree: **B1.3.3.1.1.1 Inadequate Poppet Seat Retention** regarding previous findings of similar hardware.

This cause has not been dispositioned by the RCCA. RCCA Fault Tree Node 2.2.6.3 NTO seepage behind poppet seal and RCCA fault tree node 6.1.5.2 Inadequate engagement of poppet swage still need to be dispositioned.

The recommendation for this intermediate cause is already captured in R.4 Pressure behind the Poppet Seat

<u>Contributing Factors</u>

Contributing Factor 1: Throat Erosion
Minor throat erosion would be difficult to detect and cause lower potential Chamber Pressure (Pc) but increase the thrust. However, since lower Pc is the trigger for jet fail-off FDIR, minor, undetectable throat erosion could be contributing.

Contributing Factor 2: Traditional Volumetric Teflon Swelling
This is a known effect of Teflon when in the presence of NTO and is captured in most prop system designs. Through the failure mode of poppet extrusion, it undoubtably played a role.

Contributing Factor 3: Solar Beta
Solar Beta is a known contributor to the thermal environment of a spacecraft and therefore is an inherent contributor to this failure mode.

Contributing Factor 4: Tail-Sun Heating
The placement of the CFT solar arrays require the vehicle to fly tail-sun, thus it is highly likely that this would contribute to the increased thermal load upon the vehicle.

Contributing Factor 5: Pulse Density / Mechanical Thruster Demand (Non-thermal)
As illustrated earlier Figure 1: Failed Thruster Across All Flights in comparison to temperatures, Starliner flight history demonstrates not all failed thrusters were among the hottest temperature thrusters, and not all hottest temperature thrusters have experienced failure. Furthermore, there is some correlation between thruster Pc reduction following high pulse density burns. This is demonstrated in Figure 33: CFT Thruster pulses per burn vs Thruster Pc.

At the time of writing of this report, members of the PIT have presented and discussed this data with Boeing and CCP prop experts. There has been some debate regarding the extent that the IDH testing performed to date addresses this potential contributor. Closure of the SM RCS in-flight anomaly (IFA) should include rationale for either accepting unexplained thermal inconsistencies or pursuing additional testing to determine the impact of non-thermal contributors such as Pulse Density or Mechanical Demand. For additional context refer to **Recommendation: R.1- Flow path restriction (Poppet Extrusion).**

[redacted]

Figure 33: CFT Thruster Pulses Per Burn vs. Thruster Pc

Organizational Factors

Organizational Factor 1: Insufficient Anomaly Resolution Process
Multiple RCS thruster failures occurred on OFT 1 and OFT 2. While fault trees were developed, due diligence to reach direct and root cause was not performed and adequate block closure rationale was often incomplete.

During OFT1, multiple SM RCS jet failures (Fail OFF and Fail ON) were annunciated during, and subsequent to, anomalous OI burn (per OFT-12, MET Epoch Failure) based on thruster chamber pressure (Pc) readings. There were 10 thrusters failed by thruster redundancy management (AR

31). In-flight thruster testing showed nine of these were transducer-only problems and one thruster (B2R3) had both transducer problem and was inoperative (AR 58). The associated ARs were closed with the rationale of AR 31 and 58 were caused by MET Epoch-related firings (AR). MET Epoch has been corrected for OFT2 and subsequent flights. This set the stage for OFT2 as the rationale of the thrusters still operated in excessive temperatures beyond what was expected, leading to normalization of high temperatures beyond the verification data. The verification data was already determined to not be mission representative.

During OFT 2, several RCS thruster injector temperatures approached valve design requirement, with S1A1 exceeding it during de-orbit burn. Eight thrusters experienced temperatures above 250F. This was dispositioned Unverified Failure (UVF) / UA and IFA for CFT & subs. (PCB-23-053/OFT2-76).

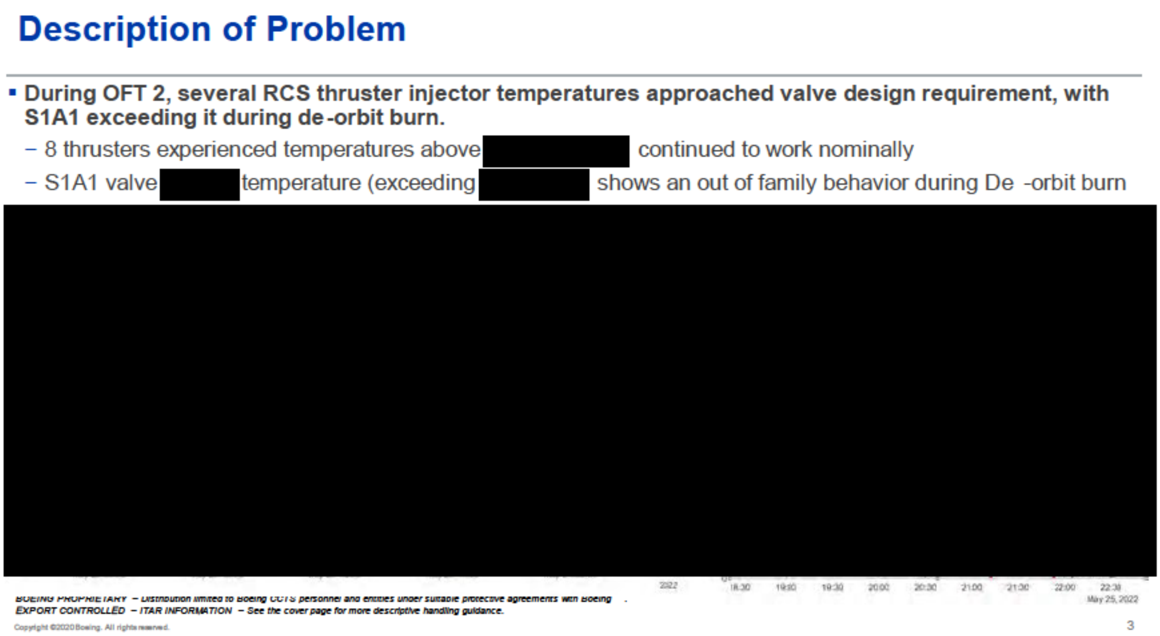


Figure 34: OFT2 RCS Thruster [redacted] Valve Temp Exceedance

The most probable cause was "a combination of the contributing factors identified during the failure analysis with the major driver being specific duty cycle (1.2), an interaction with adjacent OMAC firing (2.1.1), and smaller contributions from doghouse environment heat (solar heating, heat reflection)."

Based on these findings there were changes made to the [redacted] FDIR to minimize thruster fail off due to hot propellant, a software patch that potentially provided temperature reduction for some thruster valves, and GNC cut-outs removing the excessive heating. These changes potentially allowed for an increase the thermal environment of the RCS thruster as flight rationale stated, "Operational temperatures within the [redacted] design requirement is highly unlikely to result in loss of an engine", this was based on the therm-11a modelling which did not model the effects on internal valve components of the thrusters.

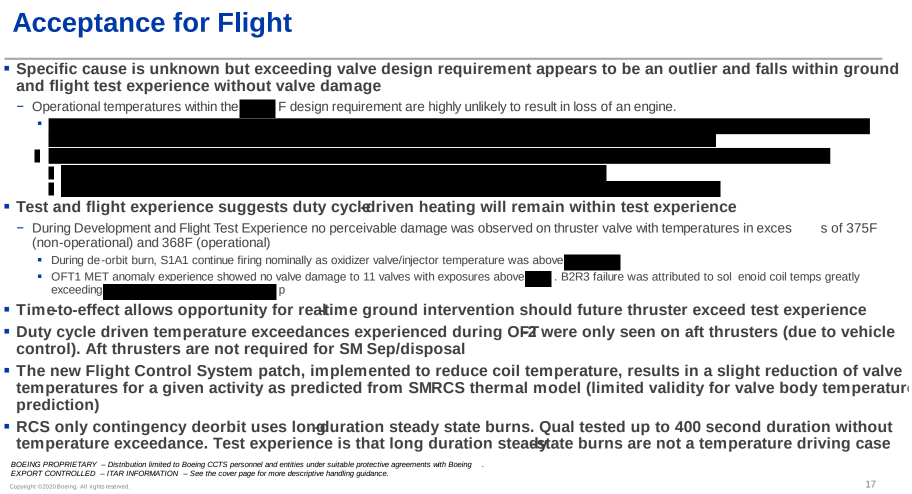


Figure 35: Acceptance Rationale for OFT2-76 Excessive Heating

The acceptance rationale for this anomaly was predicated on a firm misunderstanding of the capabilities of the thruster, as the OFT1 had hotter thrusters that still operated, but there were no tools to measure or understand how degraded the thrusters were or their effective performance. "OFT1 MET anomaly experience showed no valve damage to 11 valves with exposures above [redacted]. B2R3 failure was attributed to [redacted] temps greatly exceeding [redacted] limit, not the [redacted] valve temp."

During the OFT2 SM RCS Thruster Failure Investigation, hot [redacted] valve as a result of poppet seat swelling causing reduced propellant flow was identified as a contributing factor. It was also noted in backup of the charts from OFT2 SM RCS Thruster Failure Investigation that "At steady state flowrates, it would take approximately 0.18 seconds to cool the [redacted] F. This is long enough to trip a low Pc shutdown."

[redacted]

Figure 36: Hot Valve Injector SM RCS Failure during OFT2 Slide 127

If there had been more qualification testing to inform the thermal model, better understanding of the limitations of the thermal model, better understanding of the thermal differences between the Pc tube and the RTDs, or better sampling rate to understand the physics of what was occurring in the thruster, it is likely this would not have been dismissed.

Organizational Factor 2: Mischaracterization of Risk in thruster Qual Gaps leads to Flawed Flight Rationale

The thermal risk for Starliner's SM RCS thrusters was mischaracterized due to reliance on simple models and inadequate qualification testing that failed to replicate mission-representative conditions. Despite clear evidence of thermal soakback and temperature exceedances, risk acceptance proceeded without resolving key environment and duty cycle concerns.

At the **November 2013 Starliner CDR**, the thermal models were **simplistic and lacked direct test data**, offering only limited predictive capability. Even at that early stage, modeling indicated a **potential soakback issue at [redacted] F**, yet this concern was not adequately addressed in subsequent qualification efforts.

[redacted]

Figure 37: RCS Thermal Model from CDR 2013, delivered as part of RCS Thruster Assembly Verification Report for 1130 Ground test VCN from DRD 111[3]

[3] Notice These data herein include "Background Data" or "Data Produced by AR pursuant to a Space Act Agreement" in accordance with the Data Rights provisions under Boeing Space Act Agreement #NNK 12MS01S and embody Proprietary Data. In accordance with the Space Acct Agreement, NASA will use reasonable efforts to maintain the data in confidence and limit use, disclosure and reproduction by NASA and any Related Entity of NASA (under suitable protective conditions) in accordance with restrictions identified in the Space Act Agreement.

[redacted]

Figure 38: Possible [redacted] F Soakback, RCS Thruster Assembly Verification Report, November 2019[4]

By **April 2019**, the RCS Thruster Verification (RD18-272A_SDT) specified a **maximum valve seat temperature of [redacted] F** during operation. However, testing showed that **valve body temperatures could reach [redacted] F post-burn due to soakback**, and the [redacted] **was expected to experience even higher temperatures**. These findings clearly indicated that **thermal environments during flight could exceed qualification limits**.

Figure 39: Valve body temperature data showing soakback effects beyond operational expectations
In **September 2019**, PCB-19-383 identified **thermal environment correlation** as the **top risk** for CFT engine qualification. The board noted that:

- Qualification testing **did not include chamber/nozzle thermal conditioning**, only propellant and line conditioning.
- There was a **lack of mission-representative duty cycle testing**, including worst-case thermal soakback and restart scenarios—**a standard requirement for human-rated engines**.

[redacted]

Figure 7.1.2.4 – Measured Thruster Valve Body Temperatures
(RCS Thruster #2 Hot Fire Test, 120 Second, Steady State, Nominal Pc and MR)

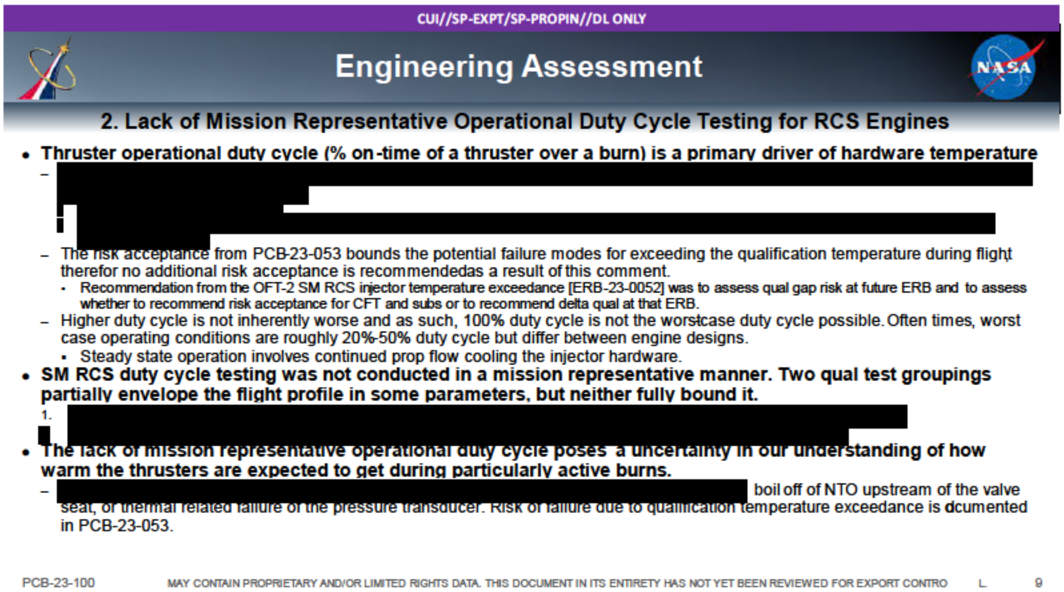
Figure 39: Valve Body Temperatures, RCS Thruster Assembly Verification Report, November 2019[5]

[4] Notice These data herein include "Background Data" or "Data Produced by AR pursuant to a Space Act Agreement" in accordance with the Data Rights provisions under Boeing Space Act Agreement #NNK 12MS01S and embody Proprietary Data. In accordance with the Space Acct Agreement, NASA will use reasonable efforts to maintain the data in confidence and limit use, disclosure and reproduction by NASA and any Related Entity of NASA (under suitable protective conditions) in accordance with restrictions identified in the Space Act Agreement.
[5] Ibid

The OFT1 mission elapsed time (MET) anomaly colored the RCS thruster flight experience, because the thrusters got hotter than expected, in a short period of time and largely still worked. Subsequently, when the thruster failures occurred on OFT2, it was deemed acceptable because thrusters got hotter and did not fail, based on experience from OFT1, as stated in PCB-23-053/OFT2-76. The Starliner Sampling Rate did not adequately capture the physics of the thruster firings/thruster performance, further complicating thruster performance understanding.

Despite these clear gaps, NASA proceeded to approve QTRs and VCNs for OFT, and later **accepted the risk for CFT**, contingent on future work. This decision was made **without resolving the core thermal qualification issues**, effectively **mischaracterizing the severity and operational impact of the thermal risks**.

In **April 2023**, PCB-23-100 reaffirmed that **SM RCS qualification testing had not been conducted under fully mission-representative conditions**, yet this was not treated as a disqualifying factor.



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Engineering Assessment

2. Lack of Mission Representative Operational Duty Cycle Testing for RCS Engines

- **Thruster operational duty cycle (% on-time of a thruster over a burn) is a primary driver of hardware temperature**
  - [redacted] from PCB-23-053 bounds the potential failure modes for exceeding the qualification temperature during flight therefor no additional risk acceptance is recommendedas a result of this comment.
    - Recommendation from the OFT-2 SM RCS injector temperature exceedance [ERB-23-0052] was to assess qual gap risk at future ERB and to assess whether to recommend risk acceptance for CFT and subs or to recommend delta qual at that ERB.
  - Higher duty cycle is not inherently worse and as such, 100% duty cycle is not the worstcase duty cycle possible. Often times, worst case operating conditions are roughly 20%-50% duty cycle but differ between engine designs.
    - Steady state operation involves continued prop flow cooling the injector hardware.
- **SM RCS duty cycle testing was not conducted in a mission representative manner. Two qual test groupings partially envelope the flight profile in some parameters, but neither fully bound it.**
  1. [redacted]
- **The lack of mission representative operational duty cycle poses a uncertainty in our understanding of how warm the thrusters are expected to get during particularly active burns.**
  - [redacted] boil off of NTO upstream of the valve seat, or thermal related failure of the pressure transducer. Risk of failure due to qualification temperature exceedance is dcumented in PCB-23-053.

PCB-23-100 MAY CONTAIN PROPRIETARY AND/OR LIMITED RIGHTS DATA. THIS DOCUMENT IN ITS ENTIRETY HAS NOT YET BEEN REVIEWED FOR EXPORT CONTRO L 9

Figure 40: Risk of Thruster Failure Due to RCS Soakback from Unbounded Duty Cycles (PCB-23-100)

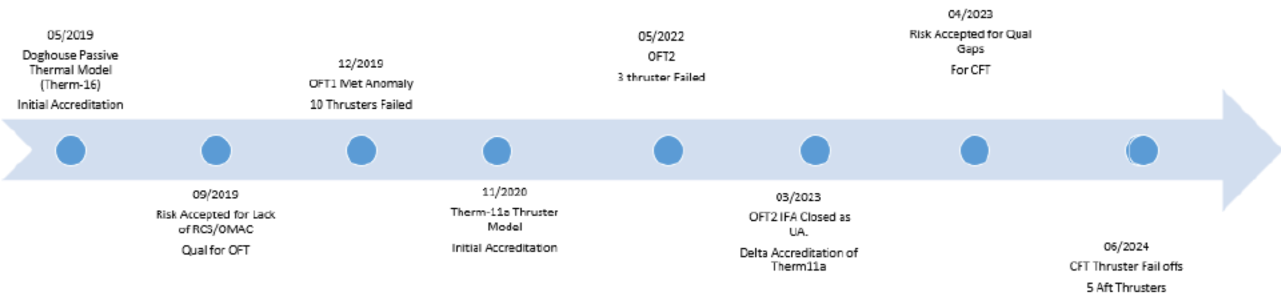

Figure 41: Timeline of Risk Acceptance

Key Points of Mischaracterization

- Thermal models lacked fidelity and were not validated by direct testing.

- Known soakback effects exceeded modeled expectations but were not fully accounted for.
- Qualification testing omitted critical thermal conditioning of key components.
- Duty cycle testing did not reflect actual mission profiles.
- Risk acceptance was based on incomplete data and deferred mitigations.

4.6 Analysis: Helium Leak

Fault tree analysis was used to determine the most probable proximate cause of the helium leaks that occurred on the CFT mission. The fault tree showed the most probable proximate cause was the material of the seals within the Starliner helium manifold being incompatible with NTO (**Helium Fault Tree Block D1.2.1**). The fault tree is graphically depicted at the end of the report. The O-ring sizing is a potential component of this failure and therefore is also a possible contributing factor for the helium leaks.

Fault tree analysis has determined the intermediate causes for material compatibility are NTO permeation and NTO leakage. The Teflon seal, which is spring energized for both the RCS and OMACs, allow for NTO to seep and permeate past. This allows for a direct path for the NTO to degrade the RCS/OMAC helium O-rings in combination with the design of the RCS/OMACs flange. It is also possible for the NTO to travel via the open path to the vent circuit on both flanges. Once the NTO reaches the helium O-ring, it is then capable of permeating past and interacting with the remaining helium manifold softgoods while on the ground and on orbit.

Contributing factors to the helium leaks include excessive lubricant (**Fault Tree Block D1.4**), flange build tolerancing (**Fault Tree Block D2.2**), and the variability of the environment during the CFT Mission. These factors are unlikely to have caused the leaks but may help to explain the variability of the leak rates, as the leak rate did not remain constant and additional leaks developed during the CFT mission.

The RCCA fault tree lists the possible proximate cause[1] of the helium leakage to be material incompatibility of the [redacted] O-ring with NTO within the RCS flange. Lack of design incorporating redundant seals in the RCS & OMAC, correct requirement flow down, and insufficient qualification testing specifically lack of NTO exposure are all listed as likely contributors. The O-rings for the [redacted] are listed as possible contributors, citing that the O-rings in these locations could be compromised by NTO exposure. O-ring [redacted] tolerances, seals in thruster solenoid valves, moisture, material temperature life limits, excessive lubricants, and wrong fasteners installed area listed as possible contributors. The Starliner PIT concurs with the RCCA regarding the most probable mechanism that resulted in the helium leakage.

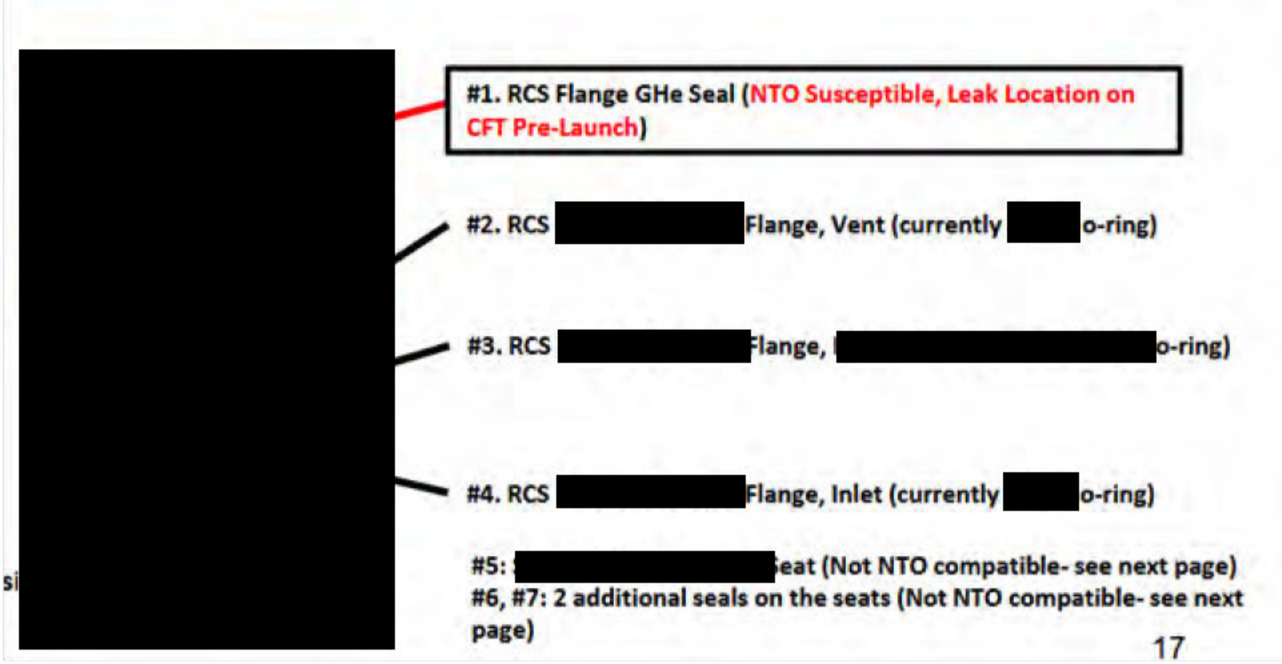

Figure 42: RCS Flange with NTO, MMH, and Helium Ports Here

4.6.1 Description of System

The SM utilizes two gaseous Helium (GHe) tanks to pressurize the eight liquid propellant tanks and to actuate the OMAC and RCS thrusters. There are three pressurant strings, one high flow string [redacted] and two low flow strings which feed [redacted], as shown in Figure 47: Upper Stage Schematic. The schematic is displayed on the following page.

[redacted]

[redacted]

[redacted]

[redacted]

11

Figure 44: Schematic of Helium Lines for at Least One Doghouse

Pressurized helium is used to open the propellant valves to fire the thruster. [redacted] as shown below in Figure 49: Schematic of the Thruster [redacted] Actuation.

Thruster 101 – Propellant Valve Flow Path

[redacted]

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Figure 45: Schematic of the Thruster Valve and Pilot Actuation

[redacted]

Figure 46: RCS Thruster Flange Schematic (Left) and OMAC Flange Schematic (Right)

4.6.2 Description of Events and Timeline

After the first CFT launch attempt, P2D2, one of the SM RCS thrusters, started leaking helium. The accepted leak rate is for [redacted]. This leakage was isolated to thruster P2D2 after the vehicle was rolled back. The helium [redacted] O-ring was determined to be the source of the leak based on the bubble testing. After reviewing the size of the leak observed during the launch attempt, Boeing said the leak was acceptable and had an ops control to manage the leak by closing the isolation manifold valves, preventing significant loss of pressurant. This was discussed and accepted at the delta Agency Flight Readiness Review (FRR) for the Boeing Crewed Flight Test (Boe-CFT) on Wednesday, May 29, 2024.

As part of these discussions, there was an alternative opinion presented. The alternative opinion stated the [redacted] sizing was insufficient for the applied application and was outside of the standards set in the Parker Handbook. This meant there would be more leaks developing over the course of the mission. While the alternate opinion was voiced, no dissenting opinion was raised. The lack of dissenting opinion and the flight rationale based on Boeing's operational workaround and management of the leaks led to launch.

Following launch, during the docked phase and the return phase of the mission, additional leaks formed. Seven of eight manifolds leaked before the end of the CFT Mission as shown below in Figure 51: Leaks Observed During CFT.

The analysis and testing performed of the Boeing system at the NESC determined that an un-degraded O-ring itself was structurally sound and should not leak. The post-launch testing done by the NESC was to establish an upper bound for a leak in a single manifold. This was done by removing the O-ring completely and using the upstream orifice to bound the helium flow.

[redacted]

Figure 47: Leaks Observed During CFT

4.6.3 Fault Tree

The following section provides an in-depth analysis of the Starliner PIT's investigation and fault tree analysis for helium leakage. Each section examines specific branches of the fault tree: software, hardware, source of leakage, and environment. Graphical representation of the fault tree is included, following the color-coding established in the Root Cause Analysis (RCA) section of this document. The branch analysis is then followed by an explanation of the most probable proximate causes.

Software

The main node of the **A Software** section is the **A1 Sensor Failure** branch**,** as shown in Figure X-Software section of the Helium Leaks Fault Tree, A1 Sensor failures cover **A1.1 Loss of a Sensor, A1.2 Inaccurate Sensor**, or **A1.3 Insufficient Sample Rate** could produce or contribute to what was observed during the CFT mission.

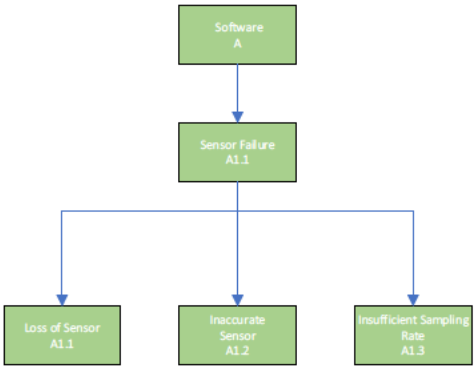


Figure 48: Software Section of the Helium Leaks Fault Tree

In this consideration there were no sensors lost, the sensors were deemed healthy and capable or relaying accurate sample data, and due to the extended periods of time required to observe the leakage by observing the pressure difference, it was determined that software did not contribute or in any way cause the helium leakage.

Hardware

The hardware section addresses the specific components that could have leaked within the pressurant system and the path of pressurant from the source, within the pressurant tank, to the final outlet of the [redacted] valve seat.

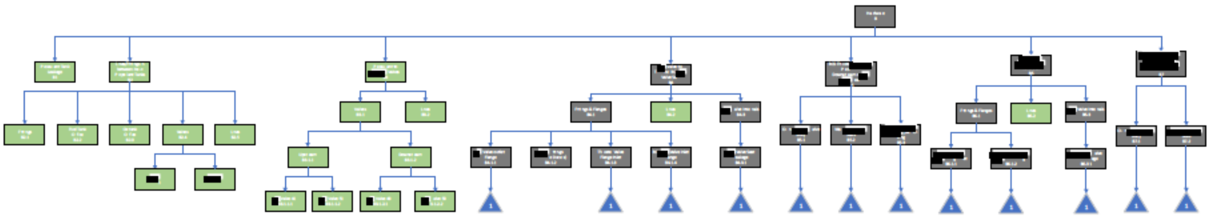


Figure 49: Hardware Section of the Helium Leaks Fault Tree

The main blocks of the hardware section are:

- **B1 Pressurant Tank Leakage**
- **B2 Lines/Fitting in between He-> Propellant Tanks**
- **B3 Pressure to the [redacted] Valves**
- **B4 [redacted] Valve to the Thruster RCS [redacted] Seat**
- **B5 RCS Thruster [redacted] Downstream of [redacted] Seat**
- **B6 Iso Valve to OMAC Thruster Valve Seat**
- **B7 OMAC Thruster [redacted] Downstream of [redacted] Seat**

The **B1 Pressurant Tank**, the **B2 Lines/fittings in between the pressurant tank to the propellant tanks**, and **B3 Pressurant to the** [redacted] were determined to not be leaking from inflight data, as there were no observed pressure decays/changes to the components upstream of the helium manifold [redacted]. Based on the sensor data available, there was no leakage from the helium tanks to the doghouse manifold [redacted]. The source of the leakage is within the helium manifolds of each doghouse, which is represented in the fault tree from branches **B4** [redacted] **Valve to the Thruster RCS** [redacted] **Seat, B5 RCS Thruster** [redacted]

Downstream of [redacted] Seat B6 [redacted] to OMAC Thruster [redacted], and **B7 OMAC Thruster [redacted] Seat.**

As shown above in the Figure 50: Schematic of Helium Lines for at Least One Doghouse, there are two separate helium manifolds for each doghouse. One helium manifold has a set of RCS thrusters, and the second manifold has RCS thrusters and OMAC thrusters' helium lines that are tied together. For the inflight leaks that occurred, it is not possible to determine if the RCS or OMAC thruster leaked because the pressure sensors observed a decay in the helium manifold which ties the thruster together. The fault tree is divided into the which of the components of the RCS and OMAC thrusters that could have leaked.

B4 [redacted] Seat covers from the outlet of the [redacted] valves to the internals of an RCS thrusters [redacted] for each RCS thruster. **B4 [redacted] Seat** is represented in the fault tree as:

- **B4.1 Fittings and Flanges**
  - **B4.1.1 [redacted] Valve Outlet Flange**
  - **B4.1.2 [redacted] Fittings (Pressure Ducers)**
  - **B4.1.3 Thruster [redacted] Inlet**
  - **B4.1.4 [redacted] Flange**
- **B4.2 Lines**
- **B4.3 [redacted] Internals**
  - **B4.3.1 [redacted] Seat Leakage**

B5 RCS Thruster [redacted] Seat covers [redacted] valve vent path within each RCS Thruster. **B5 RCS Thruster [redacted]** is represented in the fault tree as:

- **B5.1 O-ring to Main Valve Body**
- **B5.2 Main Valve Piston Seals**
- **B5.3 Pilot Valve to Main valve vent path O-ring**.

B6 [redacted] Seat covers from the outlet of the [redacted] for each OMAC thruster. **B6 [redacted] Valve Seat** is represented in the fault tree as:

- **B6.1 Fittings and Flanges**
  - in **B6.1.1 OMAC Thruster [redacted]**
  - **B6.1.2 OMAC Thruster [redacted]**
- **B6.2 Lines**
- **B6.3 [redacted] Internals**
  - **B6.3.1 OMAC [redacted] Leakage**

B7 OMAC Thruster [redacted] Seat cover from the internals of the OMAC [redacted]. **B7 OMAC Thruster [redacted]** is represented in the fault tree as:

- **B7.1 O-ring to Main Valve Body**
- **B7.2 Main Valve [redacted]**

Based on the leakage developing inflight rather than on the ground, it was determined to be noncredible that structural components such as lines and pressure transducer fittings would be component that failed. Hardware components such as lines, **B4.1.2** [redacted] **Fittings (Pressure Ducers)**, **B4.2 Lines**, **B6.2 Lines**, and manifold blocks or flanges are not considered as sources, as an additional external force through the duration of the mission would be required to explain how they are manifested. No credible additional source was identified (MMOD, fatigue, etc.).

Even though it is not possible to determine the exact source, which component failed within a given helium manifold, it is possible to look at each of the connections and softgoods for those connections and determine by what means that might have leaked. As a result, the child/leaf blocks in the hardware section, from **B4.1.1** [redacted] **Flange** to **B7.2** [redacted] **Seals** all connect to the same tree to **D Source of Leakage.**

Source of Leakage

The source of leakage fault tree section is to address the mechanism to which the helium leakage within the helium manifolds cover have occurred. **D Source of Leakage** is composed of **D1 He O-ring** and **D2 Flange Build. D1 He O-ring** represents the softgood within a given flange or connection identified within the **B Hardware**. **D2 Flange Build** represents the physical connection of interface or means to allow leakage to develop/occur.

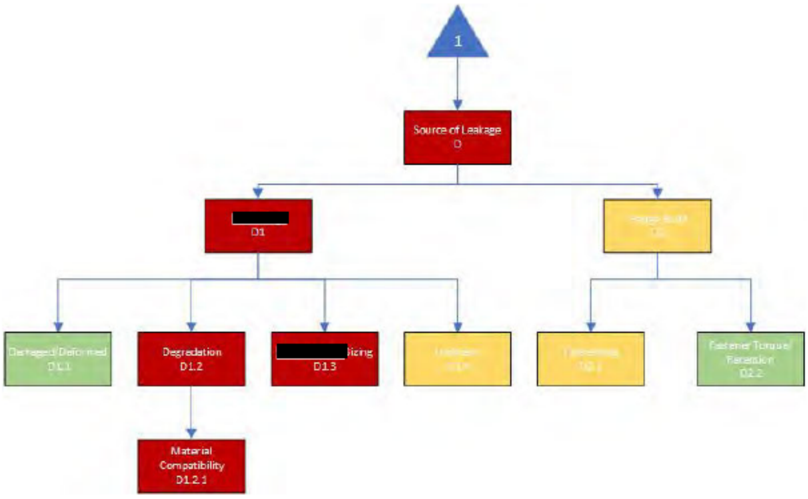


Figure 50: Source of Leakage

D1 He O-ring is divided into **D1.1 Damaged/Deformed**, **D1.2 Degradation**, and **D1.3** [redacted] **Sizing**.

D1.1 Damaged/Deformed covers that the O-ring/Softgood that a leak could be generated if it was installed was damaged/deformed at time of installation. Based on pre-launch testing this node is deemed non-credible as the leaks, other than P2D2, would have been observed in greater amount prior to launch. Following launch, the NESC performed testing and determined that even a significantly damaged O-ring within the SM RCS system is unlikely to leak. Figure X: NESC O-ring Testing shows some of images of how the O-rings were tested in the damaged/deformed state.

[redacted]

Figure 51: NESC O-ring Testing

D1.2 Degradation addresses that the O-ring/softgood became damaged overtime, and the associated child block **D1.2.1 Material Compatibility** addresses that the O-ring/softgood was incompatible with the exposure, specifically NTO.

The following table provides a list of the components within the helium manifold system which contain softgoods that are incompatible with Oxidizer. Any of these components may have contributed to the leakage observed.

Location	Softgood
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

Figure 52: Table of Components Within Each Doghouse Helium Manifold

Degradation over time of the softgood materials within the helium system due incompatibility with NTO was considered one of the most probable proximate causes. NTO is described as a "slippery molecule" as "NTO requires a metallic seal otherwise it is simply a controlled leak." The NTO source of the NTO is from the common flange on both the RCS thruster and OMAC thruster flanges, as seen below in Figure 58: RCS [redacted] Transport Mechanism.

[redacted]

Figure 53: RCS [redacted] Transport Mechanism

Below is a picture of the NTO Vapor transport mechanism across the RCS/OMAC thruster flange. Due to the nature of NTO, it is possible for NTO vapor to migrate beyond the Teflon seal of the NTO to the helium seal which would degrade the incompatible materials.

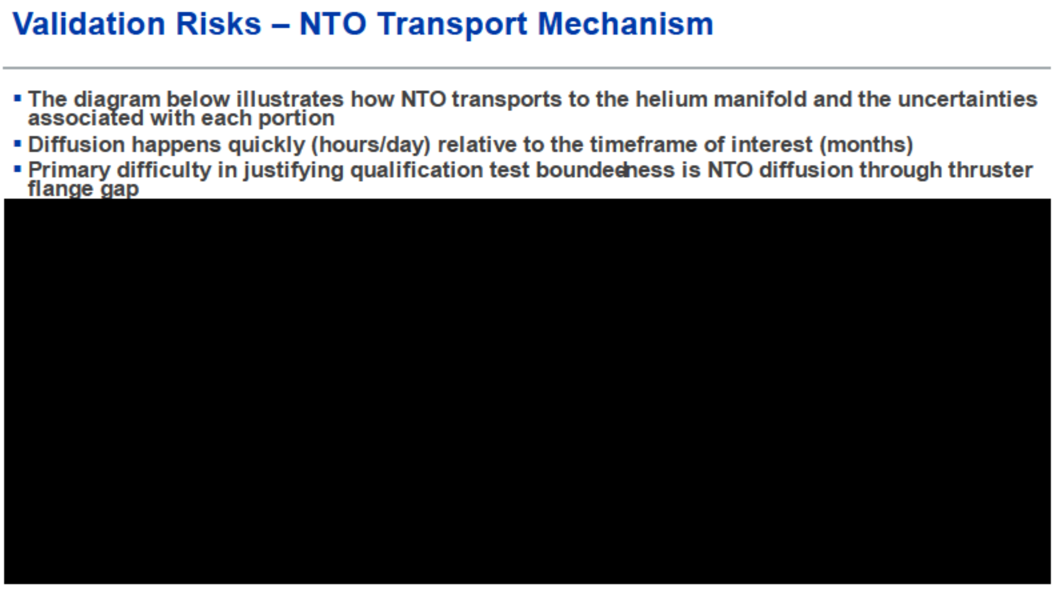


Figure 54: NTO Transport Mechanism

Based on the above information, **D1.2 Degradation** and **D1.2.1 Material Compatibility** was deemed most probable.

D1.3 [redacted] **Sizing** addresses O-ring sizing. Based on the dimensions of the RCS thruster common flange, the O-ring and associated fill area is not of the necessary dimensions to prevent leakage, as shown in Figure 58: RCS Flange Oxidizer Transport Mechanism. Gland/O-ring sizing potential issues include insufficient gland fill or insufficient squeeze of the O-ring, each of which can cause leakage. Without additional testing it is not possible to evaluate whether it is required in order to achieve the failure mode and is considered to be a potential proximate cause or a potential contributor. Prior to the CFT flight, after the initial CFT He leak was discovered, an alternate opinion (not dissenting) was brought forward by a NASA seal expert. The expert highlighted that the sizing of the helium O-ring seal was a likely contributor to the leak.

The Parker Handbook is a set of guidelines for how to evaluate the effectiveness of an O-ring and softgood dimensions/sizing to prevent leakage. Below is a set of slides detailing that based on the O-ring sizes for the RCS common flange does not meet the specifications outlined in the Parker Handbook for Glandfill and Squeeze.

NESC logo inserted after NRB approval

O-ring Gland Fill Analysis

- Parker O-ring Handbook, 3.7 Gland Fill, 2021: "Most O-ring seal applications call for a gland fill of between 60% to 85% of the available volume with the optimum fill being 75%...It is essential to allow at least a 10% void in any elastomer sealing gland."

Minimum Gland Fill		
O-ring Width	.035	in
O-ring CS Area	9.62E-04	in^2
Gland Depth	.030	in
Gland Width	.5(.230 - .057) = .0865	in
Inner Radius	.0045	in
Outer Lip Radius	.0025	in
Gland CS Area	2.59E-03	in^2
Fill Percentage	37.1%	

Maximum Gland Fill		
O-ring Width	.041	in
O-ring CS Area	1.32E-03	in^2
Gland Depth	.028	in
Gland Width	.5(.228 - .059) = .0845	in
Inner Radius	.0095	in
Outer Lip Radius	.000	in
Gland CS Area	2.33E-03	in^2
Fill Percentage	56.6%	

Referenced from: RE7631

Both the min (37.1%) and max (56.6%) gland fills fall short of the 60%-85% margin

NESC Document #: 34

Figure 55: Gland Fill Insufficient

O-ring Squeeze Analysis

- Parker O-ring Handbook, 3.6 Squeeze, 2021: "When used as a static seal, the maximum recommended squeeze for most elastomers is 30%... The minimum squeeze for all seals, regardless of cross-section should be about .2 mm (.007 inches)."

Minimum Material Condition (Min Squeeze)		
O-ring Width	.038 - .003 = .035	in
Gland Depth	.030	in
Squeeze	.005	in
Percentage Squeeze	14.3%	

Maximum Material Condition (Max Squeeze)		
O-ring Width	.038 + .003 = .041	in
Gland Depth	.028	in
Squeeze	.013	in
Percentage Squeeze	31.7%	

Referenced from: RE7631

Minimum O-ring squeeze: .005" < .007" **Maximum O-ring squeeze: 31.7% > 30%**

Figure 56: Insufficient O-ring Squeeze

Based on the above excerpt from the Parker Handbook, it was determined that **D1.3 Gland/O-ring size** was deemed a possible contributor.

D1.4 Lubricant identifies that lubricant placed on the helium O-rings for RCS Flange and the OMAC flange could be applied in excess and resulting in helium blowing past the O-ring.

The RCCA investigation found that excessive lubricant was observed on SM6 and SM7, although this could lead to some leakage, testing conducted at MSFC did not show leakage at levels consistent with those seen during CFT.

The testing performed by the NESC revealed no impact on leak rate caused by [redacted]. The NESC did comment that excess lubricant did not measurably impact the performance of a healthy O-ring, but it may affect interactions between the O-ring and propellants in flight. Based on these factors, it was determined that **D1.4 Lubricant** was deemed an unlikely cause.

D2 Flange Build covers that the connections and associated sealing surface of the RCS Thruster or OMAC thruster may have deformations or inconsistencies that could cause leakage. D2 Flange Build is divided into **D2.1 Tolerancing** and **D2.2 Fastener Torque Retention. D2.1 Tolerancing** addresses that the deformations or overall build quality of the flange/associated connections may contribute or cause the as observed leakage.

D2.1 Tolerancing was deemed to be unlikely as the leaks that may have been generated from poor build quality would have been present during pre-launch processing and been identified far earlier.

D2.2 Fastener Torque Retention covers that the flanges/connections between components may have had an insufficient amount of torque applied to prevent leakage and have the sealing surfaces come together appropriately. **D2.2 Fastener Torque Retention** was deemed noncredible as this would have been immediately identifiable and likely have other observable leakage of NTO or fuel products as well.

Environment

The environment portion of the fault tree is divided into **C1 Pre-Launch, C2 Launch, C3 On Orbit Environment**, and **C4 Vehicle Ops Environment**.

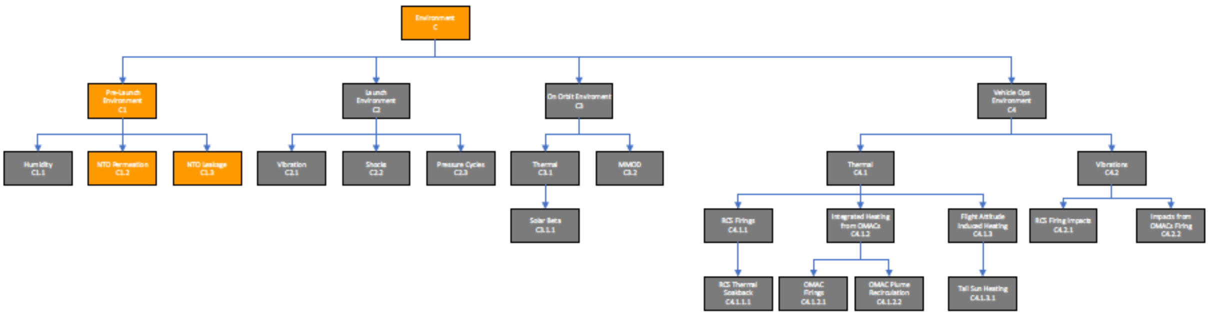


Figure 57: Environmental Section of the Helium Leaks Fault Tree

C1 Pre-Launch Environment details **C1.1 Humidity**, **C1.2 NTO permeation**, and **C1.3 NTO leakage** as possible faults/contributors to leakage. **C1.2 NTO permeation** is believed to be possible throughout the course of the mission, as the thruster flange sealing surface which allows for NTO vapor to travel, and its effects are present from pre-launch to SM jettison. **C1.3 NTO leakage** is considered as only a small amount of leakage could occur within the flange that would be greater than NTO permeation but is limited to the pre-launch timeframe. **C1.2 NTO permeation** and **C1.3 NTO Leakage** were deemed to be credible contributors to the observed leakage.

New leaks were identified following launch, so it is possible, if not likely that the **C2 Launch Environment** may have contributed to the leaks observed.

New leaks were identified in the post docking phase, so it is possible that the **C3 On Orbit Environment** and **C4 Vehicle Ops Environment** may have contributed to the leaks observed.

Due to new leaks appearing to have formed throughout the duration of the CFT flight, it was determined that environment did not cause helium leaks but may have contributed, as evidenced by Figure 52: Leaks Observed During CFT.

4.6.4 Most Probable Proximate Cause

Based on the team's evaluation, it is believed that the helium leakage occurred within the helium manifolds, [redacted] of the each of the doghouses. There were insufficient sensors to provide insight into which RCS or OMAC thruster was leaking. Due to the nature of the leaks, it is most probable that the softgoods within the helium manifolds were leaking. And it is most probable that the mechanism of leakage, or the direct cause for the softgoods to leak, is degradation due to NTO permeation across the RCS/OMAC thruster flanges, or leakage via the open path to vent circuit during ground operations. Per NASA tech fellow in chemistry, "NTO requires a metallic seal otherwise it is simply a controlled leak." O-ring sizing is a potential component of this failure. However, neither O-ring sizing nor NTO degradation can be confirmed "until testing has concluded."

[redacted]

It is important to note, variability in leakage as well as the development of additional leaks on separate manifolds as noted throughout the flight, implies that there are additional factors which may be affecting the softgoods of the helium system. Other potential contributing factors include: tolerancing of the RCS/OMAC thruster flanges, lubricant of the RCS/OMAC thruster flanges, and environmental factors. The tolerancing of the RCS/OMAC flanges may cause variation and provide a more discrete path for NTO vapor to reach the O-rings. The environmental factors such as launch loads, thermal environments, and vehicle operations such as repressuring the helium lines, cause a new sealing surface with every pressurization and potentially contributed to the leakage.

There is no analysis available to confirm the rate of degradation of the helium EPDM seals based on the rate of permeation of NTO through Teflon seals. Therefore, it is not able to be confirmed at this time that an additional O-ring would have prevented this failure. If the below proximate cause is accurate, it is expected that only metal NTO seals would have prevented NTO from permeating. The Starliner PIT offers the following proximate cause and recommendations.

Proximate Cause: Material of the seals within the Starliner helium manifolds were incompatible with NTO.

Recommendation:
R.5 [Boeing, CCP] - Material Degradation-1

When testing is complete, formally disposition SM Helium Leaks IFA and address residual risk of NTO exposure to an [redacted] seal in this location. Show via test, or analysis that the proximate cause of the failure is rectified, through replacement of the [redacted] seal, to complete necessary Starliner vehicle certification.

AR Phase 2 Material exposure testing while in flight like configuration ([redacted] and testing of the replacement material), resulted in degradation of an O-ring, but not a leak. NTO-Max testing is currently being performed to quantify seal performance. The test is gathering data on O-ring material mechanical response to NTO and O-ring leak prevention performance in the presence of controlled NTO concentration(s) while in flight like the RCS and OMAC configurations. This may confirm/validate proximate cause but testing it not yet complete.

Additional testing may include validating the proximate cause of the helium leakage that occurred by demonstrating that the RCS/OMAC flange both can act as a transport for NTO to the O-ring of the flanges, and that the O-ring will degrade to then generate the observed leaks, with the expected amount of NTO and duration necessary to mirror the CFT wetted time.

Recommendation:
R.6 [Boeing, CCP, ISSP] - Material Degradation-2

When testing is complete, formally disposition the SM Helium Leaks IFA and address residual risk of material incompatibility in the remaining softgoods (EPDM/Vespel) in the helium system. Show how these materials will meet the required 210-day mission duration, as well as ground wetted time, and complete necessary Starliner vehicle certification.

The STAR Report has identified this as a potential contributor and generated action tracked in A-13/A-14. The RCCA has implemented a change to the RCS/OMAC Flange O-ring replacing the material from [redacted]; however, this does not remove the mechanism for potential NTO exposure to downstream components by permeation.

JPRCB should disposition if the residual risk of not validating the proximate cause of this failure is acceptable. There may exist another path within the helium manifold that is the cause of the helium leaks, such as the remaining softgoods not meeting the 210-day mission requirements. This may result in a repeat of this failure on subsequent flights.

4.6.5 Intermediate Causes, Organizational Factors, and Contributing Factors

Intermediate Cause 1: NTO Permeation
This failure mode has been confirmed via the WSTF testing unit and AR Phase-2 Seal Degradation testing. This hardware, taken apart for discovery of information during the CFT launch campaign, had been prop wetted for several years, beyond the expected service life on a nominal mission.

Intermediate Cause 2: NTO Leakage
The thruster flange contains an [redacted] on the left in the image on page 83, next to the helium O-ring. It is possible that during ground ops NTO leaked and reached the O-ring causing degradation. An NTO leak during ground operations

through this vent circuit [redacted] *causing degradation. This is considered to be a lower likelihood than NTO permeation.*

A recommendation has not been generated for this intermediate cause as the STAR has identified this as a potential contributor and generated action tracked in A-13/A-14. The RCCA plans to recommend a change to limit the preflight exposure time (how long the system is wetted). The goal is to increase the likelihood of continued seal integrity throughout the mission. An additional environmental testing program is being conducted with NTO, including flight environments for materials not being replaced that are incompatible with NTO.

Contributing Factor 1: O-ring Gland Fill /Gland Squeeze
O-ring gland fill/gland squeeze is a potential contributing factor of this failure and should be considered until testing has validated proximate cause.

O-ring sizing was insufficient due to assumed design tolerance which was outside of the standards set in the Parker Handbook, as showcased in Figure 64 below. However, without a hardware change of the RCS/OMAC flange, there is no change in seal sizing that would meet all criteria for an O-ring in this location (gland fill, tolerance, squeeze, etc).

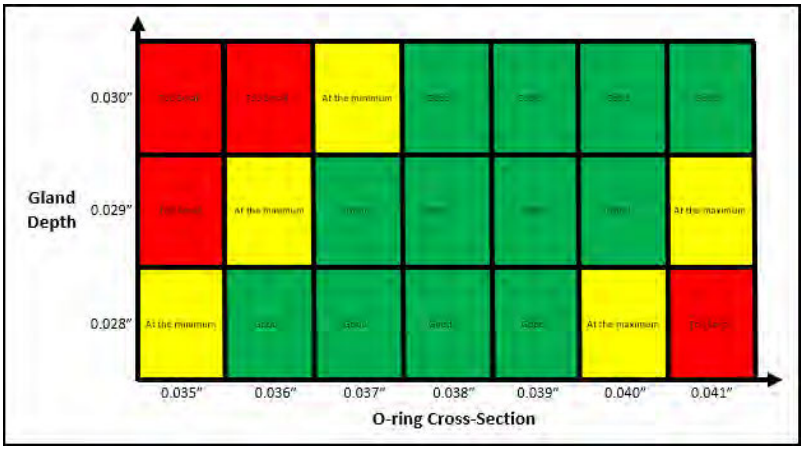


Figure 59: Sizing Constraints Based on Parker Handbook for Starliner

Recommendation:
R.7 [Boeing, CCP] - O-ring Gland Fill /Gland Squeeze

When testing is complete, formally disposition the SM Helium Leaks IFA and address any remaining residual risk of O-ring sizing. Show via test, or analysis that the proximate cause of the failure is rectified, through replacement of the [redacted] seal, O-ring sizing change, to complete necessary Starliner vehicle certification.

The RCCA has identified this as a potential contributing factor and implemented tightened O-ring tolerance to achieve squeeze within Parker Handbook guidelines for Starliner-1 and subsequent flights. Analysis from the RCCA does not address underfill. However, the tighter tolerances and selecting the right O-rings may fill in the gap.

JPRCB should disposition if the residual risk of not validating the proximate cause of this failure is acceptable as there may exist another path within the helium manifold that is the cause of the helium leaks, such as not meeting necessary gland fill outlined in the Parker Handbook guidelines and may result in a repeat of this failure on subsequent flights. The investigation team sees this risk as acceptable but recommends a full review of the data from ongoing RCCA work and testing when it is ready, at the time of IFA closure.

Contributing Factor 2: Lubricant, Tolerancing, Environmental Factors
The RCCA found that excess lubricant on GHe seal caused helium leaks smaller than what was observed during CFT. The NESC commented that lubricants may affect interactions between the O-ring and propellants in flight. The RCCA found that flange surface, seal groove, NTO [redacted]*, and flange fastener torque vary slightly between SM build to build tolerances which may influence NTO permeation. As additional leaks developed throughout the CFT mission, it is possible there are other factors that did not cause the leak but contributed to the development of the leaks such as, excessive heating, pressure cycles upon the system, and vibrations from launch.*

A recommendation has not been generated for this contributing factor. The RCCA has identified this as a potential contributing factor and implemented training to show effective application processes with Krytox, updated thermal models, and is using the IDH test to anchor thermal limits.

Organizational Factor 3: Qualification testing not performed to verify material compatibility.
The was no qualification/re-qualification testing to verify the material compatibility because there was no requirement. There was no integrated material testing required because of hypergol permeation was not investigated, understood, or quantified; despite being on a common manifold.

Organizational Factor 4: No process for integrated material compatibility as an assembled level.
The STAR report highlights there are no materials testing at the assembled level, per NASA 6016/Alternative Boeing Standard, to require integrated testing of ground units to determine material compatibility; however, NTO is known to permeate across softgood seals. The control in the hazard report simply said, "limits permeation."

Organizational Factor 5: Insufficient validation of system hardware, particularly in the reliance on heritage design without adequate verification for current mission use.
Per the STAR report, NASA did not have insight into helium O-ring material selection. It was not included in CDR. Post CFT launch there was uncertainty on what specific material remained. As noted by the RCCA, that correct requirement flow down and design evolution is a likely contributor. This directly relates to the fact that Boeing did not have sufficient insight into its suppliers and NASA was not able to validate that the controls were sufficient. The O-ring material was completely appropriate for the roughly 20-minute mission the flange was designed to support. Combining NTO, MMH, and He in a single flange makes sense for a small vehicle where mass matters and a short mission duration permit incompatibility with materials as they only need to support an extremely short mission duration.

Organizational Factor 6: Insufficient recognition of risk
Per the Inflight Anomaly presentation at JPCB on February 2nd, 2023, OFT2-42/AR114, the direct cause of the in-flight OFT-2 helium leaks was considered to be due to FOD in the valves, but this was never able to be validated because the SM is jettisoned. This was closed as a UA.

In-Flight Anomaly OFT2-42/AR114/NCR015471W: During OFT-2, GHe Manifold 2 in both Port and Starboard Doghouses exhibited pressure decays. The GHe leaks began approximately 24 hours after manifolds isolated post-docking. Port DH leak began approximately 3 hrs prior to Starboard DH leak. The helium system was quiescent; no commands or changes to manifold conditions when leaks began. Leakage continued throughout docked period including line repress that occurred during system checkout 24 hours prior to undock. Leaks no longer visible once isolation valves opened for undock. Analysis shows total leak area for each manifold is small (109 um2, 540 um2).

The IFA was closed out at a JPCB (PCB-23-057) AR-114 SM Doghouse Manifold 2 He Leak where it was deemed accepted risk as an unexplained anomaly (UA). The rationale for acceptance of the UA was "Pre-launch pressurant and prop fill procedures can be used to identify significant leak" and the significant commodity present on vehicle.

In reviewing the associated UA, there was no discussion on validating the cause. There was only discussion that if such leakage were to occur, it would be noticeable on the launchpad and to research methods for better leak detection. The main rationale for acceptance stemmed from there being such significant commodity present and operators could take action to prevent significant loss, that there was no risk to CFT. Also of note, this UA was not within the 13 listed UAs that were communicated during the CFT FRR. This UA and operational mitigation were not discussed until delta CFT FRR. This represents a missed opportunity to identify materials compatibility and a missed opportunity to identify the lack of deorbit fault tolerance.

[redacted]

4.7 Analysis: Deorbit Capability Fault Tolerance

Following the first CFT launch attempt and in conjunction with discussions regarding leaks in the helium manifolds of the SM RCS propulsion system, NASA and Boeing teams realized that the SM propulsion system was not two failures tolerant for deorbit per requirement VCN-CCT-REQ-1130-80, Autonomous Deorbit. There are many cases where Starliner is two fault tolerant (2FT) to deorbit burn. This realization was specific to the helium commodity within the SM RCS. The requirement is to be two fault tolerant for deorbit burn in all cases, meaning compliance to the FT requirement. It does not matter how likely it is to get into the failure case. The system is noncompliant even in low likelihood cases.

After diligent review it was determined that this shortcoming has been present in the vehicle design since the early stages of the design process. There have been numerous reviews, boards, and discussions regarding deorbit fault tolerance across multiple organizations of NASA and within Boeing. Joint NASA/Boeing Safety reviews (starting with Phase I in 2013) included assessment of the SM propulsion system against fault tolerance requirements. [redacted] did not support a 2-failure tolerant SM propulsion system in the Phase I level Hazard Reports provided by Boeing and jointly reviewed with the NASA Safety community. This flaw in the design was carried forward through all Starliner safety review phases leading to CFT.

The Prop System Integrated System Review (August 21, 2012) had [redacted] and sufficient level of fault tolerance for the He system in the doghouses.

The propulsion schematic from PDR (2013) also has [redacted]. During this time, the planned deorbit configuration was communicated to be two fault tolerant and that only six RCS thrusters would be utilized for maneuvers. Additionally, only four OMACs would be utilized at any one time. Below is the updated schematic and the proposed operating modes from PDR.

[redacted]

Figure 61: Prop Schematic from 2012

The propulsion schematic from CDR ([redacted]) indicates two helium manifolds per doghouse, and GNC Subsystem CDR which occurred in April of 2014 now indicates the 4 OMAC config and 8 RCS jet config for Deorbit fault tolerance. This design change between PDR and CDR is not flagged as an impact to the fault tolerance requirement for deorbit. The oxidizer and fuel lines still meet the necessary requirements, it’s only the helium, used to pressurize tanks and pneumatically control valves, that is affected.

[redacted]

Figure 62: Prop Schematic from 2013[6]

[6] This schematic is within the hazard report system [redacted],” which is included within the DPD 110 and therefore limited rights.

FMEAs (E-14.04 Failure Modes and Effect Analysis) and FMECAs (SM System Level FMECAs) delivered at CDR also indicate that the helium manifolds were reviewed during CDR. The FMECA for the [redacted] was evaluated for leakage. It was identified that leakage may result in an inability to control the vehicle during free flight, but did not list Loss of Crew/Loss of Vehicle as an end effect. The OMAC [redacted] did list Loss of Thrust and Loss of Crew/Vehicle as the end effect.

Item/functional Identification (nomenclature)	Function	Identification Number	Failure Mode	Causes	Potential Causes/ Mechanisms of Failure	Single Point Failure? (Y/N)	Design Controls	Mission Phase/ Operational Mode	Local Effects	Next Higher Level Effects	End Effects
10	11	12	13	14	15	16	17	18	19	20	21
[redacted]	ISOLATES LEAKAGE	SMPROP-HMI-LEAK	Leakage	1. Poor design 2. Improper material selection 3. Assembly area and damage 4. Over pressurization, improper handling 5. Corrosion contamination	1. Improper design tolerances 2. Improper material compatiability with hydrazine 3. Quality control failures resulting in assembly failure 4. Improper qual program to verify pressure band 5. Improper cleanliness during assembly	No	1. Robust Design, Factor of Safety 2. M&P approval, Inspection and Workmanship Screens 3. Qual acceptance 4. Qual test 5. Inspection	entry/abort	first failure - none (redundancy) 2nd failure - loss of propellant to thruster half-system 3rd failure - failed-on/excessively leaking thruster on remaining half-system	no prop flow to thruster leg/ lost of thruster leg; one half system remains unless additional failures on second half-system	inabilitiy to control vehicle during free flight

Figure 63: Failure Mode Effects Analysis (FMEA) for Hazard Report 16.01

These same failure modes, effects and criticality analyses (FMECA)s were utilized during the Phase II Safety Review (May 2017) and would be utilized in developing and informing the relevant hazard reports. While it appears that many changes did occur, when evaluating the Grp2_SM Prop FMECA (HR 16.01) and (HR 2.08), it still lists the end effects for [redacted] to be inability to control vehicle during free flight for entry/abort phases instead of Loss of Crew/Loss of Vehicle.

Item/functional identification (nomenclature)	Function	Identification Number	Failure Mode	Causes	Potential Causes/ Mechanisms of Failure	Single Point Failure? (Y/N)	Design Controls	Mission Phase/ Operational Mode
[redacted]	ISOLATES LEAKAGE	SMPROP-HMI-LEAK	Leakage	Materials Design Environment Manufacturing	1. Poor design 2. improper material selection 3. Assembly area and damage 4. Over pressurization, improper handling 5. Corrosion contamination	No		entry/abort

Failure Effects			Existing Conditions							
Local Effects	Next Higher Level Effects	End Effects	Failure Mode Detection Method	Severity	Probability of Occurance	Criticality (Sev*Occ)	Critcal Safety Item(Criticalit y ≥ 56)	Detection	RPN (Sev*Occ*Det)	Remarks
first failure - none (redundancy) 2nd failure - loss of propellant to thruster half-system 3rd failure - failed-on/excessively leaking thruster on remaining half-system	no prop flow to thruster leg/ lost of thruster leg: one half system remains unless additional failures on second half-system	inabilitiy to control vehicle during free flight	[redacted]	4	5	20	No	4	80	

Figure 64: FMECA for Hazard Report 2.08 (broken into two parts for readability)

Redundancy to combinations of SM propulsion system failures (including IPC failure) is addressed in Cause 8, Control 1 and Cause 9, Control 1 in Hazard Report (November 2019). Cause 8 is Failure to Provide Propulsive Capability for Attitude Control Authority. The relevance is that the if [redacted] were to fail/leak, the vehicle would still have sufficient RCS thrusters to maintain attitude. Cause 8 Control 1 was closed with Monte Carlo analysis and referenced the applicable VCNs (VCM7-GNC-030, *Pointing Accuracy, Pointing Stability, Attitude Rate Stability, Pointing Rate Accuracy, and Pointing Rate Stability,* VCN-SSP50808-F-547 and VCN-SSP50808-F-123).

Cause 9 Failure to Provide Propulsive Capability for Translational Maneuvers and Cause 9 Control 1 has nearly identical wording but cites translational maneuvers instead of rotational capability. The verification for Cause 9 control 1 is insufficient for closure and should not have simply referenced the redundancy in [redacted] The attachment two referenced in the Hazard Report does not list the associated burns for deorbit for two fault tolerance, as well as the GNC CDR documentation cited in the verification does not list out the associated fault tolerance. The Starliner PIT concurs with the STAR report that the associated verification for this control was insufficient.

The correct/sufficient verification would have been the correct verification evidence for the VCN to verify and confirm sufficient two fault tolerance such as Autonomous Deorbit. The VCN-CCT-REQ-1130-80, Autonomous Deorbit, R.CTS.086 (February 2021) is delivered and composed of math models and GNC Monte Carlo runs [redacted] was not considered in this VCN. The [redacted] were never identified as a single fault that could lose two thruster [redacted] were not explicitly included in the associated case matrix.

Despite multiple joint safety review panels conducted by NASA with Boeing, a fundamental system level fault tolerance design flaw in the Starliner propulsion system went undetected.

The fault tolerance issue stems from the fundamental channelization design of the pressurant system. **This basic flaw in the [redacted] of a major vehicle subsystem cannot be attributed to lack of data available given evidence this flaw was present throughout all phases of the safety review process.** The flaw appears to be evident when reviewing the basic propulsion system schematics included in the hazard reports if reviewed at a higher level than component fault tolerance.

As highlighted by the STAR report, the Boeing MO (B-MO) team identified the missing fault tolerance for deorbit capability and sent emails in 2016, 2017, and 2021. The Starliner PIT interviewed B-MO regarding emails sent to engineering teams at Boeing. B-MO personnel stated that there was a good relationship between the B-MO and Boeing Engineering, though the fault tolerance had been highlighted in multiple emails; however, there wasn't a push due to other work occurring which was given higher priority.

There were numerous processes that should have should have caught this lack of fault tolerance. This represents a failure as part of the design phase that could have been caught in deliverables presented at CDR/delta-CDR, including the GNC deliverables, and the fault tolerance verification products. This represents a process failure of the hazard report phase that has multiple review phases, tools, and individuals who are specialized in understanding fault tolerance verifying associated hazard controls. This is also a process failure in the requirements closure phase and the associated delivery of understanding what constitutes acceptable materials of closure of those requirements. Finally, this represents a failure in the operations phase with the lack of processes for capturing discrepancies, issues, concerns, or easily elevating critical items to both NASA and Boeing teams.

Below represents a timeline of the different phases of the Starliner vehicle in which this failure mode was present and never addressed prior to the first launch of crew on Starliner:

Design phase

- Boeing Delta Prop CDR (2015)
- Boeing FMEA (2014)
- Boeing FMECA 2014)
- Boeing SM Prop Abort Pressurization FT Variance (2015)

Hazard report phase

- NASA SRP/STRB (2015-2019)

Requirements closure phase

- Boeing PRA analysis for LOC/LOM (2019)
- Boeing PRA analysis for LOC/LOM (2019)
- 1130 Autonomous Deorbit requirement / R.CTS.086 (2021)

Ops Phase

- Boeing MO Flight Controllers (2016, 2017, 2021)
- 1130 Autonomous Deorbit requirement / R.CTS.086 (2021)

There is no existing process for addressing deficiency in design. If there is an existing process, it is insufficient as evidenced by this lack of fault tolerance being identified years after the design phase and not being sufficiently elevated/addressed. Spaceflight is challenging. These complex systems must allow for easy dissemination of information regarding failures which may endanger the crew or mission.

The safe return of the crew is required to be two fault tolerant for Entry, Descent, and Landing (EDL) per CCTS-REQ-1130. For the CST-100 service module to support a 2FT EDL there were 3 configurations available.

1. OMAC configuration A - 1 aft OMAC per each of the 4 doghouses
2. OMACs configuration B - 2 aft OMACs in each of 2 opposing doghouses
3. RCS configuration - 8 aft RCS jets

Due to the [redacted] it was discovered a single fault (loss of top or bottom doghouse [redacted]) results in loss of two of the above thruster configurations. A subsequent failure could result in loss of the remaining thruster configuration option necessary to safely deorbit. The primary causes for loss of a [redacted] within the doghouse are from a failed closed [redacted] or an unsustainable helium leak rate downstream of the [redacted] resulting in the need to isolate an entire manifold.

Per PCB-24-196: CFT P2D2 He Leak Risk Acceptance - Part 2 held on May 23rd, 2025, the Spacecraft Systems office requested approval of P2D2 flange leakage (AR-147, CFT-10) at 2x5 (Safety, Performance, Schedule) risk for CFT only with constraint to accept lack of fault tolerance at future PCB. This poll approved the risk level as presented, but did not formally approve the lack of fault tolerance. The flight rationale supporting acceptance for the use-as-is approach to the helium leak in the P2D2 flange stood on the following:

- Leak was known to be located at the P2D2 flange per helium detection around the port doghouse.
- Flight history showed no leaks greater than what was seen at the P2D2 flange location.
- Conducted re-assessment of seal characteristics
- Determined applicability of 11 failure modes of face seals per Parker Design handbook
- Assessed common cause
    - Determined this cannot be eliminated as a possibility.
- Bounded operational aspects and margin:
    - Ability of the vehicle to tolerate four more P2D2-equivalent GHe leaks before management is required in a nominal mission
    - Analyzed mission scenarios for "manifold-on" time
    - Analyzed worst case single leak with no O-ring resistance, worst case stack of flange flatness, and gapping due to flight pressure.
        - Conclusion: approximately 100x greater than P2D2 leak resulted in 1.3 hours of "manifold-on" time margin.
    - Consumable analysis and mission management planning conservatively assumes all leaks occur at T-0 and entire mission profile is affected. Impact decreases the later in the mission that the leak occurs.
    - MO/MSR Team confident they can detect leaks large enough to impact mission.
    - Existing flight rules and training govern management/troubleshooting plan
- Conclusion of Spacecraft office team: P2D2 is largest manifold leak experience to date, and the risk of a flange leak greater than P2D2 is low. Low risk for mission impacts.

It was noted the helium O-ring is not optimal for the flange joint according to Brian Mitchell from MSFC for various reasons including O-ring sizing and material.

Per PCB-24-199: CFT CST-100 SM Risk Acceptance Related to 1FT SM System for Deorbit - Part 2, a joint NASA and Boeing team requested, and received, approval of the following:

1. **1FT SM for deorbit at 2x5 (Safety, Performance) risk**
2. **Use of 4-RCS deorbit as a crew survivability capability at 2-3x5 (Safety) risk**
3. **Minimal increase of Elevated 1x5 risk accepted at PCB-24-141 related to SM Disposal**
    a. **SM Disposal tables to feed Flight Rule I2-153 remain unchanged**

The flight rationale supporting acceptance of the above risk stood on the following:

1. Failures are limited to loss of 4 Helium Manifolds and loss of adjacent DH OMACs. Failure modes involve: Leaks, FOD, Valve failed closed
2. These failure modes can be managed operationally:
    a. He Valves are opened pre-launch and remain open through docking
    b. He Valves are opened pre-undocking and remain open through undocking
    c. OMAC Valves are cycled prior to undocking
    d. In the event of a Helium valve that is stuck closed while docked to ISS, there is a path to pre-emptively open OMAC valves prior to undocking (forward work required before formal approval)

3. GHe leaks
    a. Assuming leaks do not grow – leak can be fed without any changes to concept of operations, which do not require closing He valves
    b. In the presence of range of large leaks, sufficient commodity exists to allow leak to be fed during critical burns. Sufficient regulated pressure from He tanks will be provided to allow OMAC injector valves to actuate
    c. Boeing MO will monitor and make Go/No-Go determinations and manage He commodity based on any leak rates observed
4. GHe Valves
    a. Valves are rated to 250 cycles
    b. Valves are acceptance tested and do not interact with any corrosive fluid
    c. GHe Valves are 1FT for Power and Open commands
    d. Noncredible for an open valve to spontaneously fail closed
5. OMAC Fuel Ox Valves
    a. Valves are rated to 250 cycles
    b. OMAC A Valves are 1FT for Power and Open commands; OMAC B valves are 0FT
    c. Improvements to NTO valves for OFT2 (sealing moisture intrusion gaps, GN2 purge)
    d. Noncredible for an open valve to spontaneously fail closed
6. FOD
    a. Past flight experience and propellant hardware inspections show that the conditions that likely led to OFT2 OMAC thruster failures are not present on SM5

It is noted in the polling statements from this PCB that approval from all polled organizations did not occur without discussion and disagreement on the exact levels of elevated risk (some preferred 3x5 on the risk matrix instead of 2x5 and some thought a lower 1x5 was correct in some instances). The PCB presentations provided a status on the four RCS option work but did not include it as flight rationale for flying the mission with a lack of entry, descent, and landing (EDL) fault tolerance. The PCB charts summarized the four RCS option and included a risk assessment varying from 1x5 to low 3x5 based on analysis. It is unclear if the four RCS options, even though presented as contingency/uncertified only, was treated as a true option even given lack of testing and the short time spent assessing the option.

Acceptance of the helium leaks and lack of EDL fault tolerance was ultimately accepted at the Delta Agency Flight Readiness Review held on May 29th, 2024. The flight rationale for Delta Agency FRR was largely unchanged from what was presented and accepted by the PCB. There was additional data related to the use of the four RCS deorbit capability presented to the Agency during the FRR.

Given the analysis showing system robustness that could support feeding multiple helium leaks on the order of the P2D2 flange leak in concert with high confidence in the helium isolation valves not failing closed and options to manage leak rates by ground operations, the program board found a 1FT SM propulsion system would be acceptable for a single flight. **The four RCS deorbit option was stated in the front of the AFRR charts as not adding a level of fault tolerance and not being a certified capability.** Additional discussion during topic D of the Delta Agency FRR for "SM Propulsion System Failure Tolerance" concluded with the following general agreement, documented in the meeting minutes as "[…] thruster burn contingency use would be used only for crew survival. A real time IMMT would be used to determine the best path of action if failures put the vehicle into a zero-fault tolerance case. **It was confirmed that crew could also be left on station and returned home by other means, as required.**"

Discovering the lack of fault tolerance for deorbit on the pad seems untenable considering this was the third flight of Starliner and the first flight of crew on Starliner. This could have resulted in a stand-down to verifying the associated case matrixes and similar analyses were valid. As detailed above, there were many areas in which this could have or should have been caught. **However, the availability of operational controls to manage the helium system and the amount of commodity available on the vehicle created acceptable flight rationale to be considered. Utilizing ISS as a safe haven and the possibility of the four RCS deorbit burn as a last-ditch capability helped solidify that the risk was acceptable to proceed to launch.**

4.7.1 Observations and Recommendations

Observation 1: Safety Review-1

NASA performed the phase I Safety Review Process (SRP) with Boeing during the CPC funding phase of CST-100, AFTER the SM PDR. The SM propulsion design reviewed by the NASA safety panel did not support meeting the two-fault tolerance for reentry requirement.

- A Phase I Safety Review should typically be performed prior to Preliminary Design Review (PDR) in accordance with SSP 30599 such that the Safety review process can inform the preliminary design. The CST-100 Service Module Propulsion Subsystem PDR was held in January 2012 during the CCiCap/CPC contract timeframes which was a year before the Phase I SRP which began in May, 2013 under the Certification Products Contract (CPC).
- The Phased Safety process was contractually levied as documented in DCC1-00459-01
  - Section 3.7 states the CCTS safety reviews will follow the phased safety process, which meets the intent of SSP 30599, "Safety Review Process"
  - Section 6.4 Figure 10 'Characteristics of Phased Hazard Reports' states the following characteristics for Phase I Safety data:
    - All of PHA/Phase 0 Plus
    - More complete definition of controls/verification approaches
    - Not maintained after Phase 2 reports are prepared
    - If new hazards are identified, new reports are prepared
- ISS Hazard System (IHS) Record # 26014 contains the CST-100 Phase I Safety Review data products. Reviewed by NASA in partnership with Boeing. Delivered in accordance with the System Safety and Reliability Plan (DCC1-00459-01) as part of CLIN 2 of the CPC.
  - The 1FT pressurant system design was present in the Phase I Safety Products, see 'CCST-100 DeltaPhase I Part 2 - CTS-02.08_CPC-Final_-_Update-Rev3_w-chgs (January_February 2014).pdf' hazard report document attached to IHS Record # 26014 for evidence.
- The following Phase I SRP meeting minute documents, attached to IHS Record #26014 indicate NASA Phase I SRP meetings were held for CST-100 from May 2013 through February 2014.
  - 'PROPRIETARY - Phase I Group 1 Minutes (May 28-31, 2013).pdf'
  - 'PROPRIETARY - Phase I Group 2 Minutes (June 11-12, 2013).pdf'
  - 'PROPRIETARY - Phase I Group 3 Minutes (July 16-19, 2013).pdf'
  - 'PROPRIETARY - Phase I Group 4 Minutes (August 5-9, 2013).pdf'
  - 'PROPRIETARY - Delta Phase I Part 1 Minutes (November 12, 2013).pdf'
  - 'Minutes_2014-02-06_CCP CST100 Dlta_PhI_Pt2.pdf'
- The Phase I safety data presented to the ISS SRP from May 2013-February 2014 included hazard causes and control strategies. NASA approvals of the CST-100 Hazard Reports are explicitly noted in the meeting minutes along with, action item assignments, and attendance logs. All of which are indicative of a completed Phase I safety review.
- The minutes of the Phase I Group 3 review indicate the correct NASA and Boeing personnel were present at the review. Data was not found to indicate what level of review was held of the safety data products prior to the Phase I review.
- The minutes of the Phase I Group 3 review held in July 2013 do call out a lack of fault tolerance issue as part of the CCTS-02.08 review. Cause 6 (Leakage of Seal) of the Hazard

Report was not approved at Phase I due to the fact the [redacted] seals do not meet fault tolerance requirements. But no mention is made of the pressurant system seals lacking fault tolerance for reentry.
- While the Phase I review is best held prior to PDR to allow for the Safety process to inform early design, evidence that the Phase I review was unable to inform the CST-100 design is lacking.

Recommendation:
R.8 [OSMA] Safety-Review-1

NASA safety processes should include focus on system level safety owned fault tolerance requirements and ensure the data used to approve hazard control strategies at Phase I is captured in the control language in the hazard reports directly. It should not be assumed to be in the verification data.

This is especially important when NASA does not own the vehicle and is not participating in subsystem designs. Early design review by NASA offers more opportunities to "catch" requirement violations. When those opportunities are limited, the opportunities that do exist must have increased due diligence.

- Do not rely on verification data only to ensure the hazard control was written appropriately. This shifts the risk acceptance to a small group of subject matter experts (verification data reviewers) who may not be reviewing with fault tolerance in mind. Control language should stand against the design of the system and be supportable by data included in the hazard report.
- The STAR report correctly outlines opportunities during the Phased Safety Reviews where the fault tolerance issues with the helium system should have been captured. The Phased Safety process as defined in SSP 30599 and implemented with the Boeing CST-100 spacecraft development should have captured the lack of helium pressurant system fault tolerance, not simply Phase I.

Recommendation:
R.9 [CCP, ISSP, SOMD] - Safety-Review-2

Hazard controls and their verification should be documented in hazard reports clearly tying the supporting verification evidence to the controls.

- Ensure clarity in hazard controls. Single controls stating entire systems have fault tolerance should be avoided when they are against complex systems such as propulsion, electrical power, etc.
- Require evidence supporting control claims be present in hazard reports (or included as support documentation)
  - Example: For systems where fault tolerance relies on [redacted], include evidence of [redacted] in hazard reports. This allows reviewers to identify the design intent meets the fault tolerance claims.
- Use specific verification evidence. Avoid references to large data packages as the sole verification evidence for hazard controls. Point to specific data within these packages that supports the hazard controls. While using large data packages for verification evidence is acceptable, specific locations within the data packages should be identified in the hazard report.

Observation 2: Safety-Review-2

The structure of the Starliner SM propulsion system hazard reports contributed to the lack of a two-fault tolerant (FT) helium pressurant system by NASA Safety.

- As captured in the STAR investigation report the verification of the SM propulsion system claim of fault tolerance was not adequate.
- CCTS-16.01 Cause 9, Control 1 states the SM propulsion system redundancy provides dual fault tolerance to the loss of translational maneuver capability. Verification 1a was Closed to the supporting evidence of the GN&C CDR presentation.
- The GN&C CDR presentation does inform some aspects of a fault tolerant design but does not contain information on the [redacted].
- The hazard report CCTS-16.01 does not contain any technical information to back up the claim Cause 9, Control 1.
- Although it is understood that the spacecraft is a complex vehicle not easily explained in simplified drawings, [redacted] of critical systems must be outlined within hazard reports so the system designs can be readily reviewed by the Safety Panel representatives as sufficiently controlling hazards.
- Final approval of a hazard reports comes after subject matter experts agree the verification evidence sufficiently supports the claims of hazard controls. When the hazard controls are written as vague or generic and reference non-specific verification evidence, such as an entire GN&C CDR presentation, versus specific data or components of a larger piece of supporting evidence, the rigor of the safety review is lost and risk acceptance shifts to outside of the safety process.
- When using references to large design review documents to close a hazard control, the reviewers of said products (such as a NASA GN&C team in this example) may not be reviewing the document with the focus of whether it adequately closes a hazard control claim of the fault tolerance of an entire propulsion system.

Recommendation:
R.10 [CCP] - Verification of fault tolerance-1

VCN deliverables for future Starliner Missions should have the associated case matrix for GNC Monte Carlos evaluated to verify accurate hardware fault tolerance.

Reruns of the GNC Monte Carlos should be performed and verify capability of the vehicle including loss of helium manifold and verify no additional failure cases are missing/lacking.

Recommendation:
R.11 [SOMD] - Verification of fault tolerance-2

In future programs, plan to invest in and utilize tools for automated evaluation of design data for mapping fault tolerance and other design requirements, instead of relying specifically on human inspection of schematic data. Keep human evaluation in the loop but increase use of evaluation tools to catch unique and nuanced design imperfections, such as the helium legs of the propulsion system.

Retroactive incorporation of this technique is unlikely to be practical, as it assumes a design/documentation philosophy that should be incorporated at the start of a new program.

Observation 3: Verification of fault tolerance
The VCN-CCT-REQ-1130-80C, Autonomous Deorbit, R.CTS.086 verification evidence did not contain helium manifolds in the associated case matrix.

Recommendation:
R.12 [OSMA] - Insufficient processes for design deficiency

NASA should verify that the provider has sufficient tools and process for addressing issues or concerns. NASA should verify the provider has a "speak up" process to appropriately elevate critical safety concerns and provides sufficient training to ensure all team members are aware of processes and safety priorities.

Organizational Factor 7: Insufficient processes for design deficiency
There were insufficient processes and tools in place to adequately address when lack of fault tolerance was identified on Starliner, directly contributing to the inability to address this discrepancy. The emails from the operations team to address fault tolerance represent a missed opportunity to address deorbit capability.

4.8 Common Observations and Organizational Factors

Each "analysis" section above looks specifically at investigating the proximate/direct cause of an individual undesirable event. This analysis of each undesirable event also looks at that events specific intermediate causes that led to the proximate or direct cause. This section will explore intermediate causes, observations and organizational factors that are common across the anomalies under investigation.

4.8.1 Testing

Observation 1: Execution of flight test objectives and acquisition of flight data
Boeing and NASA launched OFT1, OFT2, and CFT without the ability to store and retain data to ensure proper evaluation of test flights.

FTOs that were considered to only be partially met from previously flights such as V-FTO-737 (during the orbit operations & rendezvous, proximity operations & docking, departure, and deorbit mission phases obtain [redacted]) and V-FTO-1092 (during the undocking mission phase obtain [redacted], without which will cause uncertainties in the certification of the vehicle.

All post flight data reports, remark on the inability to obtain mission representative data during key portions of the mission and include recommendations to remedy this change but has not been pursued.

The low sample rate contributed to misdiagnosis of thruster failures on OFT-1 and OFT-2. That misdiagnosis allowed the launch of CFT and the repeat of thruster failures. The SM RCS qualification gaps were discussed prior to OFT (e.g. ERB-18-0045-R1 and PCB-19-383). The forward work identified during the PCB-19-383 requested, "OFT flight data to validate models and engine performance" for "Lack of mission representative operational duty cycles for OMAC/RCS engines – flight performance evaluation." This shows NASA planned to close the identified lack of qual data for SM RCS by using flight test data from OFT.

The deficiency in the decision to use OFT-1 (and later OFT-2) to gather SM RCS qualification test data to cover the gaps prior to crewed flight was not the concept but the execution. OFT-1 and OFT-2 did not have the SM RCS chamber pressure sample rates sufficient to capture developmental quality data on the thrusters to support closing the test gaps and proceeding to crewed flight on CFT. Additionally, the sample rate for recorded data from the flight was insufficient to determine what duty cycle the thrusters were commanded. Thruster duty cycle is likely a contributor to either mechanical issues with the thruster or the thermal soap back temperatures observed at the valve. This contributes to the difficulty in reconstructing the thruster of failures observed on OFT-1, OFT-2, and CFT.

Organizational Factor 8: Insufficient Verification and Validation
Boeing submitted, and NASA subsequently accepted, insufficient verification, validation, test data, and flight rationale for the CM RCS and SM RCS for the CFT mission. Starliner SM RCS was not backed by sufficient ground test, inflight testing (OFT-1 and OFT-2), and Test Like You Fly (TLYF) methodology.

Prior to OFT-1, ERB-18-0045-R1 and PCB-19-383 identified that the SM RCS did not meet the "standard for human rated engine qualification [which] includes flight representative mission duty cycle testing, including worst case thermal soak back/ratcheting and successful restart" (TLYF)). The forward plan to accept the risk prior to CFT was to "obtain OFT-1 flight representative operational data of the OMAC and RCS engines (performance and induced thermal) within the limitations of planned data from the OFT-1 existing configuration in order to validate/correlate the basis for acceptable engine performance under nominal mission conditions [...] Once OMAC/RCS engine performance and thermal conditions are validated for actual flight conditions (environments, operations, representative usage conditions) in OFT-1, residual risk for crewed flight application will be mitigated, and issue can be closed." [PCB-19-383] (TLYF).

The plan to use OFT-1 flight data to complete qualification testing could make sense. The NASA team discussed this in ERB-18-0045-R1. They weighed the risk to the ISS of the uncrewed OFT-1 mission without fully qualified SM RCS thrusters. It was rationalized and accepted that the orbits OFT-1 would make below the ISS before rendezvous and dock on flight day two would provide sufficient data about the performance of the SM RCS in a mission representative environment (TYLF) prior to rendezvous with the ISS.

The plan was to use OFT-1 as a developmental SM RCS test vice conducting further ground test to anchor analysis with test. In a modern commercial spaceflight world where you may find your program hardware poor and/or cost constrained, low dollar per kilogram to orbit values may permit such on-orbit testing vice complex and expensive simulated environments on the ground (e.g., the complex setup for integrated doghouse testing now be conducted). The deficiency in this decision was not the concept but the execution. OFT-1 and subsequently OFT2 did not have data logging or telemetry sample rates sufficient to capture developmental quality data on SM RCS thrusters.

When OFT SM RCS thrusters were put through non-mission representative profiles due to the MET anomaly, the logic for proceeding without complete qualification testing was carried from OFT-1 to OFT-2. The data logging and/or telemetry rates were too slow to capture developmental quality test data. "Flight data at [redacted] is not a suitable replacement for qualification level questions," according to OFT-2 Data in Hindsight Presentation. During an interview with NASA Engineering Propulsion Expert on Boeing Starliner Engine, the expert noted that the low sample rate likely contributed to misdiagnosis of the observed SM RCS failures on OFT-1 and OFT-2. Post-flight test reports written by Boeing and delivered to CCP, all call attention to the low sample rate for chamber pressure on the SM RCS system making it difficult to understand SM RCS performance and anomalies.

The following is pulled from the OFT-1 Report: "During the orbit insertion burn, multiple RCS thrusters were used for attitude control and pointing. This thruster usage is seen in Figure 5.2.8-17 which shows the Pc data (1st panel), RCS manifold pressure (2nd panel) and the RCS valve temperature (3rd panel). This figure is for the thrusters on manifold 1 of the Bottom doghouse. Similar data is available for the manifold 1 & 2 for all doghouses. All indications are that the RCS thruster operated as expected during this maneuver. The Pc sensor and command status bit data rates are such that it is not possible to get consistent correlations between the Pc rise and the RCS fire command to assess timing delays. [redacted]. **With these data rates, many of the RCS pulses are not captured by the data system as they are typically less than 100ms in duration.**"

Additionally, the OFT test report called for ground testing that was ultimately never conducted: "RCS thruster B2R3 is the one thruster that ultimately failed during the mission and documented in the Anomaly log as Anomaly 000058. During this MET anomaly, 7 other RCS thrusters experienced anomalous Pc behaviour as well. Later in the mission, Boeing was able to confirm proper operation of the 7 other thrusters even while the Pc readings were inconsistent and re-enabled these thrusters for use in deorbit and disposal. **As part of the RCCA for the failed thruster, B2R3 and the anomalous Pc sensors, Boeing is planning to perform ground testing of two flight RCS thrusters with the duty cycle shown in Figure 5.2.8-7 and Figure 5.2.8-8 to characterize the thruster thermal environment to aid in the failure analysis**" (Bolding added for emphasis). A discussion with a NASA Engineering Propulsion expert on Boeing Starliner SM RCS, revealed this testing was never conducted. The expert said, "There was not ground hot-fire testing of an RCS jet between roughly December of 2019 (final ATP) and July of 2024 (CFT WSTF Test). Ground testing of two flight RCS thrusters was not conducted under hot-fire conditions as that statement implies would be done. That testing is not listed as a constraint for CFT in the same PCB report, so I'm not sure how it would have been captured in the formal documentation or work plans."

Recommendation:
R.13 [CCP] – Sensor Sample Rates and Data Retention

Disposition that ground testing and analysis demonstrate no improvement (beyond format 12) in Pc sample rate is necessary for SL-1 in preparation for a crewed SL-2. A brief on the rationale for not increasing Pc sample rate should be held to align the stakeholders.

Additionally, evaluate what other sensor data and sample rates should be captured on SL-1 to support SL-2 for both propulsion and other systems (e.g., record commanded pulse width, NTO inlet pressure at higher rates to understand dynamics, DFI on a few select thrusters of interest, higher rate IMU data for parachute events, etc.).

[redacted].

Data from unexpected issues must be available. Higher recording rates that do not cover the nominal mission burns can thus not investigate nominal mission burns or the health of thrusters during those burns.

The integrated doghouse testing and single engine developmental qualification testing occurring in 2025 is extremely helpful in returning Starliner to crewed flight. But ground tests will have limitations. SL-1 is an excellent opportunity to gather data to fill ground test gaps. Prudence dictates a thorough review of opportunities to improve sensor data on SL-1 or even to add data collection opportunities on SL-1 to inform SL-2. Examples include, instrumenting NTO pressure at higher rates on select thrusters, high rate DFI systems used on OFT1, and/or record commanded thruster pulse widths for later download. Scope should be expanded beyond the propulsion system to other areas where risk and/or qualification gaps exist.

Recommendation:
R.14 [OCE] – Engineering/Development data standard

Generate an engineering data standard to define what data is necessary for model validation, vehicle system health and performance characterization, analysis, and troubleshooting.

The industry lacks a standard or best-practices document to define what engineering data is necessary for vehicle system health and performance characterization, analysis, and troubleshooting. NASA should generate a document to fill this gap and to levy as a requirement on future commercial partners. This should include recommendations or requirements defining what sample rates are necessary for what types of data, what ranges the sensors should operate within, and what metadata should be delivered, among other things.

There must be a standard/guide to evaluate if the data systems present will be sufficient. Without this standard, industry/NASA will continue to have difficulty in evaluation of systems, especially for developmental programs. This is necessary/critical for evaluation of immature systems. Simply, all standards ask for sufficient data, while there is no standard/guide for the industry for what constitutes as sufficient.

Organizational Factor 9: Integrated Prop Standard
No integrated spacecraft propulsion system to evaluate the efficacy of the CFT Prop System.

Test requirements were based on several documents used widely in industry (SMC-S-016, NASA-STD-5012, NASA-STD-6001, SMC-S-025). However, these requirement documents do not have sufficient details for specific spacecraft applications and require "interpretation" and agreement on the way individual requirements are met. In many cases, these documents require testing "in all operational conditions". Determining and agreeing on what those conditions are is challenging and leads to disagreement and misunderstanding between teams. In addition, each of these disparate requirement documents that had been levied do not consider the overall system performance effects. They are focused on individual components (valves, thrusters, etc.) and not the integrated propulsion system. This is highlighted in the STAR report.

Recommendation:
R.15 [OCE] – Integrated Prop Standard-1

Create a qualification standard for integrated spacecraft propulsion systems.

This standard should consider interactions between all propulsion system components and should focus on both individual component and system level integrated testing. In addition, teams should come to agreement prior to the start of any testing on what that testing should entail, and what conditions and environments will be tested. "Requirements" are easy, but "Verifications" are hard. Coming to an early understanding on all testing and data required to verify compliance/qualification to a requirement is critical to avoid late changes or misses in testing and analysis. Different teams will conclude that different testing and data will satisfy a requirement verification. Without agreement a-priori to testing, it is almost certain that NASA's expectations for requirement verification will differ from the testing and data provided by a partner, creating "gaps" in testing. This is highlighted in the STAR report.

Prior to release of this report a new Standard was submitted, STANDARD FOR THE CONTROL OF CATASTROPHIC HAZARDS IN HUMANRATED SPACECRAFT PROPULSION SYSTEMS, JSC-67723, has been released. This new standard may adequately accomplish the associated action, however this should be determined by SOMD.

Recommendation:
R.16 [OCE, SOMD] - Integrated Prop Standard-2

[OCE] Perform an evaluation, prior to return to crewed flight, to determine effectiveness of new integrated spacecraft propulsion systems standard to prevent CFT prop failures.

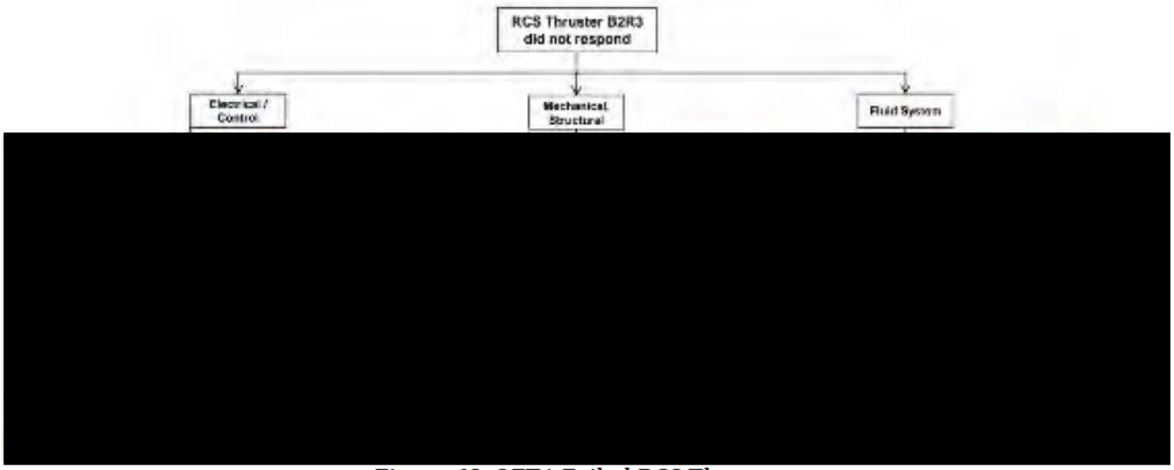
[SOMD] Evaluate the effectiveness of the standard, determine gaps to the standard (if any), and determine gaps to meeting the standard (if any) of CFT, Starliner-1, Crew Dragon, and other crewed vehicles.

Verify that the new prop standard removes any potential gaps qualification issues and address appropriately if not.

4.8.2 Best Practices

Organizational Factor 10: Anomaly Resolution Process
Insufficient Anomaly Resolution Process directly contributed to the failures seen during CFT, specifically not pursuing/validating the proximate/direct cause of the anomaly. See Organizational Factor 1: Insufficient Anomaly Resolution Process for supporting data.

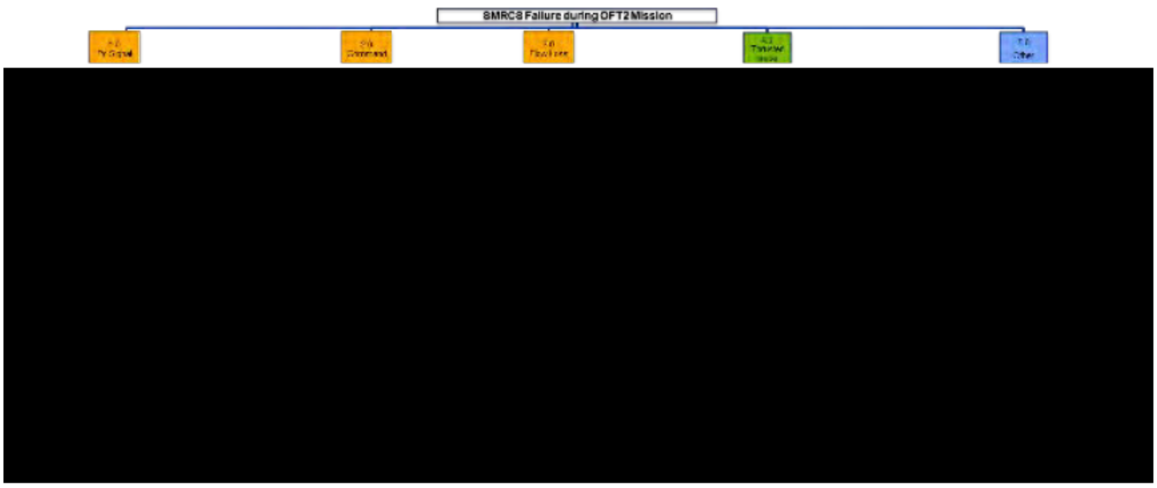
This is further evidenced by the fault tree complexity comparisons of the OFT1, OFT2, and CFT Fault Trees. The OFT1 Fault Tree had only 3 sections and only 21 failure modes sub-modes. The MET Anomaly convinced Team Leadership that the root cause of thruster failures was due to excessive duty cycle commands, thus influencing decisions to not pursue additional ground testing or a create a robust fault tree.



[redacted]

Figure 65: OFT1 Failed RCS Thruster

The OFT-2 Fault Tree had 5 sections and 83 failure modes and submodes. [redacted] masked any opportunities for additional learning, immediately became the focus of the failure investigation – better, but not comprehensive fault tree.



[redacted]

The CFT RCCA Thruster Fail off Fault Tree had 10 sections and 351 failure mode/ sub-modes. The CFT RCCA fault tree is thorough and robust, however, low data-rate sampling and lack of recovered hardware hinder post-flight evaluation of system performance.

[redacted]

Figure 67: RCCA CFT Thruster Fail-Off Fault Tree

Organizational Factor 11: Repeated Acceptance of UAs
Anomaly Resolution Process directly contributed to the failures seen during CFT, specifically not pursuing/validating the proximate/direct cause of the anomaly or seeking root cause for significant anomalies.

The STAR report cited how Starliner (Boeing/NASA) has repeatedly not sought root cause to many IFAs, instead dispositioning many as UAs, such as the thruster failures on previous flights.

Key example being the acceptance of the OFT2-76 UA, RCS thruster injector temperatures during soakback appear to have exceeded temps observed during qual, at PCB-23-053. This anomaly is directly pertinent to the most probable cause of this failure. As outlined in Loss of 6DOF **Organizational Factor 10: Anomaly Resolution Process,** there was sufficient information present to identify the thruster failure mechanisms on OFT2.

Acceptance of *OFT2-42/AR114 UA, the in-flight OFT-2 helium leaks, at JPCB on February 2, 2023. As outlined in Helium Leak* **Organizational Factor 10: Anomaly Resolution Process.**

Lack of recreation to these failures inherently generate risk as developing changes based on unidentified causes could result in repeat of the anomaly on future flights.

Current testing is not seeking to demonstrate the exact conditions of the CFT flight of the RCS thruster fail-offs. The goal of testing is seeking to demonstrate that excessive heating that occurred on CFT will not occur with the planned modifications to the Starliner service module. This inherently results in accepting risk as there may be an unidentified element that may not be understood by only seeking to prove to not recreate the event the may or may not have occurred.

There is a balance that must be pursued as to the time/money/schedule is spent to ensure safety, however, by not seeking direct cause of the failure results in a "prove it's not safe" mentality and impacts the safety culture. This directly relates and is impacted by **Organizational Factor 6: Insufficient Recognition of Risk.**

This was also identified by the STAR team. There is already a recommendation from the STAR: "Use as is dispositions should only be considered after exhausting options for hardware changes. Increase the rigor in evaluating UAs by investing in more hardware testing, recreation of failure modes, to validate fault tree closure rationale." The closure plan for the CCP Program for the associated action (A-22), is which is "Evaluate NASA participation in Boeing PMRB to ensure proper elevation of risk acceptance."

Observation 1: Mission/Appropriate usage definitions
Boeing did not define the thruster usage requirements adequately to subcontractors. As a result, the thruster profiles/operations, given to vendor/subcontractor, did not cover the worst-case operation. When combined with the insufficient definition of the thermal environment, the firing sequences for CFT (which were not worst case) resulted in the thrusters exceeding their qualified temperatures.

This observation stems from the RCCA team investigation 2.4.2 Thruster Usage/Conops Definition. This was previously tracked as a top risk prior to OFT1 for NASA as the risk of insufficient thermal environment correlation for the worst case predictions was highlighted as the top risk during Boeing RCS/OMAC (Engine) Qual Issues for CFT in September of 2019 (PCB-19-383).

4.8.3 Certification

Observation 1: Commercial Services Model Risk Acceptance
Reduced technical oversight and a shared accountability framework, by design, shifts responsibility to the provider and reduces NASA's direct insight and control. While this offers the potential to deliver speed, innovation, and cost savings, it also introduces increased uncertainty in the final product particularly when coupled with shortcomings identified in Testing section and a short and finite test flight campaign. While no amount of NASA oversight can guarantee zero risk or schedule compliance, the agency must be deliberate in acknowledging and accepting an elevated risk that missions may fall short of key objectives or even fail as a consequence.

Observation 2: Verification Discipline
Boeing submitted rationale for requirements verification that did not fully meet the intended rigor or completeness expected for the verification method or associated waivers. NASA, in turn, accepted this rationale without requiring sufficient supporting evidence or justification. This mutual departure from expected verification standards contributed to reduced assurance in system maturity. (See Variance 1: CM Prop.)

Observation 3: Shared Accountability
The Shared Accountability was not understood/fully embraced by the Industry Partner/NASA, nor were the expectations from NASA adequately captured.

As noted in the May 18, 2025, CCP Certification & CoFR charts provided to NASA Management Councils, the Commercial Crew Program utilized a new-to-NASA Shared Accountability for its certification approach. The basic premise of this approach relies on two premises:

- The Industry Partner to be responsible for the design, development, test and evaluation; culminating in their certification assertion of its CTS to transport crew to and from the ISS.
- NASA CCP is accountable for ensuring compliance to CCP's human spaceflight requirements thru evaluation and approval of the Contractor's compliance evidence and execution of NASA's insight into the Contractor's solution in accordance with a risk-based insight approach implemented under shared assurance.

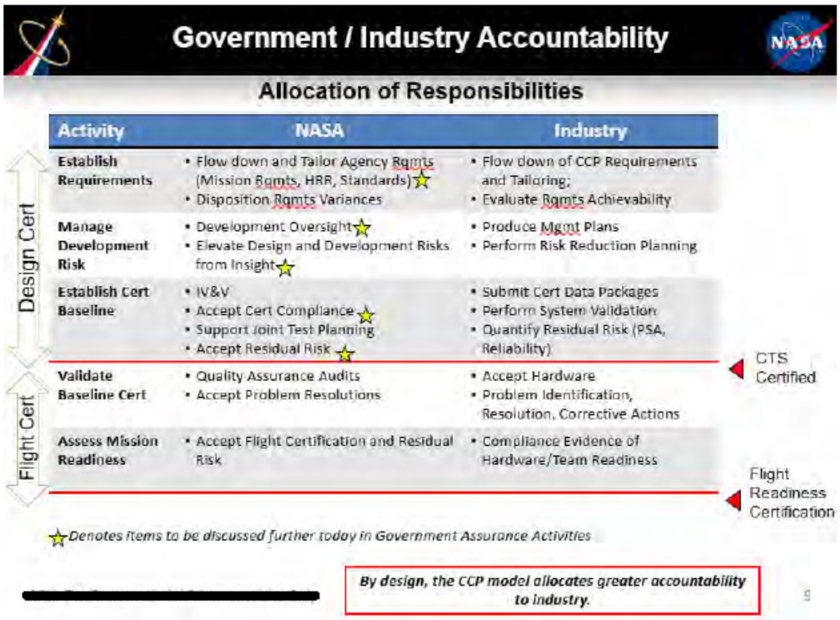


Figure 68: Allocation of Responsibilities Chart

Overall, it is unclear whether the Shared Accountability was just not understood by the Industry Partner or just not fully embraced by the Industry Partner, or both were an issue. It is recommended that in the future NASA fully documents expectations of the Shared Accountability and clearly lays out NASA and partner roles and responsibilities. NASA needs to have open and honest discussions about the risk they are accepting when they allow deviation from this contract and be willing to live with the consequences of that risk.

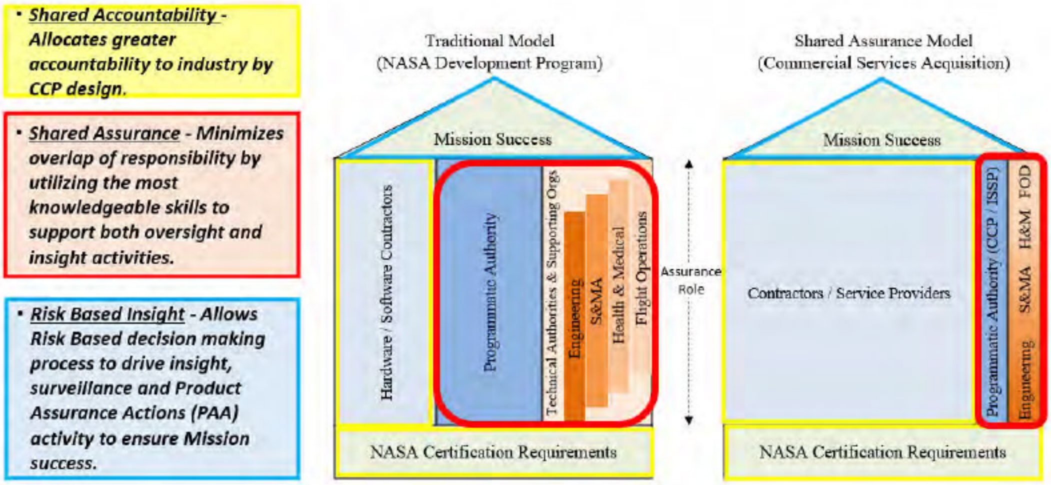


Figure 69: CCP Shared Accountability Model

In addition, some flexibility needs to be built into the contract to account for NASA's need to drill down into a system once major risks are identified. In this case, Boeing failed to supply that access for themselves so when issues arose there were problems getting the data. All future partners should be required, at a minimum, to have access and/or reach back to component-level data until after the Program goes into operational mode or, ideally, for the life of the program.

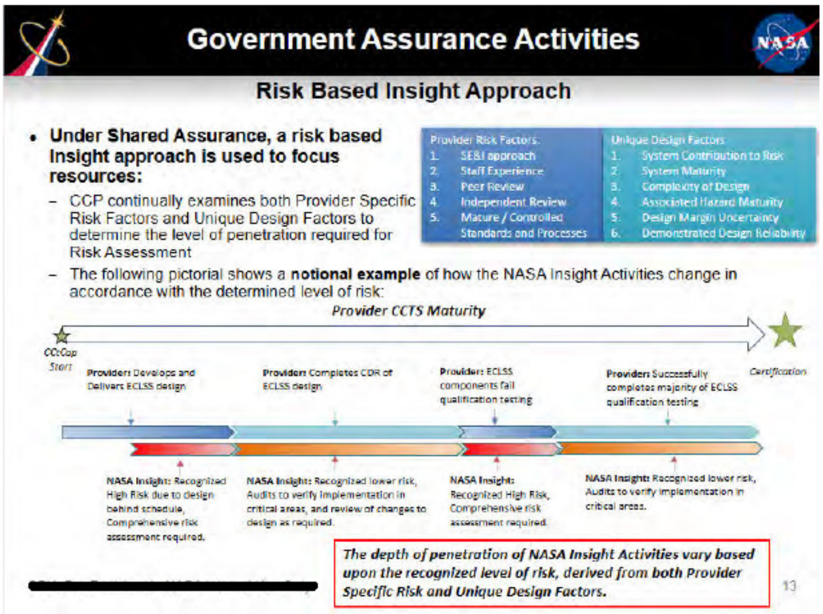


Figure 70: Risk Based Insight Approach

While in theory this model should work, its execution had issues for this Program. It is recommended that those issues be studied, and lessons learned from its execution on CCP be thought through before applying this model to new Programs. Some of the examples of issues with execution and of this model and shared accountability addressed in interviews include:

- Several standards and/or requirements were not flowed down from Boeing to its subcontractors (NASA-STD-5017).
- ATP hotfire requirements
- Boeing failed to ensure adequate insight for their own team into not only Aerojet Rocketdyne's design but also to the suppliers below, including the thruster provider, Moog, Inc.
- Boeing failed to attend component level PDRs and CDRs in the propulsion area.
- When issues arose with propulsion components, Boeing did not have adequate documentation on the components to fully understand the issues.
- Surveillance plans were supposed to be based on phase 2 hazard reports (which were provided in the 2018/2019 timeframe), however, designs were set well before that date and system builds were occurring already in the 2015/2016 timeframe.
- Boeing failed to adequately implement the Validation part of V&V.
- Integrated doghouse testing was not performed.
- Integrated software testing was limited.
- Human-in-the-loop testing was limited.
- NASA approved oversight documents even though insight data was required to fill in gaps from the document.

Recommendation:
R.17 [CPMO, OCE] - Shared Accountability

Develop and implement new guidance/standards for shared accountability on new/developmental Programs.

Observation 4: Lack of Understanding Certification of Flight Readiness (CoFR)

NASA's overall understanding of the functional distinctions in certifying a new commercial vehicle, compared to traditional NASA programs, appears limited. This is evident by the surprise and/or emotional response to available information on a system once a failure has been realized.

Comparison of Engineering Certification of Flight Readiness (CoFR) on "traditional" Program vs. Engineering CoFR on Commercial Crew

When looking at engineering CoFR for traditional cost-plus contracts for human spaceflight programs (e.g., Shuttle, Orion) and comparing it to the engineering CoFR for the commercial contract implemented for the CCP, the biggest difference is the CCP CoFR covers only safety of flight whereas the traditional program CoFR covers both safety of flight and mission success. Safety of flight focuses on preventing accidents and injuries to both the astronauts and personnel on the ground. Mission success focuses on achieving the predefined objectives and desired outcomes of the mission. A flight can be safe and not meet all mission objectives but generally mission success can't be declared unless the flight is safe. This means safety of flight is a subset of mission success.

In addition, some of major differences between the different approaches deal with the depth of penetration into the design. This includes access and insight into sub-vendors data below the system/subsystem level, FMEA/CIL data requirements, level of VCN and cert package data review, audit use solely for insight, and risk-based review only in many areas. In each case, the traditional programs had more stringent requirements in these areas and better access to all design and verification data at different levels.

These differences are what NASA bought into with the commercial contract. The CFT propulsion system failures on CCP perhaps demonstrate the need for a compromise approach to the commercial contract. We are not advocating for returning to the full SSP or lesser Orion approach, but perhaps finding a middle ground where deeper penetration is required in the commercial contract via contract (i.e., requirement for access to sub-vendor data, more type I deliverables in these areas, earlier access to design, etc.) in areas that are traditionally more risky (i.e., propulsion, pressure vessels (welding and fracture control issues are common), parachute systems, systems containing valves, etc.) and that the commercial programs set aside adequate funds for risk buy down in these areas.

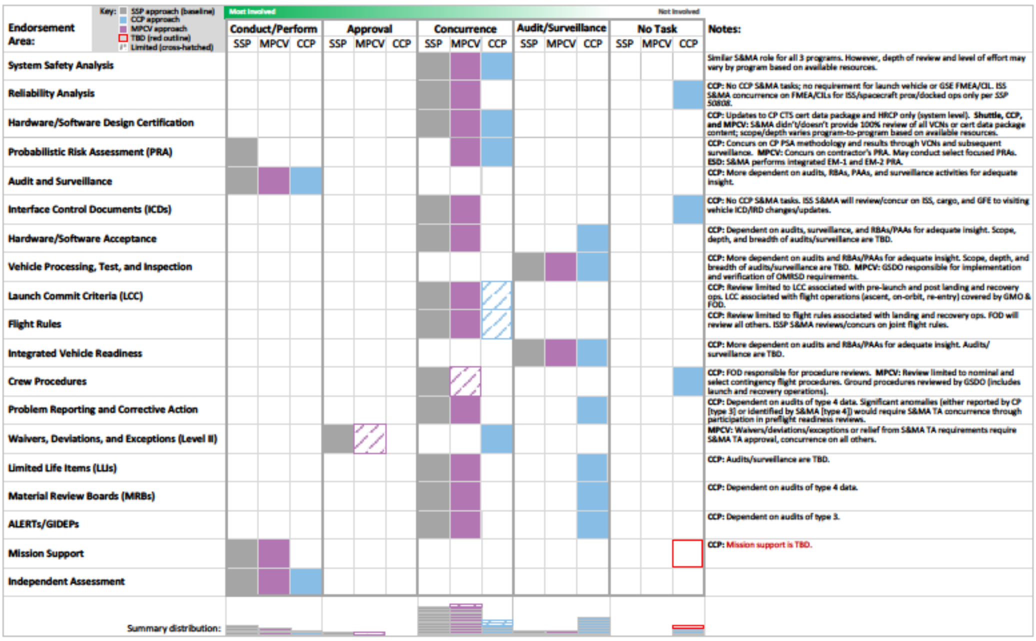


Figure 71: SMA CoFR Comparison Study – 2016 Timeframe

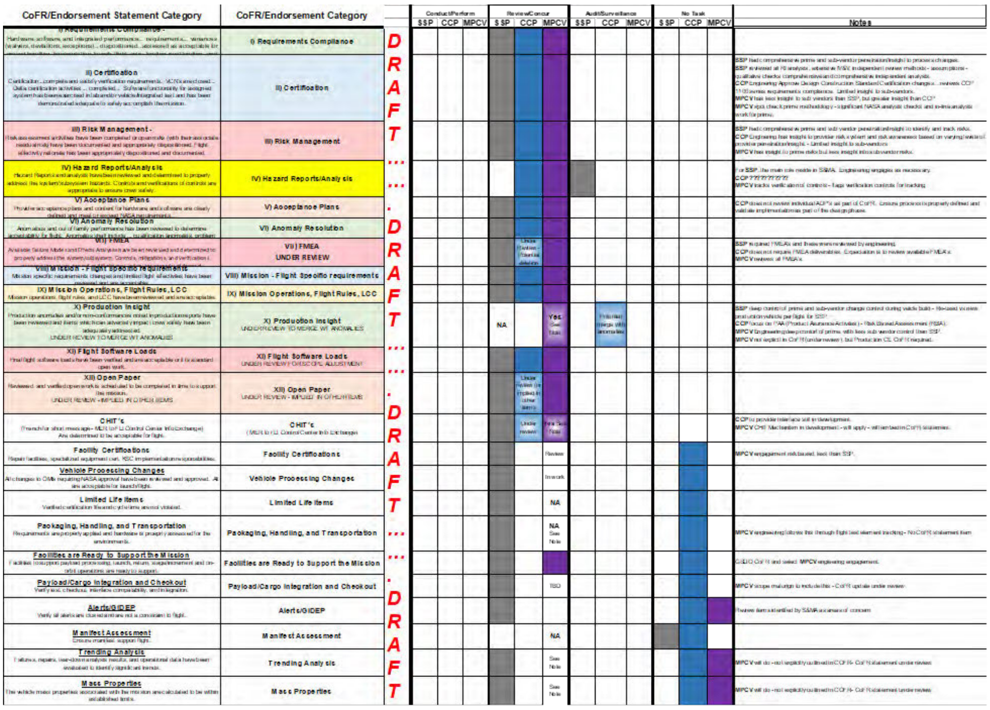


Figure 72: Engineering CoFR Comparison Study – 2017 Timeframe (Draft Version)

4.8.4 Oversight/Insight

Organizational Factor 13: Oversight Data

The implementation of the contract model did not allow for sufficient depth/understanding to independently verify that the contractor had completed certification.

The implementation of the oversight/insight model, coupled with limited resources of the CCP team and enabled a strong reliance on Boeing to perform risk assessments, resulted in Boeing determining what risks to elevate to NASA and the data necessary to assess those risks.

Agreements made between Boeing and its subcontractors made it difficult for NASA personnel to gain access to relevant design and testing data from subcontractors to validate/independently verify provided data for requirements and certification.

Organizational Factor 14: Subcontractor Insight

Boeing did not consistently obtain access to component-level data from their suppliers. As a result, NASA and Boeing lacked sufficient insight for anomaly resolution, due to subcontractor constraints.

This reluctance/inability to share data made it very difficult to foster a sense of "one team" to address the major flight anomalies and increased mistrust between NASA and Boeing as well as delayed decision making. Further the contract arrangement appeared to focus on milestones and cost first. Boeing relationships with subcontractors through contract arrangements initially did not provide for subcontractor real-time support during the CFT mission. However, this changed following the anomalies on CFT.

Relationship with subcontractors through contract structure placed detailed design and qualification data and knowledge with the subcontractor such that Boeing engineer knowledge was relegated to how the systems integrated with the Starliner vehicle. During the initial anomaly resolution process this lack of Boeing detailed knowledge of SM RCS design, qualification, and performance made the anomaly resolution process inefficient, delayed decision making, and increased the sense of mistrust between NASA and Boeing.

This was identified by the STAR team. There is already a recommendation from the STAR: "Insight access should be provided across the NASA/Boeing teams. Suppliers build quality/variability insight should be rectified." The closure plan for the CCP Program for the associated action (A-21), is which is "Work with Boeing to ensure insight access should be improved across the NASA/Boeing teams, to include suppliers' data."

4.8.5 Schedule

Organizational Factor 15: Continuous Aggressive Launch Schedule
While schedule milestones are required to coordinate and drive program progress, lack of runway to artificial milestones should not be a primary driver in decisions to implement critical design updates.

The cost of this strategy includes incremental risk assumption, continuous erosion of trust with the stakeholder community and consistent high pace of work over time. These factors contribute to workforce burn out and a de-prioritization of work items deemed unable to work due to schedule.

The same strategy is perceived to being utilized in readiness to fly Starliner-1 in the fastest achievable configuration. This results in debates regarding deferring upgrades or improvements, proceeding at risk, optimistic assessment of test plan, and avoidance of openly discussing opinions on how best to return to crewed flight.

Figure 73 shows a heatmap of CFT proximity to launch over a five-year period. For 41 months out of that period, CFT was within six months of the published launch date. In comparison, Artemis II, a comparable developmental first-crewed test flight that has incurred launch slips for hardware and software issues, came within six months to launch for the first time in the Fall of 2025 for a February 2026 launch.

Flexibility with launches and moving schedules to accommodate work is a delicate balance, but repeatedly moving launch dates a little at a time will have a negative impact on team dynamics.

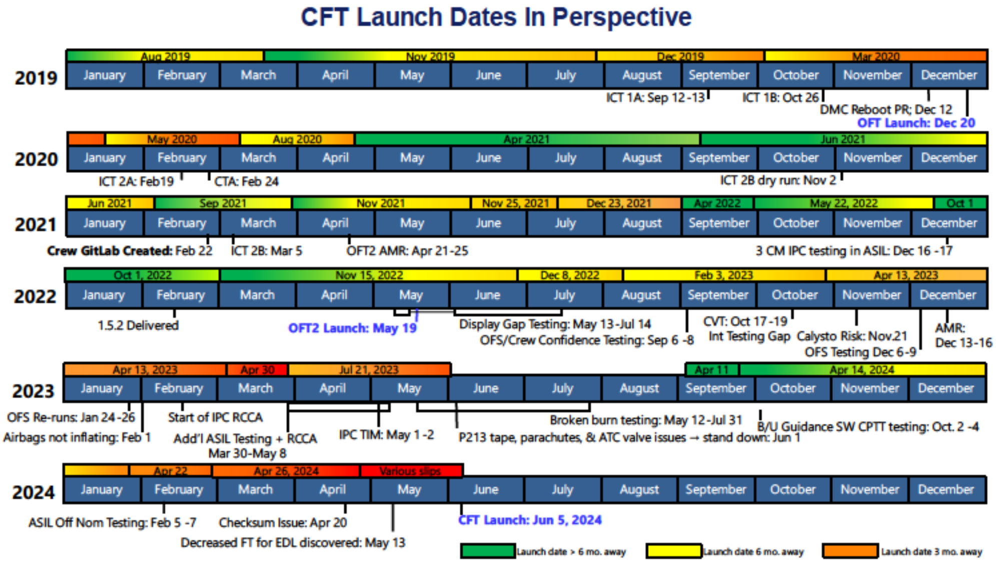


Figure 73: Heatmap of CFT Launch Schedule

5 Culture and Decision-Making Process During the Mission

5.1 Objectives and Approach

This investigation team was simultaneously tasked to review the culture of the near-real-time operations decision-making and process used during the mission. For the purposes of this report, "near-real-time" refers to the environment outside of the Flight Control Room (FCR), which is considered "real-time" operations. Near-real-time includes, but is not limited to, meetings such as the Starliner Mission Management Team (SMMT), ISS Program Mission Management Team (IMMT), Spacecraft Reviews, CCP Program Control Boards (PCBs), working-level and working group meetings, analysis reviews used to inform recommendations, outside-of-board (OSB) conversations and decisions, and other mission governance activities.

For the purposes of this report, "team" refers to the large joint team between Boeing and NASA. This includes all the NASA organizations supporting the mission, including: CCP, ISSP, SOMD, Agency Leadership, Engineering, SMA, HHP, FOD, and their support structures across multiple centers. Where applicable, the team also includes subcontractors to Boeing. In this sense, "team" is the amalgamation of organizations that participated in the mission.

While earlier portions of the report focus on the propulsion system anomalies and their root causes, this portion focused specifically on the mission execution timeframe. The analysis is positioned around the period between the pre-flight Agency Flight Readiness Review (AFRR) and the Starliner landing.

This section addresses:

- How data was collected
- How findings are categorized
- What tools were utilized to analyze the data
- Overview narrative for context
- Observations and recommendations

Interview Overview

As the primary data collection tool, key personnel were interviewed regarding their experience during the CFT mission. Participants included individuals from both NASA and Boeing, selected to ensure depth and breadth across the organizations. The interview pool spanned agency-level management down to line engineers and included government, contractor, and provider program management teams. Representation included multiple levels of the CCP, ISSP, Boeing, Engineering, Safety and Mission Assurance (SMA), Human Health and Performance (HHP), the NASA Engineering and Safety Center (NESC), Flight Operations (NASA and B-MO), Center Management and Agency Management. These teams encompassed NASA personnel from multiple centers, including Kennedy Space Center, Johnson Space Center, Marshall Space Flight Center and Langley Research Center (KSC, JSC, MSFC, and LRC), as well as NASA Headquarters. The organizations of Engineering, SMA, and HHP all include primarily matrixed program support in addition to a smaller amount of independent Tech Authority representatives. However, these organizations are often referred to broadly as the "Tech Authorities" both colloquially in the interviews and within this report.

The purpose of the interviews was to identify factors that positively and negatively influenced decision-making and to assess the effectiveness of the organizational culture during the mission. Interviewees were asked to respond to questions focused on six key areas: organizational structure, communication, team dynamics, organizational culture, resources, and decision-making processes. These key areas are defined in **Table 4.** below.

Definitions	
Organization Structure	The framework for how the large joint team (Boeing, NASA – Programs, TAs, FOD, etc.) functioned with roles and responsibilities and lines of authority.
Communication	Process for sharing and exchanging information across the organizations and individuals within the organization
Team Dynamics	How the large joint team worked together including behavioural interactions that influence decision making.
Organizational Culture	The shared values, beliefs, and behaviours that define a work environment.
Decision Making	The process by which intention and informed decisions are made.

Table 4: Definitions of Key Areas

A total of 66 interviews were conducted between March and May of 2025. Each interview lasted approximately one and a half hours and included two to five panel members from the investigation team. All interview data was catalogued to identify common themes. These themes produced noteworthy observations and recommendations

Additional support for these observations was derived from reviewing programmatic and agency documentation, meeting minutes, transcripts, follow up conversations, as well as supplementary diagnostic tools. These diagnostic tools included a review utilizing the NASA Human Factors Analysis and Classification System (NASAHFACS), collecting survey data on team effectiveness, and performing timeline re-construction. Below, you will find background and context for each of these specific tools. More detailed information can be found in the appendices.

5.1.1 NASA Human Factors Analysis and Classification System (NASAHFACS)

To understand the human and organizational factors impacting the mission, the NASA Safety Center (NSC) worked in conjunction with the core investigation team to conduct a NASAHFACS review. The full and detailed analysis can be found in **Appendix A.** The NASAHFACS report is a tailored framework specific to human factors, designed to assess human and organizational factors within NASA's unique operational context. Rather than examining a specific mishap, this analysis explores broader organizational processes and decision-making dynamics. It identifies key human factors across three NASAHFACS tiers—Organizational, Supervision, and Preconditions—highlighting both deficiencies and strengths.

The NASAHFACS study was used as a secondary way of examining the interview data. The analysis from the study was utilized as one of the input tools for the final observations and recommendations provided at the end of this section. It is important to note that NASAHFACS reports should not be used as a standalone conclusive report.

The study highlighted vulnerabilities in the commercial crew led shared assurance/shared accountability and a fractured trust relationship across key organizations. These vulnerabilities pose an elevated risk to future human spaceflight missions and programs. Addressing cultural, procedural, and contractual misalignments is essential to strengthening mission safety, organizational performance, and interagency collaboration.

5.1.2 Likert Scale Survey Data on Team Effectiveness

In addition to answering interview questions, participants were asked to rate the effectiveness of key focus areas using a 6-point Likert scale, where one indicated least effective and six most effective. These ratings were intended to explore perceptions across the broader NASA and Boeing teams, including CCP, ISSP, Tech Authorities, FOD, and multiple centers. A sample question asked to interviewees was "Rate the effectiveness of the organizational structure during CFT."

The results, summarized in Appendix A, indicate that most categories skewed toward the lower end of the scale. Many interviewees noted the difficulty of assigning a single rating to a large, multi-organization team over an extended period. Nonetheless, the overall sentiment suggests consistent concerns across focus areas.

The 6-point Likert scale, which lacks a neutral midpoint, required respondents to lean positive or negative. While the scale provides ordinal data—where higher numbers indicate greater effectiveness—the intervals between values are not necessarily equal or known. The midpoint of the scale is 3.5. Summary statistics, including the mean and mode, are presented in Table 4 below. Figure 80 illustrates the distribution of responses using a diverging stacked bar chart.

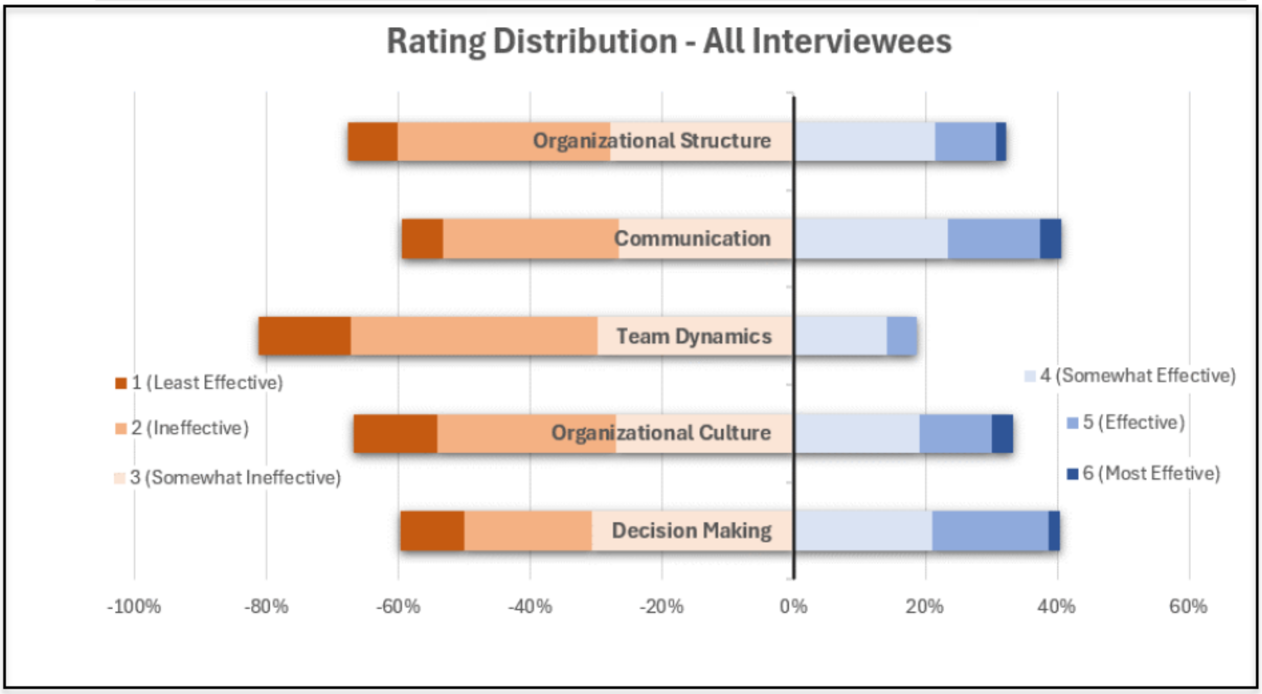


Figure 74: Rating Distribution of all Interviewees

Area of Assessment	Mean Score (out of 6)	Mode
Organizational Structure	2.99	2
Communication	3.25	3
Team Dynamics	2.59	2
Organizational Culture	3.00	3
Decision Making	3.30	3

Table 5: Key Focus Area Effectiveness Ratings

Additional data analysis of these effectiveness ratings can be found in Appendix B, including breakdown by organizations, breakdown by "level" of position, noted limitations of the data set, and key takeaways.

5.1.3 Top Level Meetings Timeline

The timeline below (Figure 75) serves to illustrate a portion of the meetings, tests, and analysis reviews that the team worked through during the CFT mission. The graphic is designed to provide insight and give context to the number of scheduled events and meetings the team was asked to support while continuing to fly the mission and work through the large-scale anomalies. While the four rows are separated out by the type/level of meeting or event, the exhaustive cadence is clear when the rows are layered. This graphic does not reflect ongoing real-time operations, planning for operations, testing cadence, organizational internal discussions, working group meetings, anomaly resolution meetings, spacecraft reviews, etc., that were occurring in parallel.

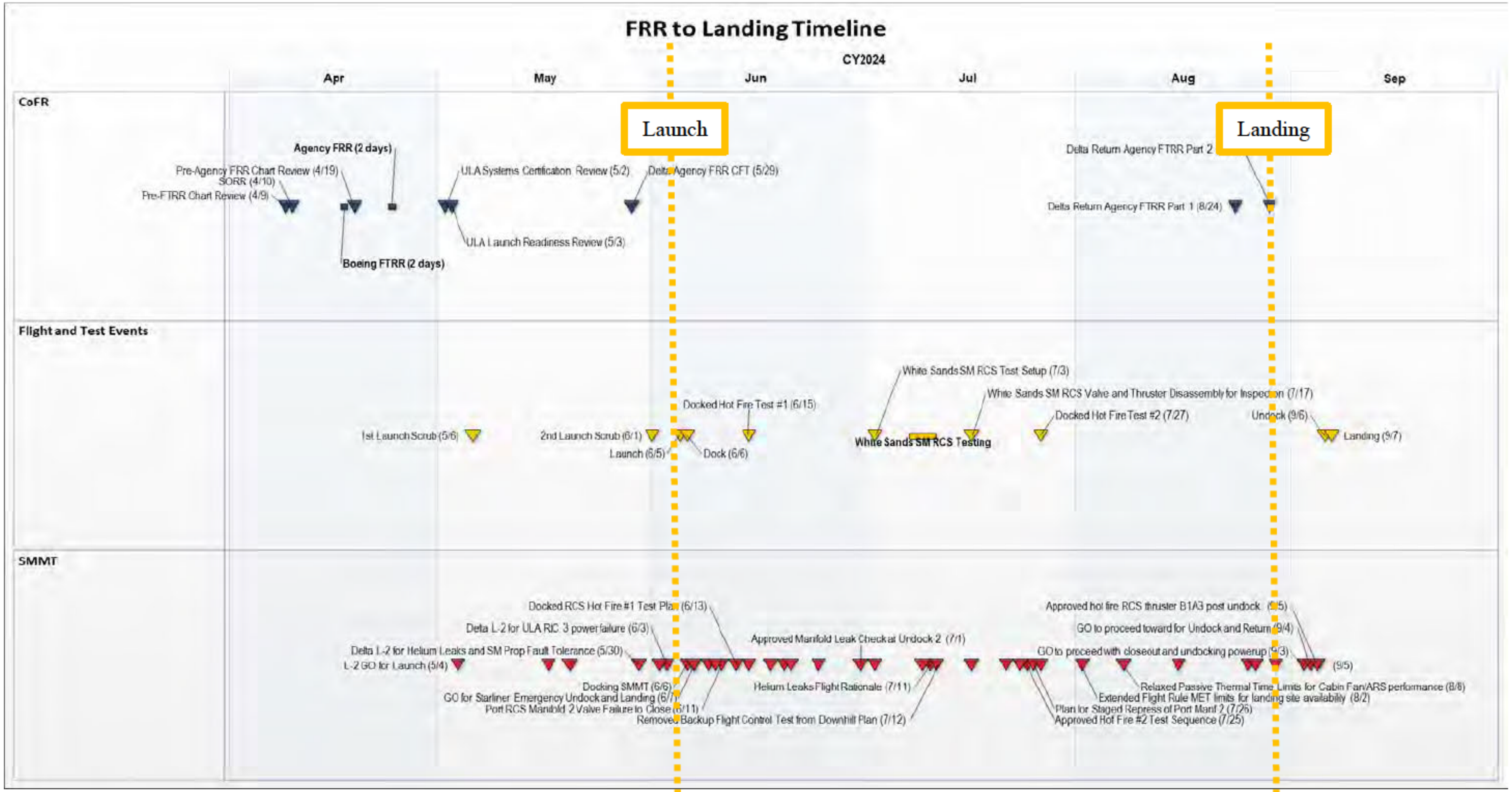


Figure 75: Meetings FRR to Landing

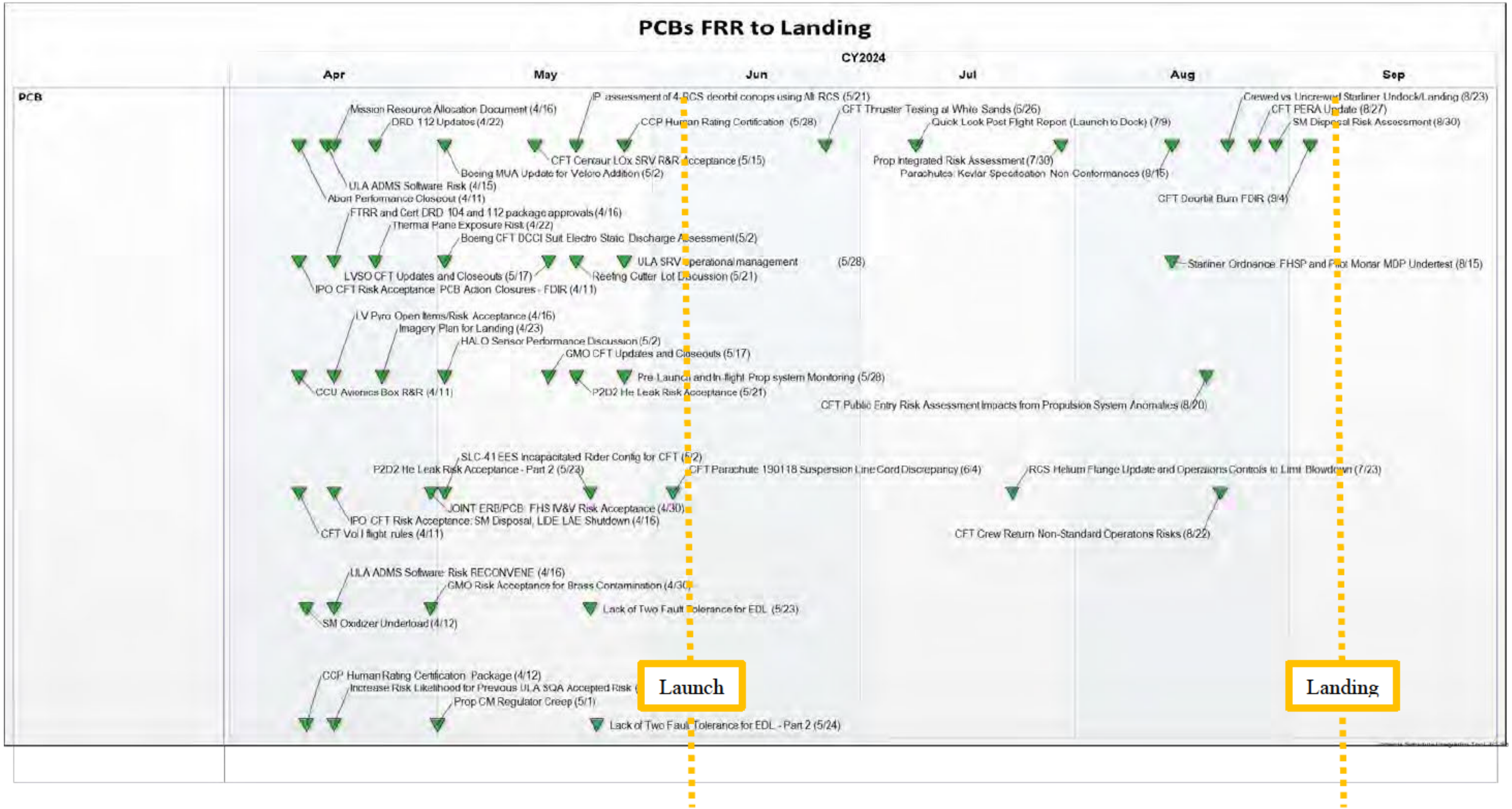


Figure 76: PCBs FRR to Landing

5.2 Observations and Recommendations

The NASA Boeing Starliner CFT was a landmark mission that tested the technical capabilities of the spacecraft as well as the resilience of the individuals on the integrated NASA-Boeing team. The observations in the following sections showcase how a previously fractured relationship across the team was magnified. Each observation has a correlating recommendation included at the end of the section. Issues in the near-real-time decision making process were exposed and amplified when working to address the potential high consequence of the Loss of 6DoF during rendezvous, the subsequent work to understand the cause for jets failing off, and the quantization of risk for using those jets for return. These factors ultimately led to confusion in the team roles and responsibilities and a fractured team culture. The final observations have been grouped into 4 key areas: **Process and Communication, Authority, Leadership, and Trust**.

The most significant technical challenge during the mission centered on the SM RCS propulsion system. The engines, critical for deorbit burn, motion control, and manual piloting, exhibited anomalies that created uncertainty about their reliability during return. Even though CFT was a test flight, losing the ability to advance towards the ISS during the rendezvous underscored the need for a clearer understanding of the SM RCS system. Lack of understanding led to the debate over whether there was sufficient comprehension of the anomalies to justify a crewed return. This became the crux of the mission's decision-making conflict.

It's important to remember that the below observations and recommendations are focused on how the large joint team can improve and how lessons can be shared to other programs. The "Summer of CFT" is more often described as fraught with disagreement, chaos, disorganization, frustration, and exhaustion. However, the governance model for process and decision making, though cumbersome, was able to forge a path for the crew to return safely to Earth.

It is important to note, findings in this portion of the investigation are categorized as observations as defined below.

Observations: A factor, event, or circumstance identified during an investigation that did not contribute to the mishap or close call, but if left uncorrected, has the potential to cause a mishap or increase the severity of a mishap; or a positive factor, event, or circumstance that should be noted.

The observations in each section are based on the experience and perceptions of the individuals interviewed. It is important to remember that the perception of the team regarding the shared values, beliefs, and behaviors is what defines the team culture and thus influences the execution of the decision-making process. Below you will find a narrative summary of each of the main themes and their associated observations and recommendations.

5.2.1 Process and Communication

The communication environment during the CFT mission was described as overwhelming and, at times, counterproductive. The volume and frequency of meetings detracted from focused problem-solving and contributed to a sense of rush and disorganization.

Interviews indicate that stakeholder inclusion and data transparency were also areas of concern. A duality emerged where participants outside of CCP and Boeing felt excluded or inadequately informed, while CCP and Boeing felt beleaguered trying to include external voices. This disconnect contributed to a breakdown in confidence in the decision-making process.

The use of resources was another point of contention. While the "all hands-on deck" mentality was praised, many interviewees noted that the number of people on calls and in meetings was often unnecessary. Contractual layers within Boeing and its subcontractors additionally complicated access to expertise and data.

Process and Communication Observations

Observation 1: Crew safety was the primary focus of discussion throughout CFT. The in-flight decision-making process and governance prioritized crew safety and forced alternative viewpoints to be discussed.

It is not lost on this investigation team that while there are many things to learn and grow from as a team and agency, the actual final decisions on when and how to return Butch Wilmore and Suni Williams, resulted in their safe return to Earth. Many individuals made extensive sacrifices in their personal lives in dedication to making the right decisions with the right data. Time off was canceled, people persevered through loss, personal strain, natural disasters and more in order to be as prepared as possible for providing input when and if it was called upon.

Observation 2: There was a distinct mismatch in the assessment of performance predictability post-undock and the possible consequence to human life when discussing the risk for using the SM RCS on the Starliner return.

The most distinctive disagreement came down to how much to rely on engineering judgment. Neither group was specifically more *tolerant* to putting the crew at risk, but the assessment of the amount of residual risk drove discontinuity and division in the team.

Through the mission NASA CCP, NASA Boeing Spacecraft Lead Engineer, Deputy SMA TA, and Boeing, believed available data was enough to justify the return of the crew and the vehicle. NASA ISSP, Eng, SMA, HHP, FOD did not agree that enough data that was rooted in test and qualification, was available to make that judgment. Ultimately, the deliberation culminated in an Agency level delta FTRR where NASA unanimously agreed to return the vehicle uncrewed. Additionally, Boeing expressed returning the NASA crew was a NASA decision to make. Both express a shift in the team in a short time at the end of the mission.

Observation 3: Getting the Starliner and crew to the ISS was the correct decision, despite the many failures faced during rendezvous. The real-time teams on console performed exceptionally well.

During interviews, team members were asked to start with what worked well during the mission. A recurring theme was the exceptional performance of the crew, and flight control team. One interviewee stated: *"I would say the on-console operators performed amazingly [...] They, I view, are the reason that CFT, despite all of the failures, was able to successfully dock despite undergoing* *numerous and catastrophic failures, arguably. The work performed by those folks cannot be fully quantified for the fact that we were, in my mind, only successful because of them, despite all the hurdles placed in front of them*."

Observation 4: While the crew was safely docked to the ISS, teams working on addressing the Starliner's major prop failure did not have a full understanding of the parameters and timeline for making a decision because there was a lack of an overarching, multi-program process to define parameters.

Once Starliner was docked to ISS, the decision of how to respond to the CFT prop anomalies became a multi-program challenge to resolve. ISS provided a safe haven to allow CCP and Boeing to troubleshoot the prop system and determine if the Starliner vehicle was safe for return. As has been discussed previously, it is uncommon in human spaceflight to have options for delaying a crew return decision and alternative ways to bring the crew home. People approached the problem with different expectations of how much time there was to decide whether the crew would return on the Starliner or not. This led to ineffective conversations about what troubleshooting and testing plans made sense. Clear parameters and a timeline for a decision needed to be pre-defined for the team with respect to what would be required to make the crew return decision.

Without an integrated assessment of impacts to both ISSP and CCP, realistic schedules could not be defined or communicated. Teams worked very long hours, long weekends, and cancelled vacations. The interviewees shared many stories of fatigue and managers worrying about burn out and stress-induced factors penetrating the workforce.

Observation 5: NASA faced challenges in aligning efforts and making timely, cohesive decisions without a unified integrative authority.

A single entity of integration was identified as missing or necessary for successful intersection of the entire CFT Boeing/NASA team. There was not an effective NASA forum where the different technical experts and those with differing perspectives could have an open exchange about disagreements regarding the major prop anomalies and the resolution plans. The Provider-led MMT was not the right environment for having that internal-to-NASA integration. It led to Boeing personnel feeling like they had to "integrate NASA" which is not their responsibility.

The NOM is the only NASA position that is supposed to be polled at the SMMT but there wasn't an effective way for the NOM to gain the NASA position with so many stakeholders out of alignment. For anomalies of this magnitude, it may be asking too much for the NOM to be responsible for this level of integration.

Observation 6: Lack of a CCP MMI equivalent on the Boeing side led to disconnects and a lack of understanding of goals and objectives for meetings. Boeing should have a CCP MMI equivalent to help manage the content, logistics, development of data, presentation, SMMT timing and agendas.

The CCP MMI didn't have an equivalent mission manager at Boeing. The CCP MMI was supposed to work directly with the Boeing SMMT Chair who was the NOM's direct counterpart. This mismatch hindered communication.

Observation 7: While Boeing and NASA documents defined the process for risk-based decision making and anomaly resolution, the implementation of these processes during the CFT was largely viewed as ineffective for the propulsion system issues.

Under this commercial services contract (Commercial Crew Transportation Capability (CCtCap) Contract No. NNK14MA75C), NASA delegates operational responsibilities, including anomaly resolution, to its commercial partners. The CCP Mission Integration Plan (MIP) supports collaboration during real-time anomalies through the formation of a CCP Tiger Team (CCT-PLN-2110 section 3.4.8). However, for non-real-time anomalies, the MIP specifies that "the partner will define and initiate the appropriate anomaly resolution path forward."

Although the CCP Tiger Team construct supports an integrated approach for near real-time anomalies, it was not implemented for the SM RCS issue. Additionally, without a formal declaration of an Integrated Anomaly, the familiar ISS Multilateral Anomaly Resolution Team (MART) structure was not activated.

Boeing's MIOMP delegates anomaly resolution responsibility to the Boeing Chief Engineer representative, who is tasked with troubleshooting CST-100 Starliner issues and coordinating responses across affected elements. The Boeing CCT Mission Anomaly Resolution Plan further assigns the Spacecraft Chief Engineer (SCE) to lead anomaly investigations and provide recommendations to operations and management.

While this approach was sufficient for many anomalies, the visibility and consequences of the CFT propulsion system issues prompted broader NASA involvement. This uncoordinated engagement strained the Boeing team, who were simultaneously analyzing the anomaly and fielding requests from multiple NASA organizations conducting parallel assessments. The lack of centralized coordination led to the circulation of outdated or disproven information, hindering effective resolution.

The NASA team took the evaluation of information, specifically regarding SM RCS and the capability for crewed return, from the near-real-time process in MMTs, back to the program pre-mission process for PCBs. In the July 30th Program Control Board (PCB), CCP offices informally polled "go" or "go pending" for a crewed return, while Engineering, SMA, HHP, and FOD polled "no-go." The inability to reach consensus persisted through August, culminating in NASA's decision to return the Starliner vehicle uncrewed. Notably, even those who had previously supported a crewed return shifted their positions by the August 23rd PCB. This reflects either a flip in their assessment of the data or an inability to close out open work.

The final polling statement from the August 23rd PCB cited unacceptable risk due to uncertainties in understanding the margins for completing all functions required of the SM to execute the deorbit burn and SM disposal. The decision to return the vehicle uncrewed was ultimately adjudicated through NASA CCP PCBs and finalized at an Agency Delta Flight Test Readiness Review (FTRR). It was here that two formalized alternate opinions were also lodged by NASA personnel. These alternate opinions did not result in formal dissent by the individuals but rather acceptance of the final decision to return the Starliner vehicle uncrewed. This non-traditional path contributed to confusion about who held final authority and the process for where decisions should be made.

Observation 8: Technical teams did not have enough time to evaluate data, develop theories, and integrate within their respective organizations. This turned higher level meetings into "working group" discussions instead of productive meetings.

Even within the officially chartered teams, the overall process did not allow technical teams sufficient time to collect and analyze data, develop and test theories, resolve differences of opinion, and present to respective technical managers for concurrence ahead of "seemingly decisional" SMMTs or other program level meetings. This was compounded by other parallel teams also performing assessments, where again without an opportunity to integrate and adjudicate differences, separate but functionally aligned NASA factions would weigh in with uncoordinated positions. It was unclear who was representing positions of the formal Technical Authorities.

Consequently, the process failed to allow the NOM an opportunity to hear, weigh, assess, and bring forward an integrated NASA position to the SMMT. With various disparate positions weighing in, and limited opportunity to integrate and adjudicate them through the various technical and organizational representatives, many interviewees felt the process degraded. The SMMT and PCB were perceived to have lost effectiveness when the decisional body was used as a working meeting with detailed technical information being presented for the first time for many stakeholders. Frustrations grew regarding the perceived need to "educate" team members who were not directly involved in previous discussions.

This highlights the lack of a structured and integrated systems engineering approach that appropriately evaluated the technical issues, implemented team constructs and interfaces, established and tracked actions, developed achievable schedules, and posted meeting agendas and minutes for the team's awareness. An interviewee stated, "We never really found a good rhythm for inflight decision-making. We kept trying different structures, but none worked well."

Observation 9: The absence of published agendas for the SMMT fuelled the interest and high attendance in meetings because every meeting seemed like it could be the pinnacle return decision meeting.

The unclear implementation of the decision-making process made it seem like any MMT or PCB could be "the one" that was going to make the big crew return decision. At the same time, people felt they had to attend the MMT/PCB because it was the only place where all of the data was available.

Observation 10: The NESC provided valuable independent resources and analysis, but it was unclear how to integrate their support into the team to streamline decision making.

Many interviews highlighted the NESC as helpful for adding resources to the team and providing technical expertise on particular focus areas. There were some concerns brought up in interviews about how their support was overall integrated into the decision-making process. Particularly for Boeing personnel, the NESC role and plans for supporting the anomaly resolution were unclear.

The rules of engagement for the NESC were also unclear, with some interviewees reporting that a NESC representative was slow to accept the decision to accept the helium leak risk. They found that it was distracting from the other prop anomalies to continue to litigate this decision despite the Commercial Crew Program hearing all the data and making a risk informed decision on this topic.

Observation 11: NASA personnel presenting provider data created a false sense of concurrence. This also caused frustration regarding who should be representing data and positions for risk-based recommendations.

Anomaly resolution requires collaborative effort, especially in flight. It is important that teams work together. However, it is also important to maintain clear lines of who is presenting and representing data or positions. An interviewee noted, "There were times where you were sitting in a meeting, you would not know if [the speaker] was a representative of Boeing." This blurred lines of who was presenting the data and positions.

There was also confusion because many on the Boeing engineering teams had worked directly with the NASA Boeing Program Lead Engineer for many years. This created a general assumption that this input was the only NASA voice needed for agreement to move forward with information and recommendations.

Observation 12: Pre-mission preparation activities did not adequately prepare the team for a major anomaly resolution process.

While pre-mission activities included technical training, simulations, and coordination efforts for addressing in-flight anomalies, these exercises did not sufficiently prepare the NASA/Boeing team for executing the large-scale integrated anomaly resolution during the mission. This gap contributed to uncertainty regarding roles, escalation paths, and expectations during decision-making. The table-tops addressed roles and jurisdiction but did not exercise collaborative problem-solving or cultural alignment.

Similarly, the preparation activities did not consistently include leadership participation beyond operational phases, and did not reinforce how NASA and Boeing would share data, engage technical authorities, or build consensus during a crisis. Interviewees noted this missed opportunity to bridge NASA's and Boeing's differing decision-making cultures. The differing decision-making cultures contributed to friction and uncertainty during the mission. Boeing team members were not fully versed in NASA's decision-making style including open communication of data, engagement of technical authorities and subject matter experts, provider presentations followed by NASA assessment, and consensus-building approaches. The lack of shared rehearsal in these cultural aspects contributed to friction and confusion during CFT.

Observation 13: NASA and Boeing utilize different risk management processes to identify and score risks, creating inefficiencies, divergent risk tolerances, and deterioration of team dynamics.

Risk definitions and assessments are subjective and often depend on a person's experiences and position responsibilities. Previous job experiences create valuable knowledge sets which influence risk assessments and risk positions. All CCP stakeholders and team members should have a shared understanding and appreciation of differing constraints and critical thresholds with respect to risk tolerances. Both the Commercial Partner and NASA stakeholder organizations should appreciate the varying responsibilities and perspectives necessary for a successful CCP mission, while agreeing on a definition for mission success.

Observation 14: There was a perceived shift in the responsibility for the burden of proof for vehicle safety. NASA personnel felt they were required to prove the system unsafe for crew return, instead of Boeing having to prove it was safe.

The interviews make clear that NASA technical teams were placed in the untenable position of having to prove that the SM RCS was unsafe for crew return, rather than Boeing demonstrating that the vehicle was safe. This reversal of the burden of proof not only violated established safety principles but also eroded trust, hindered effective risk management, and delayed critical decisions.

Simultaneously, many of the interviewed Boeing team members believed that no matter what information they brought to the table, it "would never be enough." While this broken relationship is further explored in the Trust section of these findings, this sentiment also reflects a finding from the CCP STAR report regarding the reversal of the burden of proof that existed in the workforce, leading up to the CFT mission. It highlights the need for clearer governance, stronger technical accountability, and a cultural shift toward transparency and shared responsibility in future missions. These interviews were conducted approximately six months post landing, and interviewees expressed this reversal in the responsibility for the burden of proof has continued.

Observation 15: Some interviewees saw relationships improved in their own peer groups during the mission.

Many interviewees cited the resilience of their teams and the overall desire of the collective team to drive to a solution, despite differing views as an overall positive. An interviewee noted, "A lot of those relationships, I think are still holding in a good way. So, I think that is probably the best thing that happened during the mission. I think we (internal team) built a strong team that can work together and understand each other much better than it had been before the mission."

Observation 16: Interviews cited historical concerns for dedicated resources to support CCP, particularly for two providers during the certification process, and the consistent decline to provide adequate funding to increase those dedicated resources. However, this was not reported to be an issue during CFT.

During the mission, no interviewees reported or recalled any concerns with lack of resources or the ability to acquire resources as needed. However, when asked about resource availability, many were prompted to inform the investigation team about the historical lack of available resources for CCP to acquire and certify two commercial providers.

Since the inception of CCP, NASA's vision of procuring crew launches as a service and putting as much of the development, certification, and operations responsibility on the commercial providers was similarly coupled with a desire to keep associated NASA resources minimal with continuous downward pressure. This was further evidenced when a second provider was added to a NASA team that was only sized to accommodate one provider, and yet when a second provider was selected, the resources to accommodate the additional technical work were not fully accommodated in the new budget. In subsequent years, the projected outyear CCP NASA staffing reductions did not materialize as planned, due to continuing certification efforts, unplanned life extension or upgrades, anomalies, etc.

The need to have each provider be successful, coupled with insufficient resources for certification, created an environment rich for inadequate insight and lack of oversight. This led to a failure of the shared accountability concept that was central to the success of CCP at its inception (as self-identified by CCP in the STAR report).

Process and Communication Recommendations

R.18 [SOMD, CCP, ISSP] - Establish a multi-program anomaly resolution process with entrance and exit criteria, and who gets to decide when it gets turned on/off.

R.19 [ARMO] - Implement a common tool for risk evaluation across commercial providers.

Implemented correctly, this process should provide a technically based risk characterization. Strong consideration should be given to using the *7 Elements of Effective Flight Rational* created after Columbia, that appropriately assesses:

1. Technical Understanding
2. Condition Relative to Experience Base
3. Bounding Cases
4. Self-Limiting Aspects
5. Understanding of Margins
6. Assessment Based on Data, Testing, & Analysis
7. Interactions with Other Elements/Condition.

R.20 [CCP] - Establish structured communication path and forums with clearly defined expectations and responsible parties in an anomaly.

This should include meeting agendas, expedited meeting minutes with action tracking, and meeting cadence plans. Meeting cadence and length should accommodate stakeholder sync time with organizations to facilitate the development of respective positions.

Expectations for out brief communication (i.e. summary emails) with identified responsible parties should be stipulated.

Attendance for stakeholders should be defined and reasonable limitations placed on attendance to preserve the roles of delegates.

Decisional versus working level forums should be clarified and leadership is responsible for ensuring that forum objectives are preserved.

The process should facilitate the engagement of delegated technical experts from NASA to participate on provider led teams. Those delegates are responsible for representing their technical organization and carrying back results from the team to their technical organization as time allows.

CCP, provider mission management, and anomaly resolution documents should be updated to reflect the new processes.

R.21 [CCP] - Establish a clear process for integrating technical expertise from different teams and organizations within NASA, ensuring that all relevant perspectives are considered, to enable the NOM to provide the NASA voice at the SMMT.

The importance of roles, responsibilities, and authority path should be reiterated to technical organizations along with the importance of cross discipline integration and authority delegation.

Process should ensure that all associated technical work is coordinated through the delegated technical team and that parallel efforts are not spawned without careful consideration.

Anomaly process timeline and scheduling should accommodate coordination and adjudication of technical positions with respective organizations as time allows.

Process should require separate but functionally aligned organizations to integrate across respective elements and provide integrated input as time allows at each respective level of the anomaly resolution team hierarchy, culminating at the MMT or PCB.

R.22 [Boeing] - Create an equivalent MMI position.

R.23 [AA] - Document expectations or provide training that NASA interfaces to contractors be very clear whether they are speaking with the full authority of their organization/NASA *<u>or</u>* are info gathering/collaborating/sharing personal views.

R.24 [OCE] - Define the process and rules of engagement for how NESC participates in the in-flight anomaly resolution process. Provide information to commercial contractor partners about the NESC and rules of engagement before, during, and after a mission.

R.25 [ALL] - Communicate all updates via mandatory training for programs and stakeholders.

R.26 [CCP] - Incorporate structured pre-mission training including dedicated briefings, tabletop exercises, and integrated team simulations to rehearse real-time decision-making processes.

Prior to launch, convene multi-level NASA/Boeing teams for a series of targeted briefings and tabletop exercises that walk through the anomaly resolution process. These sessions should focus on reinforcing expectations around conflict resolution, escalation through technical and management forums, communication standards, and data dissemination practices. Engagement should include all decision-making tiers, from working-level technical teams to senior management.

Building on current practices, existing mishap table-tops and large-scale simulations should be redesigned to go beyond jurisdictional awareness or nominal “big event” rehearsals. Future exercises should specifically stress-test integrated anomaly resolution under realistic, time-critical conditions and include both leadership and technical participants across NASA and Boeing. To ensure readiness, attendance at these simulations should be mandatory for leadership and key decision-makers from both organizations, avoiding gaps where either NASA or Boeing is absent from critical rehearsal opportunities.

These sessions should explicitly address cultural alignment including open data sharing, engagement of technical authorities and SMEs, NASA/provider decision sequencing, and consensus-building, so that expectations are clearly set before launch. Pre-mission planning should also include team-building opportunities and kick-off sessions to align roles, goals, and expectations.

R.27 [CCP, ISSP] - Provide regular training for program management teams, direct reports, and stakeholder members, regarding strategies for risk-based decision making including the use of 7 Elements of Flight Rationale, Risk Scoring processes and Cumulative Risk balancing strategies, to ensure the team maintains a baseline understanding to prevent skewed understanding even with changeover from team members. Include providers. Include any differences for applying techniques pre-flight vs. in-flight. Determine appropriate interval for refreshers (i.e., yearly).

R.28 [CCP] - Implement STAR action for Burden of Proof (A-25) "Provide guidance to program team (NASA and Providers), on verification evaluations should be considered with a "prove it's safe" mindset.

R.29 [AA] - For current and future programs, NASA should ensure that resources are sized to the oversight/insight burden required to meet the risk acceptance posture the Agency has chosen for that acquisition and number of providers in flow. This should be reassessed if additional providers are added. Depth of penetration into qualification test and analysis are a direct correlation to risk assumption with a provider.

Process (Data Management)

Observation 1: There was insufficient access to system design details, as well as performance, qualification, and test data for in-flight anomaly resolution.

Interview data corroborated the lessons learned outlined in the STAR report indicating difficulty in obtaining technical data, test data, access to subcontractor experts, and data from Boeing team members in large part influenced by the contract structure between NASA and Boeing and the contract relationship between Boeing and its subcontractors limiting direct access by NASA to both personnel and data. This issue accessing data existed well before the CFT mission and was magnified by the pressures of resolving a major inflight anomaly.

NASA engineers often felt the contract structure caused Boeing and subcontractors to deliver to the letter of the contract and hence, restrict open and honest conversations. Additionally, there was often noted an apparent reluctance on the part of Boeing or Boeing subcontractors to share information with the NASA team due to perceived contract obligations or data sharing agreements. This reluctance to share data made it very difficult to foster a sense of "one team" to address the challenging flight anomalies and increased mistrust between NASA and Boeing.

Boeing's relationship with subcontractors through contract arrangements did not provide for subcontractor real-time support during the CFT mission. The relationship with subcontractors through contract structure placed detailed design and qualification data and knowledge with the subcontractor such that Boeing engineer knowledge was relegated to how the systems integrated with the Starliner vehicle. During the initial anomaly resolution process several interviewees noted a lack of Boeing detailed knowledge of SM RCS design, qual, and performance made the anomaly resolution process inefficient, delayed decision making, and increased the sense of mistrust.

Observation 2: NASA was overprotective of information and gatekept the information.
An artifact of how Insight is setup and implemented between NASA and Boeing is that a few NASA employees are seen as "gatekeepers" of information that is provided by Boeing as part of contractual Insight. This does not accommodate the need for data access required during a major anomaly resolution.

Observation 3: Stakeholders faced challenges accessing both archived and ongoing data, including but not limited to meeting agendas/minutes/actions, test results, vehicle schematics, etc, which were critical to the decision-making process because there was a lack of a central repository of information.

It was difficult to access critical data in a timely manner. There were multiple layers of difficulty for decision makers to find the right data. Due to the difficulty, people tended to reach out to experts closer to the issue instead of digging through SharePoint lists. This pulled experts away from other urgent tasks, especially as experts were trying to understand the anomalies and the next steps.

Observation 4: Throughout development and during the flight, NASA engineering attempted to engage Boeing regarding problems and items encountered by SpaceX but were limited in discussions because of proprietary information concerns.

Process (Data Management) Recommendations:

R.33 [OP] - Evaluate contract structures for services contracts to determine level of NASA insight/oversight, expected overall participation in design decisions and reviews throughout project lifecycle, and expected support for real time operations and anomaly resolution. Specifically:

Require contract structures chosen for commercial services to have and determine NASA expectations for quick and ready access to subcontractor design experts at all stages of system design and especially to aide in efficient anomaly resolution.

Evaluate contract structures and shared accountability implementation with providers to determine what level of insight/oversight NASA needs during the design phase, test flight phase and into operational phases.

Ensure contract structure enables subcontractors to provide insight during missions for anomaly resolution. Else, accept the risk that the data is not accessible.

R.31 [OP] - Ensure that future contracts include provisions for integrated anomaly resolution planning, including expectations for transparency and data sharing.

R.32 [CCP] - Establish a central repository of information for use during missions to enable quick access to data critical to near-real time decision making. Update repository using modern tools to improve searchability to quickly locate the data.

R.33 [AA] – Re-evaluate a data sharing infrastructure with the stakeholder community. This should include/ensure a clear and efficient access to information during a mission. Along with data sharing expectations and protocols across teams, along with decisions on which teams and roles need access to information. NASA needs a mechanism to enable sharing data across providers and programs in critical situations. Assign a role that is responsible for ensuring communication and information is coordinated and integrated across teams during missions. Include a dedicated annual meeting topic or training about insight into provider information and where to find information. Ultimately, this is to ensure that a proper infrastructure and central repository is in place when responding to an anomaly resolution process. This central repository should be accessible to all stakeholders with a need-to-know.

R.34 [OCE, CKO] - Establish a NASA facilitated Lessons Learned Conference to allow providers to come forward and share lessons learned on their own accord to facilitate success of United States human spaceflight.

NASA should facilitate a conference to encourage sharing of information for potential or known issues/anomalies/experiences that may be common across providers. This would be the providers sharing the information that they deem valuable/credible/worthwhile of their own accord. NASA would host the conference but would not be presenting. NASA would keep and track to inform future providers. NASA should seek to alleviate proprietary information concerns regarding systemic issues across multiple vehicle providers. The barrier to entry would be those providers who are on contract with NASA.

5.2.2 Authority

Throughout the interviews, an emergent theme was confusion over programmatic authority, technical authority, and decision-making structures. The SMMT, led by Boeing, was responsible for evaluating the readiness of the vehicle and making recommendations to the IMMT. However, the IMMT held final authority for joint operations. This led to confusion as the roles and responsibilities within the SMMT were not well understood by many team members. A lack of clarity led to frustration and inefficiencies, particularly during the anomaly resolution process.

The SMMT structure, while documented and practiced in simulations, failed to scale effectively during the propulsion system anomalies. Interviewees noted that the process broke down under the weight of real-time demands and high-consequence decisions. This led to a prevailing negative sentiment and the presence of multiple layers of upper management in meetings further muddled the chain of command. As one interviewee put it, "Who's in charge here?" became a recurring and rhetorical question.

Additionally, the perception that certain groups (i.e., the technical authorities and FOD) had disproportionate influence because during polling they "go together as a group" highlighted a disconnect in how technical authority was exercised and perceived. While the MMT and PCB processes are not designed to be democratic, the desire for consensus was strong, and the lack of it contributed to lingering frustration.

Ultimately, interviews revealed that the repeated question "Who's in charge here?" alongside confusion of roles and responsibilities created challenges throughout the anomaly resolution process. This is explored further in the provided observations below.

Authority Observations:

Observation 1: The implementation of programmatic decision-making authority resulted in confusion during the CFT mission. The confusion stemmed from conflicting guidance documentation, inconsistent practices, and unanticipated gaps in how operational scenarios applied the guidance.

During this investigation, the PIT reviewed mission management documentation from CCP, ISSP, Boeing, and for greater context and contrast, documentation from SpaceX. This review included an examination of program-level governing documents, provider-required deliverables, and Starliner and Joint/ISS flight rules. These materials revealed multiple instances where the interpretation of decisional authority during the CFT mission appeared confusing or conflicting, both from a CFT and overall mission authority perspective. Throughout the interview process, multiple individuals expressed their frustration with determining when and who to bring their concerns to so their concerns would be properly represented and addressed by NASA. There was also confusion as to who in the NASA authority structure was ultimately going to make decisions on the vehicle's viability to return the crew.

As previously noted regarding the design and certification of commercially provided spacecraft under CCP, NASA delegated operational responsibilities to its commercial providers.

CCT-PLN-2100 Rev C, the **CCP Mission Implementation Plan (MIP)**, explicitly states:

> "The commercial providers are responsible for conducting their own respective MMT Meetings: The Starliner MMT, chaired by Boeing, and the Dragon MMT, chaired by SpaceX. These commercial Provider MMTs are the CCP's decision-making bodies responsible for programmatic, safety, and risk-based decisions associated with launch countdown and major in-flight activities."

Appendix E of the MIP reinforces this by stating:

> "The Commercial Providers are responsible for the identification and resolution of any IFA (In-Flight Anomaly)."

Boeing's **Commercial Crew Transportation System (CCTS) Mission Integration and Operations Management Plan (MIOMP)**, DCC1-00974-01 Rev E, reflects this philosophy. The CCTS MIOMP designates the Starliner Mission Management Team (SMMT) as an adjunct to the CCTS Program Control Board, chaired by the Starliner Mission Director (SMD). The SMD holds responsibility and authority for near real-time decisions when the flight control team determines that operating outside the FRR-approved CST-100 mission plans and constraints is necessary. These constraints are defined by certification limits and operational documentation, including Launch Commit Criteria (LCC), Flight Rules (FRs), and procedures.

Alongside the MIOMP, Boeing's **CCTS Mission Anomaly Resolution Plan**, DCC1-01314-01 Rev D, [redacted]

[redacted]

Similarly, the **CCP MIP** affirms that only the NOM has the authority to accept additional risk to the crew, vehicle, or mission. The NOM is also the sole NASA voting member of the SMMT and DMMT and is responsible for integrating inputs from other CCP program elements, including the Chief Engineer, Chief Safety Officer, Chief Medical Officer, Flight Operations Director, and, when applicable, the ISS Program, through the CCP MMT.

Regarding ISSP, the MIP states that the ISS Program Manager or delegate, typically the IMMT Chair:

> "Provides GO/NO GO to the NOM for increased ISS and ISS crew risk acceptance and/or identifies decisions that need to be reviewed by the IMMT for risk acceptance. Provides insight into ISSP readiness and ISS impacts associated with the CCTS anomalies or mission changes."

In the event of a potential "Integrated Anomaly," the **CCP Mission Anomaly Resolution Plan** directs Boeing's Mission Support Room (MSR) Manager to notify the ISS MER Manager, who then determines whether to convene an anomaly team.

However, the **CCP Mission Management Team Charter** (CCT-P-4005 Rev A) and associated flight rules further complicate the picture. The charter delegates that:

> "The CCP MMT is the approval authority of technical program decisions during real-time mission operations for changes to the established mission risk posture, certification limits, rules, procedures and flight plans, certified by CCP and authorized by NASA at the AFRR."

Meanwhile, the CCP MMT, per the CCP MIP, is chaired by the NOM and includes the NASA Recovery Director (landing only), Launch Rescue Director (launch only), Flight Operations Director, Chief Medical Officer, CCP Chief Engineer, Chief Safety Officer, and Mission Manager. Furthermore, the CCP MIP states:

> "CCP conducts an MMT responsible for providing the NASA CCP GO/NO GO decisions during the ISS and Commercial Provider MMT polls for all phases of flight."

The Boeing MIOMP states:

> [redacted]."

From a flight rule perspective, Flight Rule J1-22 and its associated rationale showcase the agreed-to authority structure of the integrated mission management teams:

> **FLIGHT RULE J1-22** **MISSION MANAGEMENT TEAM AUTHORITY [CST]** ®[DN 102]
>
> A. THE ISS MISSION MANAGEMENT TEAM (IMMT) IS RESPONSIBLE FOR POLICY DECISIONS AND WILL BE CONSULTED AS SOON AS POSSIBLE WHENEVER INTEGRATED OPERATIONS OUTSIDE THE FLIGHT RULES ARE REQUIRED.
>
> *Reference Rule {B1-4}, ISS MISSION MANAGEMENT TEAM (IMMT) AUTHORITY.*

B. THE STARLINER MISSION MANAGEMENT TEAM (SMMT) IS RESPONSIBLE FOR CST-100 POLICY DECISIONS AND WILL BE CONSULTED AS SOON AS POSSIBLE WHENEVER STARLINER OPERATIONS OUTSIDE THE FLIGHT RULES ARE REQUIRED.

Reference Rule {I1-54}, MISSION MANAGEMENT TEAM (MMT) AUTHORITY.

C. THE CST-100 STARLINER MISSION MANAGEMENT (SMMT) REPRESENTATIVE WILL SUPPORT THE ISS MISSION MANAGEMENT TEAM (IMMT) WHEN REQUIRED AND PROVIDE ALL NECESSARY CST-100 RELATED INPUTS AND RECOMMENDATIONS TO THE IMMT. ®[DN 102]

Once the spacecraft receives Authority to Proceed into the ISS Approach Ellipsoid from the IMMT, the IMMT oversees integrated operations, including ISS docked operations, rendezvous/proximity operations, docking, undocking/separation, and communications between vehicles during proximity operations and the docked timeframe. During this time, the IMMT is responsible for near real-time decisions when the flight control team identifies that operating outside pre-approved ISS and/or CST-100 mission constraints including, flight rules and procedures, is required. Any issue requiring IMMT attention will be closely integrated with the SMMT, as time allows.

The SMMT will conduct a Critical Events Readiness Review prior to the IMMT for dynamic events such as entering Approach Ellipsoid, port relocation, and undocking to assess readiness for the event, as time allows. Additional specialists may be called in to support these meetings. The SMMT chair will provide the Go/No Go response when polled at the IMMT. The SMMT will meet as necessary to address any CST-100 or relevant ISS anomalies to determine course of action in accordance with responsibilities described above. In addition, as part of the undocking review, the SMMT will conduct a review on all decisions involving deorbit, landing, and recovery operations.

This is reinforced by the delegated real-time operational authority to the ISS Flight Director:

FLIGHT RULE J1-4:

DURING ISS/CST-100 INTEGRATED OPERATIONS, STATION FLIGHT HAS OVERALL RESPONSIBILITY FOR ISS/CST-100 CREW AND VEHICLE SAFETY. STATION FLIGHT IS ULTIMATELY RESPONSIBLE FOR ALL SAFETY CRITICAL CST-100 GO/NO GO CALLS.

While the MIP states:

> "Based on the phase of flight, the mission authority transitions between the ISS MMT and the Commercial Provider MMT as defined in the joint Flight Rules."

it similarly notes:

> "Any decisions regarding Commercial Provider CTS/crew operations that exceed the risk baseline established at the Flight Readiness Review (FRR) and defined by the Flight Rules and operational procedures must be approved by the NOM."

Subsequently, the governance of a provider led MMT was not universally understood by the whole stakeholder community prior to the mission. This led to confusion about the role and authority of the NOM and the overall anomaly process. CCP NASA participants had many flight experiences with SpaceX cargo and crew missions, and though CFT is a CCP mission, the MMT structure for Boeing is somewhat different than the MMT structure for SpaceX. While it is documented in CCP files, this distinction was confusing for many of the participants outside of CCP, especially participants pulled in during the mission timeframe without deep Boeing Starliner experience leading up to the mission.

Ultimately, NASA leadership made a formal decision on whether to return the CFT vehicle crewed or uncrewed—a decision widely regarded as appropriate, and that decision was made at a NASA CCP PCB and went forward to a NASA governed and chaired Agency Flight Test Readiness Review.

However, even without addressing how technical organizations such as Engineering, SMA, HHP, and FOD contributed to that decision, the referenced documents clearly demonstrate the potential for misunderstanding who holds decisional authority in such scenarios. The roles of the SMD, NOM, CCP Program Manager (via the PCB), and IMMT each appear to carry definitive authority depending on the document referenced. This overlap creates a high potential for confusion or conflicting conclusions and is supported by the interview data.

Observation 2: Participation of upper management clouded the chain of command and created confusion as to who was responsible within respective technical areas and the confusion was a distracting misuse of resources.

The attendance of the senior leaders at SMMTs and PCBs was driven by the desire to have access to direct information relevant to potentially contentious decisions and the decision-making process. Having multiple levels of authority from each technical area participating in SMMTs and PCBs was inefficient and made it unclear who was representing the stakeholder organizations in the meetings. In some cases, participation at the agency level triggered other layers of management to feel compelled to participate, increasing the negative effects of having multiple levels of authority present. Most interview data did not find that these extra participants negatively impacted the technical discussions, but extra participants did weaken the perception of authority of the SMMT, PCB, and their associated representatives. It is important to note, it also tied up agency resources for multi-hour meetings.

Observation 3: There was insufficient understanding of and a lack of agreement related to how to embrace the Technical Authority (TA) role.

NASA established the Technical Authority (TA) process as part of its system of checks and balances to provide independent oversight of programs and projects in support of safety and mission success. The TA construct is central to NASA's governance, providing checks and balances that ensure independent oversight of programs and projects.

The TA role, established in response to the Columbia Accident Investigation Board (CAIB) recommendations in a manner consistent with NASA's existing organizational constructs, is intended to guarantee that the distinct perspectives of NASA's independent engineering, safety, and medical institutions are integrated into programmatic decision-making, and that the opportunity to formally dissent is afforded to team members and adjudicated at the appropriate level.

The TA process was successfully demonstrated during the CFT mission since engineering, safety, and medical were able to provide an independent perspective and concerns, as well as having their respective recommendations considered. While the purpose and value of TA were fully exhibited and appreciated by many, confusion and misperceptions related to TA or questioning of the role TA plays were also noted by some interviewees.

When individuals are unaware of the TA process, untrained in the implementation of the process, or do not fully embrace the TA roles and responsibilities, it creates confusion and misunderstandings.

As misunderstandings arise it can erode trust between NASA organizations, as well as with commercial partners and create unnecessary tension in the decision-making process. Boeing and some NASA participants demonstrated limited understanding of the role of the TA in mission operations, including when and how it would be applied. This contributed to friction when decisions elevated to senior NASA leadership were viewed by others as overrides or intrusions into programmatic authority, rather than as appropriate execution of the responsibility NASA has formally delegated to the TAs for crew safety and mission assurance.

Formal training has been created and is available to address this gap. NASA's SATERN course, "Empowering Technical Authority & Embracing Formal Dissent" (SMA-OV-WBT-136), was developed to provide employees with a baseline understanding of Technical Authority, its origin, the distinctions between programmatic and technical authorities, and the role of formal dissent in ensuring safety and mission success. The absence of consistent understanding across participating groups suggests a missed opportunity to establish a shared understanding of TA expectations, escalation paths, and responsibilities across both NASA and Boeing teams.

Authority Recommendations

R.35 [SOMD, CCP, ISSP] - Implement a unified programmatic decision authority framework, and flow for escalation, for making near-real-time mission related decisions, accommodating:

Nominal mission execution where the provider retains responsibility for executing mission activities, including leading and coordinating anomaly resolution activities, with integrated NASA participation.

When deemed appropriate by NASA or when NASA crew and NASA assets are deemed above the baseline risk accepted by NASA at the FRR, NASA shall assume leadership of MMT and any or all anomaly resolution activities, with integrated provider participation.

Unified decisional authority and mission management that integrates NASA Commercial Crew Program and NASA International Space Station program mission management authority and execution structures.

R.36 [CCP] - Develop and document specific guidelines for how a provider MMT must respond to NOM non-concurrence, and similarly process for how NOM should adjudicate non-concurrence/formal dissent from CCP MMT.

R.37 [CCP] - Formalize policy for how NOM is to include or not include inputs from CCP offices and support organizations in readiness for SMMTs.

R.38 [CCP] - Create consistency between provider implementations (e.g. NOM CCP MMT polling during provider MMT) of program deliverables.

R.39 [CCP, ISSP] - Update CCP, ISSP, and provider documents and FRs to ensure consistency and clarity with programmatic decision authority for near-real-time mission related decisions.

R.40 [CCP, ISSP] - Create mission specific refresher information to be reviewed by programs and their support organizations just prior to flight, highlighting any residual nuances or differences in the implementation of near-real-time operations.

R.41 [CCP, ISSP] - Ensure clarity during mission management meetings including who has delegated authority to represent the position of various stakeholder organizations, irrespective of more senior leaders being in attendance or asking questions.

R.42 [CCP, ISSP] - Implement targeted briefings and training sessions for NASA and provider team members on NASA's TA process, expectations, and escalation paths as part of pre-mission preparation.

R.43 [CCP] - All updates need to be broadly communicated via mandatory training for team members.

R.44 [All HSF] - Evaluate MMT report structures through all mission phases, giving consideration to the multi-program/multi-MMT construct and decision making, mission execution responsibility, and NASA authority to ensure NASA is operating programmatically unified, even to the potential extent of a NASA Mission Directorate led and integrated activity, and verify all multi-program documentation supports the same authority structure and concept.

5.2.3 Leadership

Another recurring theme emergent within interviews was challenges with leadership. Interviewees viewed the direct Starliner operational leadership (NASA and Boeing) as obstinate and too ready to accept risk without hearing or seeking alternate inputs. Many interviewees also felt that CCP Program Management failed to facilitate disagreements effectively, allowing them to impede progress. There was a perception of bias toward Boeing, with some NASA teams observing their inputs being dismissed. Examples included CCP management expressing views before NASA technical teams could contribute, Boeing minimizing concerns, and NASA's voice being diluted in meetings. While these themes relate to leadership, additional aspects are further explored in the "Trust" section.

Additionally, interviewees consistently expressed a desire for stronger guidance from the Space Operations Mission Directorate (SOMD) level of leadership, particularly in relation to managing inter-organizational dynamics and enforcing a unified approach to mission governance. The overall lack of unified leadership (within CCP, CCP/ISSP, Programs to SOMD, etc.) contributed to a fragmented decision-making environment.

Leadership Observations:

Observation 1: A posture of risk acceptance was communicated by CCP and Boeing leadership, creating division within the large working/joint team and eroded trust.

During the mission, CCP and Boeing operational leadership consistently conveyed a position of risk acceptance and readiness to undock, which many perceived as premature and dismissive of unresolved technical concerns. This was particularly apparent regarding the Service Module RCS thruster anomalies. This posture gave the impression that completing the sortie mission was prioritized over a thorough assessment of crew safety risks.

One interviewee noted, "People said, 'Why bother? He's driving in one direction and that's what he wants.'"

Some interviewees also mentioned the shuttle operational background of the SMMT Chair, NOM, and CCP PM, and the possible preconceived notion that accepting risk to return the vehicle and crew was the only real path forward. This mirrors decisions made for the shuttle when no safe haven in LEO or alternative return capability was available.

This forward leaning approach led to a breakdown in open dialogue. NASA institutional stakeholders, including ISSP, FOD, and Technical Authorities, felt their input was undervalued or ignored, requiring governance intervention to ensure additional data analysis occurred before a final crew return decision. The perception that CCP leadership had formed a position before hearing all viewpoints created organizational silence, resistance to collaboration, and stagnation in decision-making.

Strong personalities within CCP and Boeing were seen as overly optimistic in presenting data, which some interviewees interpreted as lobbying rather than objective analysis. This dynamic discouraged dissenting views and contributed to a growing sense of distrust. As one interviewee described, opposing positions felt like "pushing a rock uphill."

The situation improved later in the mission when key personnel changes were made within the Boeing team and there was collective recognition that senior leadership should have played a more active role in facilitating respectful engagement across differing perspectives. These changes allowed for more productive conversations regarding the technical qualification campaign of the hardware and testing at the WSTF. The lack of early intervention to address team dysfunction allowed conflict to overshadow mission objectives and delayed consensus on critical decisions.

Observation 2: Early, continual undock planning by the SMMT chair at the beginning of the mission distracted from anomaly resolution. The continual undock planning added pressure to proceed in nominal undock during a major anomaly resolution process. This further divided the team into factions and drove premature discussions regarding risk acceptance and preparation for return.

Many interviewees felt this tactic was an extension of the pre-flight Boeing pattern to plan for launch in an unrealistic timeframe, driving decisions centered around the date for the dynamic event, rather than technical readiness to proceed.

Observation 3: SOMD Leadership did not identify the need for a coordinated, multi-program solution space. The team needed to define time constraints for problem-solving, link impacts across both programs, and evaluate options in terms of their relevance to Starliner alone or across multiple providers.

This observation is an additional portion to O.4 in the Process section and O.1 in the Authority section, which emphasize the need for an overarching process to be triggered by and govern multi-program anomalies. Multiple interviewees mentioned a need for stronger guidance from SOMD.

Specifically, some interviews highlighted that SOMD leadership was reactive rather than proactive, did not appear to help manage inter-organizational dynamics, and did not enforce a unified approach to mission governance.

Observation 4: Interviews identified a need for Program Managers to directly communicate more effectively and/or more visibly with each other to provide clear and unified direction to their teams.

Team members felt singularly responsible for integrating the program managers and putting together a unified direction for how to proceed. A healthy tension and a healthy working relationship existed between most CCP and ISSP direct counterparts.

Despite tensions, ISSP and CCP successfully coordinated on critical operational aspects, such as:

- Extending Starliner's stay on station
- Conducting on-orbit thruster testing
- Planning for alternate crew return options (e.g., via SpaceX)

These actions demonstrated functional integration, even amid cultural and structural challenges including not understanding if the program managers were "on the same page" or even talking about the options and overall consequences for both programs.

Observation 5: Ineffective communication styles, including times of unprofessional behavior and language, culminated in dysfunctional team dynamics.

Although ineffective communication was not observed in every meeting, there were enough instances of frustrating and/or unprofessional communication styles being exhibited and tolerated as part of the culture of decision making that multiple interviewees brought the subject up without prompting. Numerous interviewees mentioned defensive, unhealthy, contentious meetings during technical disagreements early in the mission. The recommendations for conducting more productive meetings and that support structure can be found in the process section. This is included here to specifically reflect leadership challenges and to provide a picture of the cultural environment for which the mission was being conducted.

Individual interviews reported instances such as:

- "There was yelling in meetings. It was emotionally charged and unproductive."
- "I stopped speaking up because I knew I would be dismissed."
- "If you weren't aligned with the desired outcome, your input was filtered out or dismissed."
- "I heard them berate the safety engineers off muted mics."
- "It was probably the ugliest environment that I've been in."
- "We were told our questions were inappropriate. But there was no other forum to ask them."
- "It's not an environment that is inviting to dissenting opinions."
- "There are some people that just don't like each other very much, and that really manifested itself during CFT."

- "[…] they treat me as a joke."
- "There wasn't a clear path for conflict resolution between the teams. That led to a lot of frayed relationships and emotions."

Observation 6: Ineffective meeting practices reduced team productivity and overall performance. This led to unclear direction and increased stress that could have been more effectively controlled and managed by the leadership team.

The previous process section addresses several observations and recommendations for updating the meeting structure and meeting practices to support information adjudication and decision velocity. This observation is included in the leadership section to denote a missed opportunity for the leadership team. Interviewees referred to the working pace as unreasonable and unrealistic in trying to find a solution. The sheer volume of meetings and lack of downtime was cited as a major issue for both technical teams and leaders alike. There did not seem to be an effort to protect the team from burnout.

An interviewee noted, "Somebody should have stepped in and said, 'Hey, we are not making progress here. We're keeping people until 10:00 at night and expecting them back at 6:00 a.m.' That is unreasonable." However, it was mentioned in several interviews that CCP SCO daily notes helped improve communication and direction.

Observation 7: Workforce frustrations remain regarding perceived insufficient leadership accountability, post-mission.

Following the mission, many interviewees perceived a lack of accountability among senior leaders, noting a greater emphasis on managing public perception instead of acknowledging and addressing the mission's significant failures. Rather than demonstrating ownership of the issues, leaders were perceived as deflecting responsibility, which undermined trust within the workforce and among key stakeholders.

Although this section focuses on near-real-time decision-making during the docked phase, numerous interviewees reflected on broader concerns regarding leadership's response to the mission's challenges. They expressed disappointment that NASA leadership had not adequately acknowledged their roles in the mission's shortcomings or taken steps to address how mission preparation and execution could have been improved.

Demonstrating responsibility for decisions and outcomes—particularly in high-pressure, technically complex environments—is essential to fostering trust, credibility, and resilience within teams.

One interviewee captured this sentiment, stating:

"NASA wasn't blaming Boeing, but everybody else was. […] You know, it's our program. We're responsible too. Nobody said that. And nobody within NASA [or outside of NASA] has been held accountable. Nobody. We're 11 months after it happened, and there's been no accountability at all, from any organization."

To uphold the standards of leadership expected in government and spaceflight operations, it is imperative that senior leaders visibly and consistently model accountability, especially in the aftermath of mission-critical events.

Leadership Recommendations:

R.45 [SOMD] - Speak openly to the joint team about leadership accountability, the results of CFT and the path to build in accountability in order to move forward – which can include but not be limited to, concurrence with this report and reclassifying as a Mishap (see R.61)

R.46 [CCP, Boeing] - Conduct a leadership-led stand down day focused on reflection on the CFT mission, address concerns raised regarding leadership accountability and to primarily focus on building trust across the workforce and moving forward by reframing the open work and objectives.

<u>Key components should include:</u>

- **Lessons Learned update,** including specific plans and assignment for what needs to be finalized and implemented prior to the next flight of Starliner.
- **STAR/SDRT update,** including specific plans and assignment for what needs to be finalized and implemented prior to the next flight of Starliner.
- **Trust and team building recommendations** from the Trust section below.
- **Interactive forums** for workforce members to ask questions about the mission, relationship with the provider and NASA, long term plans for the spacecraft and an open time to engage in dialogue with the leadership.
- **Path forward briefing** including hardware corrective actions, cultural initiatives and governance changes being implemented to ensure improved performance going forward.

Include technical support organizations, ISS, SOMD, flight crew, etc. as much as possible, to reach the key stakeholders for mission prep and execution activities.

R.47 [CCP] - Cultivate a respectful and transparent CCP team culture including direct reports and additional support organizations. Use recommendations in trust, process and authority sections to show progress.

This does not mean everyone must agree on programmatic decisions, rather it means that differing opinions can be heard without being dismissed and recommendations considered without having to fight for appropriate review.

Implement a leadership development plan that outlines steps in continuously developing leadership skills. Include strategies that encourages opposing inputs to be heard without fear of dismissal, including a balanced style that continues to motivate the team towards progress while also being willing to take recommendations**.** This recommendation is paired with the process and authority recommendations to create boundaries for solving complex problems. This could include, but not limited to, obtaining an executive coach to ensure continued improvement in growing leading people skills.

R.48 [ISSP,CCP] - Model openly collaborative program to program information exchange between leadership teams including being deliberate to communicate when programs agree or disagree on an approach or issue and provide unified direction for problem solving.

R.49 [CPMO] - Utilizing NASA assets and resources for facilitated discussions, hold a Program Managers forum to communicate program manager lessons learned. Including creating a once per year recurring discussion format to speak across programs about technical and non-technical issues and share perspective for problem solving and managing risk. This should include (but not limited to) specific identification of how to incorporate LEO/non-LEO lessons learned, differences in mission phases and parameters around accepting differing levels of risk (ascent/entry different than in-orbit operations; LEO different than Lunar Surface, etc).

5.2.4 Trust

The mission timeframe became the magnifier of trust and culture issues that had fractured over time. A lack of trust became a defining characteristic of the CFT mission, with interviewees citing unprofessional conflict and conduct, heightened friction, and reduced collaboration. These challenges have been longstanding, originating during the development phase and earlier test flights and persisting into the crewed mission.

Integration proved especially difficult between certain teams. Trust issues were evident between CCP and Technical Authority teams, between NASA Technical Authority teams and Boeing, and the appearance of mistrust between CCP and ISS leadership. While some relationships improved over time, many remained strained throughout the mission and persist currently.

The breakdown in trust and confidence stemmed from a complex interplay of direct causes and indirect influences that also addressed in other observations throughout the report. This includes factors such as poor management of technical disagreements, inadequate data transparency, and confusion around roles and team integration.

Other key issues identified through the interviews to have affected team trust included:

1. Lack of confidence in Boeing's past performance
2. Evolving expectations from NASA
3. Perception of personal relationships/favoritism
4. Concerns over selective information sharing
5. Notable trust deficits emerged between certain stakeholder groups.

Trust Observations

Observation 1: Lack of trust in Boeing's past performance made it difficult to accept engineering judgment and increased the need for qualified data to accept risk

Interviewees recognized that there was a perceived bias from many on the NASA team of mistrust towards Boeing due to past performance and decisions. Not only had the team just encountered the helium system leak in prelaunch, but leaks continued to emerge and change through the mission. Additionally, during the prelaunch timeframe there was robust discussion regarding lack of fault tolerance for deorbit burn capability that was missed through the design and development process. This was coupled with observations from team members that had worked this program with Boeing for many years and seen exceptions and variances come through on systems such as the fault tolerance on the Crew Module RCS (VR-01). Interviewees recognized that these issues and the contentious conversations around them created a lack of trust during the mission**.** Interviewees and team members commented that concerns persist, post-mission.

Observation 2: Boeing believed expectations from NASA were constantly and unrealistically evolving.

Boeing team members expressed receiving significant pushback from NASA. Interviewees felt they were bringing NASA the "wrong rock" or getting stuck in a "gotcha" moment.

An interviewee described, "Felt like not openly sharing concerns and waiting until big meeting. Felt like we kept getting stuck in gotcha moment- we'd just wait to get to the MMT and get it. Felt also like some people made up their mind very early. Felt it from both sides. Helped to work with Flight Directors who are good at communication."

Another stated, "There were elements of the NASA community trying to solve the problem, but a larger majority it was adversarial. We'd bring a rock; they'd break the rock. It wasn't NASA bringing solutions to the problem. It was an endless game of playing gotcha."

Boeing felt they had solid flight rationale but believed that the NASA teams continued to probe for more information and changing requirements. This created a perception that teams had already made up their minds early on and resulted in the polarization of teams. Once it was finally time to decide to bring back the vehicle crewed or uncrewed, Boeing felt the decision had been made without them.

Observation 3: There was a perception that personal relationships had a negative impact on professional and/or engineering technical judgment (former shuttle colleagues; former Flight Directors; etc).

Governance structures alone are insufficient if personal dynamics undermine trust and transparency. Many that work on the Starliner on both the Boeing and NASA teams have worked together for many years on the Starliner and other NASA programs, specifically Space Shuttle Program and Human Exploration programs. The amount of overlap between the teams can be touted as a positive, in that teams should already be bonded over previous successes, failures, and understanding of expertise and capabilities is also well understood.

However, these relationships were also seen as pitfalls in decision making, with many viewing CCP program management and Boeing management as blurring boundaries. This led to the appearance of lack of objectivity, difficulty in managing conflict, and the appearance of favoritism. Even if the perceptions are not correct, they exist and are rampant in hallway conversations and outside of board discussions.

Numerous interviews indicated that CCP and Boeing had historical relationships that led to private conversations that the rest of the team was not privy to, leading to decreased trust and increased frustration. An interviewee explained, "You're talking decades-long history with folks that [...] muddied authority and roles and responsibilities. I think friendships might have gotten in the way."

Observation 4: Lack of access to data led to concerns over the possibility of selective information sharing.

Access to data was a frustrating point for many interviewees. While there was also a notion of the existence of little or limited data to utilize. Some stakeholder communities believed that data was being withheld from their teams or from the decision makers to "cherry pick" a recommendation or avoid deeply technical conversations in the larger forum. Specifically, there was a perception that information was either filtered, selectively chosen, or sanitized for the purpose of manipulating and interpreting the outcome which eroded confidence in the vehicle, process, and people.

Some identified that Boeing's engineering team presented only favorable data, withheld dissenting views, or minimized risks. Boeing was operating under the belief that NASA was either too risk-averse to handle full transparency or did not understand the systems well enough to appreciate the risk trades required for decision making.

NASA engineers reported being told their questions were "too detailed" or "out of scope," with no follow-up mechanisms to ensure those concerns were addressed.

Many interviews noted inconsistency in how information and data was presented in meetings and shared across teams. This included lacking insight into meeting notes and decisions, as well as accessing data and information outside of meetings to enable teams. There did not appear to be an aligned approach or process for team members to access adequate information critical to decision making. This disconnect evolved into a perception that information was presented in a way that was biased toward the agenda/objective to bring the crew back in the Starliner vehicle vs letting the data speak for itself or being presented with the entirety of the issue.

Observation 5: Notable trust deficits emerged between the CCP team and various Technical Authorities.

These were cited between CCP and various Technical Authority teams, as well as between NASA's Technical Authority and Boeing. Additionally, there was a perceived lack of alignment and mutual confidence between CCP and the ISS leadership. Although some interpersonal and organizational relationships showed gradual improvement over the course of the mission, many remained tense and unresolved. These strained dynamics not only complicated collaboration during critical phases of the mission but continue to influence inter-team interactions to this day.

Trust Recommendations

R.50 [CCP] - Establish and immediately implement a strategy to repair trust and strengthen partnerships through clear expectations, open accountability, and facilitated team-building sessions. Led by CCP, the plan should begin with leadership and expand to all team members to restore confidence, address past issues, and align on shared values of safety and mission success. (Sample plan in App. E)

These sessions should explicitly address cultural alignment on important topics including open data sharing, engagement of technical authorities and SMEs, NASA and provider decision sequencing, and consensus-building. This ensures expectations are clearly set before launch. MMT-specific simulations should be added to ensure senior-level management forums are fully prepared and organized. Pre-mission planning should also include team-building opportunities and kick-off sessions to align roles, goals, and expectations. To mitigate stress and fatigue impacts, leadership should conduct regular "pulse checks," rotate high-pressure responsibilities, and ensure contingency staffing to provide fresh perspectives. Protecting time for deep work and proactively addressing burnout will also improve decision-making effectiveness under mission conditions. See Appendix E for sample plan.

R.51 [CCP, Boeing, Support Orgs] - Team leadership to rectify and repair trust across teams

Openly discuss the perception how leadership personal relationships could have caused team members to question leadership's judgement and effectiveness during the mission. This should include steps forward to repair this perception, to rebuild trust across the teams. Examples: NASA and Boeing, CCP and TAs and FOD, ISSP and CCP, Boeing and NASA TAs, etc.

R.52 [CCP] - Establish and ensure alignment of leadership and teaming expectations around transparency, risk acceptance, and engineering rigor.

R.53 [CCP] - Outline how information, processes, and data will be presented, discussed, debated among technical teams to ensure meetings and presentations uphold credibility standards and requirements/metrics to make decisions.

6 Root Causes

It is important to establish a shared definition of root cause to understand how the Starliner PIT team has determined the root causes presented in this section. The PIT team utilized the following definition:

Root Cause: An event or condition, primarily associated with organizational factors, which existed before the intermediate cause and directly resulted in its occurrence (indirectly caused or contributed to the proximate cause and subsequent undesired outcome) and, if eliminated or modified, would have prevented the intermediate cause from occurring and the undesired outcome. Typically, multiple causes contribute to an undesired outcome. In the absence of a prevalent organizational factor, the root cause may be identified as undetermined.

These root causes are derived from considerate review of the summation of all previously discussed proximate, intermediate, organizational and observational causes and factors. While the technical concerns are rooted in data and analysis, the organizational factors and observations are often generated from interviews, documentation, meeting attendance, minutes reviews, listening to meeting recordings and group discussions. Responses from interviews will have inherent bias/opinion with responses, however; when these observations are taken as a whole they describe and inform the cultural environment that contributed to the CFT anomalies.

While the below root causes are specifically separated to clarify the rationale for each, it is nearly impossible to consider one without the others.

NASA created and implemented the contract structure; Boeing built the vehicle. Together the organizations agreed to fly.

Root Cause 1: NASA's hands-off approach during contract initialization resulted in insufficient systems knowledge and available data to the government for accepting a development vehicle as a service.

NASA's adoption of a commercial services procurement strategy through the CCP prioritized provider-led development and minimized traditional NASA insight and oversight. This contributed to the creation of the previous intermediate causes and organizational factors that produced insufficient data for NASA to fully understand system qualification of the Starliner spacecraft. This approach led to gaps in end-to-end verification, validation, and interface management, ultimately contributing to crew and mission risk. In accordance with the SAA and guiding documentation, NASA teams were prohibited from providing feedback during key design phases or requiring closure on feedback submitted. NASA engineering identified the lack of encompassing flight envelope for RCS thrusters in the pre-Preliminary Design Review (PDR) timeframe but were unable to work to resolution at that time.

Supporting summary from the STAR report:
Critical designs were set prior to CCtCap, with limited government interaction. This resulted in NASA being unable to provide critical comments and feedback prior to key design milestones, such as prior to hardware acquisition; thus, NASA Engineering was prohibited from providing comments to

provider, which may have constituted as an unfair advantage prior to contract finalization. This resulted in a disconnect in the system engineering process, as the hardware was already purchased, rendering any potential NASA comments as moot. Also, NASA staffing plans post-award were not tailored for each provider's schedule and culture, with limited dedicated teams for each provider. At the beginning of CCtCap, the focus was on SpaceX human spaceflight design maturity, with a preconceived notion that Boeing was more experienced in human spaceflight.

Recommendation:
R.54 [OP]– For development vehicles, the provider and NASA must partner in the development and qualification plan of known troublesome systems during the design phase. Make this contractually required.

- **For Transportation vehicles, this consideration may include Propulsion, Parachutes, Heatshields and H/SI.**
- **For Orbiting vehicles this consideration may include Life Support, MMOD protection, etc.**

While appropriate initial areas should be identified at contract initiation, there should also be the flexibility to add additional areas as warranted during the system development. NASA has had many lessons learned across multiple spacecraft types. The goal of this recommendation is to rebalance the known risk acceptance in a commercial services contract type through increase investment in known-problematic systems and to appropriately address unforeseen challenges as they arise.

Root Cause 2: Boeing employed inadequate systems engineering and integration in the design phase which resulted in operating Starliner propulsion system hardware outside of qualification.

Boeing did not adequately apply systems engineering and integration processes, procedures, or resources to verify all operational environments, lifecycle phases, and use cases. This resulted in insufficient certification/delta certification for new environments as they evolved in the design and development phase of the systems engineering process.

- Ex: Helium softgoods – NTO exposure resulting in leaks, SM RCS – heat, mechanical demand, contributing factors resulting in reduced thrust, CM RCS – corrosion caused by reuse environment resulting in failed jet

Supporting data from interviews with key personnel and Boeing's Enterprise Root Cause/Corrective Action (eRCCA) review:

"In Boeing's design and acquisition of hardware phase, there was an over-emphasis on heritage design and the successful qualification and use of that hardware in different applications. During this phase, the integrated system constraints, operational mission environments for all phases of flight, and ground processing were not well understood. The subcontractor deliverables were then insufficient to perform the independent verification and validation of the Starliner specific use case.

Boeing initially acquired hardware at-risk by procuring one-time hardware lots during the design phase, without specified sustaining arrangements with suppliers/subcontractors. This results in a shortage of spares influencing testing availability and replacements to mitigate inflight anomalies through post-certification missions. While using subcontractors with proven hardware is an acceptable strategy, the inadequate integration resulted unknown risk acceptance and effectively underbidding the contract."

Recommendation:
R.55 [Boeing] – Provide evidence to demonstrate all Starliner subsystems have been re-evaluated for qualification due to missing operational environments during development/initial design phase.

Refer to eRCCA 2.0 Define and Develop Functions Corrective Actions.

- Rereview documented risks/anomalies to see if rationale still holds
- Review other hardware or system being used outside of test/qual baseline requirements
- Evaluate assembly acceptance testing, servicing, and maintainability and manage any associated risks

In turn, CCP should evaluate all deviations, waivers, variances, and directives to determine if the acceptance criteria is still valid.

Recommendations related to test/qualification are captured in the 4.8.1 Testing section of the report.
For programs and vehicles in developmental phases, plan/contract robust test campaigns (flight and/or ground) with requirements and deliverables including associated models and criteria for determining success of a test, substantiated by accredited and rigorous analysis. Verify that data available from the test (flight or ground) will allow clear determination of pass/fail for objectives and performing diagnostics on unexpected conditions/anomalies.

There is no substitute for test. Flight tests and integrated ground tests are ideal for understanding whole system interactions. Campaigns of multiple flight tests may not fit a given program's objectives. Wherever possible the associated models and criteria for determining success criteria of flight test should be substantiated by accredited, rigorous analysis based in ground test.

Root Cause 3: NASA's Commercial Crew Program has a culture based on a top-level objective for the two selected providers to be successful. This heavily influences risk-based technical discussions, emphasizing risk acceptance that supports flight rationale over additional investigation with a goal of verifying proximate cause AND less likely causes. This approach leads to an increase in accepted risk.

Any pressure to be successful with two providers that inappropriately influences acceptance of elevated risk erodes trust regarding technical rigor between NASA and Boeing, inside of NASA/CCP and between CCP and their support organizations. Many within the CCP community see this pressure when met with push-back regarding the contractor “going away” or “pulling out” as rationale for not engaging in difficult conversation topics. This reluctance to challenge Boeing’s interpretations and failure to act on engineering concerns has contributed to risk acceptance and a fragile partnership dynamic. While this root cause is specific to the history of the anomalies seen on CFT, several of those interviewed as part of this investigation denoted no change in this culture, post-CFT.

There are several hypothesized reasons for this distinctive culture in CCP, though none can be fully concluded as the singular source:

- Ensuring a second provider to ISS is available for redundancy and cost trades has a higher than outwardly communicated priority
- Any instance or issue seen as a “failure” of the provider could reflect poorly on CCP and/or NASA
- Pressure from the NASA Agency level at Headquarters to ensure the success of Boeing
- Withdraw of a commercial provider or not accepting a development vehicle for its initially contracted service is seen as failure of the program

Recommendations for cultural changes and rebuilding trust are captured in the Culture and Decision-Making Process section of this report. Additionally, recommendations regarding the path to returned crewed flight on Starliner and the overall objectives for Starliner in the future (Section 7), will help serve to baseline expectations going forward.

7 Additional Observations from the Investigation Team

Observation 1: No clear criteria for Starliner-1
There is no clear objective for utilizing Starliner-1 in returning to crewed flight.

Recommendation:
R.56 [CCP, Boeing] - Return to Crewed Flight
Create/disposition criteria for returning to crewed flight.
Include, but not limited to:

- The top-level objectives for Starliner-1 and future tests that must be completed to sufficiently reduce risk to the crew.
- A detailed listing of all configuration differences between CFT, Starliner-1, and Starliner-2 and clear risk justification if deltas are identified.
- Re-examination of all CFT Flight Test Objectives (FTOs) that were not met, or only partially met, on CFT and determine if these will be met on Starliner-1, or in other ways, prior to Starliner-2.
- Define qualification envelope for SM RCS and CM RCS. Show tested range and operational range for critical parameters (e.g., inlet valve temperature, mixture ratio duty cycle, etc).
- Identification of any new, critical FTOs that must be achieved on Starliner-1.

Starliner-1 should be utilized to obtain necessary data to ensure there is a reduction in risk for future Starliner missions. Reductions in risk include validating the new therm11-c with Starliner-1 data, validating GNC firings for RCS Thrusters and validating thrusters RCS thruster performance during key phases of flight.

Observation 2: Starliner Longevity (Mission Suitability)
Hardware and launch vehicle availability raise longevity concerns for current and future programs.

As noted by the STAR report and PIT interviews, Starliner has limited hardware spare availability. This is a concern for being able to complete remaining flights to ISS due to limited life nature of some components and ability to replace critical components when failures occur or utilizing hardware for testing.

Long term use of Starliner requires a launch vehicle transition. If Starliner is to continue to provide access to Low Earth Orbit for humans, this will it require moving Starliner off Atlas V and onto another launch vehicle as the Atlas V is being phased out by ULA.

Recommendation:
R.57 [CCP, SOMD] - Longevity of Starliner
[CCP] Evaluate capability shortfalls with hardware sparing of [redacted]. Assess ability of Starliner to fulfill contracted missions to ISS. Identify associated technical work to be completed by CCP/Boeing, and where gaps exist implement an action plan to appropriately invest in the Starliner vehicle for the remainder of ISS missions.

[SOMD] Evaluate long term capability shortfalls, overall Human Rating, and sparing for Starliner missions in CLDP. Identify associated technical work to be completed by

CCP/Boeing, and where gaps exist and implement an action plan to appropriately invest in the Starliner vehicle to reduce risk for future crewed missions.

As noted by the STAR report and PIT interviews, Starliner has limited hardware spare availability. This is a concern for being able to complete remaining flights to ISS due to limited life nature of some components and ability to replace critical components when failures occur or utilizing hardware for testing.

Observation 3: Root Cause Analysis (RCA) knowledge and skills are a critical skill tool in conducting thorough and complete investigations. The availability of skilled personnel to lead a team through this process is limited and skilled personnel educated in RCA should be retained to conduct thorough investigations.

These unique and specific skill includes capability to create detailed fault trees, including necessary software capabilities, the ability to distil technical designs into fault tree nodes and deep enough understanding to lead a team through the process. This includes organization of and justification for fault tree box closures to generate proximate cause, followed by the development of causal factor trees and/or follow on questions for interviews to get to root cause. This may include the "five whys" method, causal factor trees or other appropriate tools. Retention of these skills should be deliberately trained for retention.

Recommendation:
R.58 [OSMA] - Assign Root Cause Analysis (RCA) investigation skill as a required skill set to be maintained and retained within the context of human spaceflight investigations of all types, regardless of classification or specific process called upon for use. Require SMA to build up the required skill set through training and benchmarking and develop a retention plan. This skill set can then be utilized by all NASA programs for various levels of anomaly investigations.

Observation 4: Serving as a member of a root cause investigation team should start with training on investigation tools used and agency capabilities to utilize to complete a thorough investigation.

Recommendation:
R.59 [OSMA] - For Program Investigations governed by OA-WI-007, establish an effective training protocol for those named to the investigation team, to be completed at assignment to the team.

Observation 4: There is no singular repository for PIT final products. A repository of products would serve multiple functions such as:

- ***Educating new PITs on style and expectations***
- ***Enabling sharing of program lessons learned through the ability to query and browse a one-stop-shop***

Recommendation:
R.60 [OSMA]- Create a consolidated PIT product repository.

Observation 5: During CFT, leadership and team members who were not previously involved with or fully educated on the system being discussed caused frustration because of the perception of needing to educate these team members.

Current NASA Human Space Flight management in varying levels across multiple centers and HQ, primarily have Low Earth Orbit mission experience/background (Space Shuttle, ISS, CCP). These are programs with traditional vehicle knowledge or few primary providers. With Artemis operating in the lunar regime, there is risk of LEO mental frameworks and systems knowledge being incorrectly applied, which could be compounded by multiple providers and multiple vehicles of different type and function in a given scenario. As risk discussions elevate, the need for educating a higher leadership team may be imperative. Strategizing how to do this, pre-flight may alleviate trust eroding encounters during the mission.

Observation 6: The propulsion system failures on CFT are significant and should be classified and documented according to the NASA Mishap definitions and process (NPR 8621).

The PIT has determined that the loss of 6 Degrees of Freedom (6DOF) control of the Starliner spacecraft during the CFT meets the criteria for a Type A mishap under NPR 8621.1D. The severity of the event, its potential for escalation, and its alignment with the definition of "unexpected spacecraft departure from controlled flight" warrant formal classification and documentation in the NASA Mishap Information System (NMIS).

Despite the significance of the event, it was not formally classified as a mishap or a high-visibility close call. This decision was criticized by multiple interviewees during the PIT investigation, who expressed concern that the absence of classification left a major safety event unrecorded in NASA's official mishap database. The PIT concludes that this omission undermines institutional accountability and lessons learned.

Justification for Type A Classification

NPR 8621.1D defines a Type A mishap to include "unexpected aircraft or spacecraft departure from controlled flight," unless such departures are pre-briefed or mitigated through the flight test process. While the thruster anomalies themselves may not independently constitute a mishap, the resulting loss of 6DOF control represents a significant escalation in risk, should have led to the responsible NASA officials to declare a Type A mishap, and is the primary factor in the PIT's assessment.

Although the Commercial Crew Program (CCP) references Revision B of NPR 8621.1 in the contract with the provider, which lacks the "departure from controlled flight of spacecraft" language, the current version of NPR 8621.1D takes precedence per CCT-PLN-1010. While the provider may not be required or obligated to use a version updated after their contract agreements, that does not stop NASA from performing its own evaluation based on the currently agreed to parameters and making a declaration.

Alternate classification for High Visibility Close Call

Troubleshooting during the rendezvous allowed for the spacecraft to regain control and proceed into a safe docking with ISS in auto control. This ability to regain the control capability could be used as justification to assign the High Visibility Close Call classification.

Supporting evidence:

While the PIT was not chartered as a formal Mishap Investigation Board (MIB), it was directed by SOMD to follow most of the mishap process outlined in NPR 8621.1D but also employ the guidance in the Program Investigation Team OA-WI-007. The PIT conducted a thorough, evidence-based investigation with the same diligence and integrity expected of a formal MIB. The decision to not declare the event a mishap has broader cultural implications. It risks signalling a lack of confidence in NASA's established mishap investigation processes and may inadvertently undermine workforce trust in the agency's commitment to transparency and accountability. This approach also diminishes the perceived seriousness of the event, potentially confusing the workforce about the thresholds and expectations for formal mishap classification.

The concurrent execution of the CCP STAR/SDRT, PIT and the Root Cause and Corrective Action (RCCA) process introduced coordination challenges, including overlapping scopes and occasional resistance to collaboration. These parallel efforts created the potential for missed opportunities in information sharing and subject matter expertise resource utilization. A key structural limitation was that, unlike a formal MIB—whose members are relieved of their normal duties to focus exclusively on the investigation—PIT members were expected to balance their participation with full-time responsibilities. This part-time engagement hampered the investigation schedule and further contributed to the perception that the effort was not being treated with the seriousness it warranted.

And if nothing else, the discussion of "shouldn't this be a mishap" served as a significant distraction to the team, fielding questions and concerns regarding the authority and acceptance of the end product.

Additionally, NPR 8621 allows for a mishap or HVCC to be classified per the NPR but utilize an approve alternate investigation strategy, if the NPR requirements are met. Knowing that every anomaly investigation faces its own challenges and nuanced considerations, it stands to reason that an event could be classified as a mishap or HVCC and also utilize the more local PIT process. This includes many of the advantages that were sought in standing up this Starliner Prop PIT, in looking for a team that was already educated to some degree on the anomalies and could take minimal time to get up and running in the investigation.

Without formal classification:

- The event is not entered into NMIS.
- There is no requirement for a CAP with defined actions, timelines, verification, and closure.
- Transparency, trust, and institutional learning are compromised.

Recommendation:
R.61 [OSMA] - Given the severity of the event and its alignment with the Type A mishap definition, the PIT recommends that:

- The event be formally classified as a Type A mishap.
- The event be entered into NMIS to ensure institutional learning and accountability.
- The PIT be considered the investigative authority for this mishap, and the report should be considered the final mishap report. (do not standup another investigation team or an MIB)

The PIT's recommendations follow the formal review, approval, closure, and verification as required under NPR 8621.1D. In the future, consider separate actions for assigning classification and specifying investigative approach. Depending on the severity/seriousness of the anomaly/investigation leadership should consider dedicated full time investigation teams without the need to fulfil the duties of their assigned role during the investigation.

8 Consolidated Recommendations

Below is the set of all recommendations from the investigation. The investigation recommendations have been grouped to assist in delivery and assignment and are shown in Table 1. All of the recommendations from throughout the investigation report can be found in Table 2. Recommendations will be actioned by the chartering body of this investigation, the Associate Administrator, Space Operations Mission Directorate. All actions will be delivered and verified closed by SOMD at a DPMC.

Follow up expectations:

Table 2 assigns all recommendations to responsible organizations, the organization they report to, and if evaluation/implementation of the recommendation is required prior to the next flight of Starliner. Where more than one responsible organization is listed those organizations should collaborate on a response where possible. It is understood different programs may necessitate unique responses and response timing. Actual definition, determination of forward path, resolution plan, etc may be delegated as is deemed necessary and appropriate by the responsible organization. However, it is ultimately the duty of the responsible organization to status when a recommendation has been implemented or provide sufficient rationale for not implementing.

Expected outcome:

- Reduced risk to crew and mission objectives.
- Improved certification confidence and anomaly closure.
- Stronger NASA-industry collaboration and accountability.
- Scalable model for future commercial and exploration missions.

Table 1: Consolidated Recommendation Categories						
#	**Recommendation Category**	**Recommendations Summary**	**Expected Outcome (intent of recommendation)**	**Associated R#s (Table 2)**	**Responsible Orgs**	**Recommended Response time (SL1, Crewed Flight or Long Term)**
A	Disposition of IFA and mitigation of thruster valve/poppet extrusion issues	Complete testing and formally disposition IFA findings; implement hardware/software fixes	Verified resolution of failure causes and improved thruster reliability for certification	R.1, R.4	CCP	SL1
B	Evaluation and validation of GNC changes and thruster health	Analyze GNC changes and validate inflight thruster health thresholds	Increased confidence in GNC performance and inflight thruster diagnostics	R.2, R.3, R.10	CCP	SL1
C	Seal material compatibility and O-ring sizing issues	Test and replace incompatible seals and adjust O-ring sizing as needed	Reduced risk of seal failures and improved material compatibility for mission duration	R.5, R.6, R.7	CCP	SL1
D	Criteria and planning for return to crewed flight	Define and document criteria for crewed flight readiness, including test objectives and configuration deltas	Clear roadmap for safe return to crewed missions and risk-informed decision-making	R.56	CCP	SL1
E	Sensor Sample Rates and Data Retention	Analyze sensor sample rates and data retention adequacy for critical systems and align stakeholders on rationale	Consensus on telemetry sufficiency and reduced ambiguity in mission data needs	R.13	CCP	SL1
F	Improvements to the Anomaly Resolution Process	Standardize communication, data access, and technical integration for anomaly resolution.	More efficient and transparent anomaly resolution with better cross-team collaboration.	R.20, R.21, R.22, R.23, R.24, R.25, R.31, R.32, R.33, R.35, R.36, R.37, R.38, R.39, R.40, R.41	CCP/ ISS/ SOMD	SL1

Table 1: Consolidated Recommendation Categories						
#	**Recommendation Category**	**Recommendations Summary**	**Expected Outcome (intent of recommendation)**	**Associated R#s (Table 2)**	**Responsible Orgs**	**Recommended Response time (SL1, Crewed Flight or Long Term)**
G	Evaluation of capability shortfalls and investment planning	Assess and address hardware and capability gaps through strategic investment	Improved readiness and sustainability for future missions	R.57	CCP, Boeing	Crewed Flight
H	Trust, Transparency, and Leadership Culture	Foster a respectful, transparent culture through leadership accountability, forums, and communication.	Rebuilt trust, improved morale, and a culture that supports open dialogue and shared responsibility.	R.27, R.45, R.46, R.47, R.48, R.49, R.50, R.51, R.52, R.53,	CCP/ ISSP	Crewed Flight
I	Root Cause 2: Integration Process	Provide evidence to demonstrate all Starliner subsystems have been re-evaluated for qualification due to missing operational environments during development/initial design phase.	Rereview other hardware or system being used outside of test/qual baseline requirements and evaluate assembly acceptance testing, servicing, and maintainability and manage any associated risks.	R.58	Boeing	Crewed Flight
J	Verification of hardware fault tolerance and model-based design tools	Use automated tools to evaluate fault tolerance and improve case matrix accuracy	Enhanced fault tolerance validation and reduced reliance on manual inspection	R.11	SOMD	Long-term
K	Safety culture, training, and communication processes	Provide training and ensure clear processes for raising and addressing safety concerns	Improved safety culture and responsiveness to critical issues	R.8, R.9, R.12, R.28, R.59, R.60, R.61	OSMA	Long term

Table 1: Consolidated Recommendation Categories						
#	**Recommendation Category**	**Recommendations Summary**	**Expected Outcome (intent of recommendation)**	**Associated R#s (Table 2)**	**Responsible Orgs**	**Recommended Response time (SL1, Crewed Flight or Long Term)**
L	Standards development for data, propulsion systems, and engineering practices	Develop and implement engineering standards for data and propulsion systems	Consistent design practices and improved system reliability across programs	R.14, R.15, R.16	OCE	Long term
M	Shared accountability and roles clarity	Define and document roles, responsibilities, and recovery plans for milestone failures	Clearer accountability and improved response to partner performance issues	R.17	CPMO. OCE	Long term
N	Knowledge sharing and lessons learned	Establish forums and processes for sharing lessons learned across programs	Institutional learning and reduced recurrence of past issues	R.34	OCE, CKO	Long term
O	Programmatic Governance and Decision Authority	Establish clear, unified decision-making frameworks and clarify roles across mission phases.	Improved coordination, reduced ambiguity, and faster, more accountable decision-making.	R.18, R.43, R.44, R.45, R.46, R.47, R.55	CCP/ ISS/ SOMD	Long term
P	Independent Technical Authority and Escalation	Train teams on Technical Authority (TA) processes and ensure consistent updates and escalation paths.	Strengthened technical independence and more effective issue escalation and resolution.	R.42, R.43	CCP/ISS	Long term
Q	Unified Approach to Risk Evaluation and Framing	Implement common tools and training for risk-based decision-making and leadership alignment.	Consistent, data-driven risk assessments and improved leadership alignment on risk posture.	R.19, R.26, R.27	OCE/ CKO/ ARMO	Long Term
R	Contract Structures and Oversight in Commercial Services	Reassess contract structures to align oversight with risk and ensure access to technical expertise.	Better alignment of contract terms with mission assurance needs	R.29, R.30	AA/OP	Long term

Table 1: Consolidated Recommendation Categories						
#	**Recommendation Category**	**Recommendations Summary**	**Expected Outcome (intent of recommendation)**	**Associated R#s (Table 2)**	**Responsible Orgs**	**Recommended Response time (SL1, Crewed Flight or Long Term)**
			and improved NASA insight capabilities.			
S	Root Cause 1: Contract initialization	For development vehicles, the provider and NASA must partner in the development and qualification plan of known troublesome systems during the design phase. Make this contractually required.		R.54	OP	Long term

Table 2: Full list of Starliner Final Report Recommendations

R#	Recommendation Statement	Responsible Orgs			Reporting Org	Recommended Response Time
R.1	When testing is complete, formally disposition the SM RCS Thruster Fail Offs IFA and address residual risk of poppet extrusion effecting a thruster valve. Show via test or analysis that the proximate cause of the failure is rectified, through hardware/GNC software modification, to complete necessary Starliner vehicle certification.	Boeing			SOMD	SL1
R.2	When Therm-11c is complete, perform analysis and evaluation to validate the impact of GNC changes made between OFT2 and CFT and verity the did/do not pose additional risks to CFT/Starliner.	CCP	ENG		SOMD	SL1
R.3	Validate threshold and associated logic for determining the health of a thruster.	Boeing			SOMD	SL1
R.4	When testing is complete, formally disposition the SM RCS Thruster Fail Offs IFA and address residual risk of poppet extrusion effecting a thruster valve. Show via test or analysis that the proximate cause of the failure is rectified, through hardware/GNC software modification, to complete necessary Starliner vehicle certification.	CCP	ISSP		SOMD	SL1
R.5	When testing is complete, formally disposition SM Helium Leaks IFA and address residual risk of NTO exposure to an [redacted] seal in this location. Show via test, or analysis that the proximate cause of the failure is rectified, through replacement of the [redacted] seal, to complete necessary Starliner vehicle certification.	CCP	Boeing		SOMD	SL1
R.6	When testing is complete, formally disposition the SM Helium Leaks IFA and address residual risk of material incompatibility in the remaining softgoods ([redacted]) in the helium system. Show how these materials will meet the required 210-day mission duration, as well as ground wetted time, and complete necessary Starliner vehicle certification.	CCP	ISSP	Boeing	SOMD	SL1

Table 2: Full list of Starliner Final Report Recommendations						
R#	**Recommendation Statement**	**Responsible Orgs**			**Reporting Org**	**Recommended Response Time**
R.7	When testing is complete, formally disposition the SM Helium Leaks IFA and address any remaining residual risk of O-ring sizing. Show via test, or analysis that the proximate cause of the failure is rectified, through replacement of the [redacted] seal, O-ring sizing change, to complete necessary Starliner vehicle certification.	CCP	Boeing		SOMD	SL1
R.8	The NASA safety processes should include focus on system level safety owned fault tolerance requirements and ensure the data used to approve hazard control strategies at Phase I is captured in the control language in the hazard reports directly and not simply assumed to be in the verification data.	OSMA			SOMD	Long term
R.9	Hazard controls and their verification should be documented in hazard reports clearly tying the supporting verification evidence to the controls.	CCP	ISSP	SOMD	SOMD	Long term
R.10	VCN deliverables for future Starliner Missions should have the associated case matrix for GNC Monte Carlos evaluated to verify accurate hardware fault tolerance.	CCP			SOMD	SL1
R.11	In future programs, plan to invest in and utilize tools for automated evaluation of design data for mapping fault tolerance and other design requirements, instead of relying specifically on human inspection of schematic data. Keep human evaluation in the loop but increase use of evaluation tools to catch unique and nuanced design imperfections, such as the helium legs of the propulsion system.	SOMD			AA	Long term
R.12	NASA should verify for that the provider has sufficient tools and process for addressing issues or concerns and has a “speak up” process to appropriately elevate critical safety concerns and provides sufficient training to ensure all team members are aware of processes and safety priorities	OSMA			AA	Long term

Table 2: Full list of Starliner Final Report Recommendations						
R#	**Recommendation Statement**	**Responsible Orgs**			**Reporting Org**	**Recommended Response Time**
R.13	Disposition that ground testing and analysis demonstrate that no improvement (beyond format 12) in Pc sample rate is necessary for SL-1 in preparation for a crewed SL-2. A brief on the rationale for not increasing Pc sample rate should be held to align the stakeholders.	CCP			SOMD	Crewed Flight
R.14	Generate an engineering data standard to define what data is necessary for vehicle system health and performance characterization, analysis, troubleshooting, and model validation.	SOMD			AA	Long term
R.15	Create a design and construction standard for integrated spacecraft propulsion systems.	OCE			AA	Long term
R.16a	NESC should perform an evaluation, prior to return to crewed flight, to determine effectiveness of new integrated spacecraft propulsion systems standard to prevent CFT prop failures.	OCE			AA	Crewed Flight
R.16b	NASA should evaluate the effectiveness of the standard, determine gaps to the standard (if any), and determine gaps to meeting the standard (if any) of CFT, Starliner-1, Crew Dragon, and other crewed vehicles.	SOMD			SOMD	Long term
R.17	Develop and implement new guidance/standards for shared accountability on new/developmental Programs.	CPMO, OCE			AA	Long term
R.18	Establish a multi-program anomaly resolution process with entrance and exit criteria, and who gets to decide when it gets turned on/off.	CCP	ISSP	SOMD	AA	Long term

Table 2: Full list of Starliner Final Report Recommendations						
R#	**Recommendation Statement**	**Responsible Orgs**			**Reporting Org**	**Recommended Response Time**
R.19	Implement a common tool for risk evaluation across commercial providers.	ARMO			AA	Long term
R.20	Establish structured communication path and forums with clearly defined expectations and responsible parties in an anomaly.	CCP	ISSP	SOMD	AA	Long term
R.21	Establish a clear process for integrating technical expertise from different teams and organizations within NASA, ensuring that all relevant perspectives are considered, to enable the NOM to provide the NASA voice at the SMMT.	CCP	ISSP	SOMD	AA	Long term
R.22	Create an equivalent MMI position.	Boeing				Long term
R.23	Document expectations or provide training that NASA interfaces to contractors need to be very clear when they are speaking with the authority of their full organization/NASA or are info gathering/collaborating/sharing personal views.	AA			AA	Long term
R.24	Define the process and rules of engagement for how NESC participates in the in-flight anomaly resolution process. Provide information to commercial contractor partners about the NESC and rules of engagement before, during, and after a mission.	OCE			AA	Long term
R.25	Communicate all updates via mandatory training for programs and stakeholders.	ALL			SOMD	Long term
R.26	Incorporate structured pre-mission training including dedicated briefings, tabletop exercises, and integrated team simulations to rehearse real-time decision-making processes.	CCP			SOMD	Long term
R.27	Provide regular training for program management teams, direct reports and stakeholder members, regarding strategies for risk-based decision making including the use of 7 Elements of Flight Rationale, Risk Scoring processes and Cumulative Risk balancing strategies, to ensure the team maintains a baseline understanding to prevent skewed	CCP	ISSP		SOMD	Long term

Table 2: Full list of Starliner Final Report Recommendations

R#	Recommendation Statement	Responsible Orgs			Reporting Org	Recommended Response Time
	understanding even with changeover from team members. Include providers. Include any differences for applying techniques pre-flight vs. in-flight. Determine appropriate interval for refreshers (i.e., yearly)					
R.28	Implement STAR action for Burden of Proof (A-25) "Provide guidance to program team (NASA and Providers), on verification evaluations should be considered with a "prove it's safe" mindset.	CCP				
R.29	For current and future programs, NASA should ensure that resources are sized to the oversight/insight burden required to meet the risk acceptance posture the Agency has chosen for that acquisition and number of providers in flow. This should be reassessed if additional providers are added. Depth of penetration into qualification test and analysis is a direct correlation to risk assumption with a provider.	AA			AA	Long term
R.30	Evaluate contract structures for services contracts to determine level of NASA insight/oversight, expected overall participation in design decisions and reviews throughout project lifecycle, and expected support for real time operations and anomaly resolution. Specifically: a. Require contract structures chosen for commercial services to have and determine NASA expectations for quick and ready access to subcontractor design experts at all stages of system design and especially to aide in efficient anomaly resolution. b. Evaluate contract structures and shared accountability implementation with providers to determine what level of insight/oversight NASA needs during the design phase, test flight phase and into operational phases. c. Ensure contract structure enables subcontractors to provide insight during missions for anomaly resolution. Else, accept the risk that the data is not accessible.	OP			AA	Long term

Table 2: Full list of Starliner Final Report Recommendations						
R#	**Recommendation Statement**	**Responsible Orgs**			**Reporting Org**	**Recommended Response Time**
R.31	Ensure that future contracts include provisions for integrated anomaly resolution planning, including expectations for transparency and data sharing.	OP			AA	Long term
R.32	Establish a central repository of information for use during missions to enable quick access to data critical to near-real time decision making. Update repository using modern tools to improve searchability to quickly locate the data.	CCP			SOMD	Long term
R.33	Reevaluate a data sharing infrastructure with the stakeholder community. This should include/ensure a clear and efficient access to information during a mission. Along with data sharing expectations and protocols across teams, along with decisions on which teams and roles need access to information. NASA needs a mechanism to enable sharing data across providers and programs in critical situations. Assign a role that is responsible for ensuring communication and information is coordinated and integrated across teams during missions. Include a dedicated annual meeting topic or training about insight into provider information and where to find information. Ultimately, this is to ensure that a proper infrastructure and central repository is in place when responding to an anomaly resolution process. This central repository should be accessible to all stakeholders with a need-to-know.	AA			AA	Long term
R.34	NASA should establish a Lessons Learned Conference to allow providers to come forward and share lessons learned, on their own accord, to facilitate success of United States manned spaceflight.	OCE	CKO		AA	Long term

Table 2: Full list of Starliner Final Report Recommendations						
R#	**Recommendation Statement**	**Responsible Orgs**			**Reporting Org**	**Recommended Response Time**
R.35	Implement a unified programmatic decision authority framework, and flow for escalation, for making near-real-time mission related decisions, accommodating: 1. Nominal mission execution where the provider retains responsibility for executing mission activities, including leading and coordinating anomaly resolution activities, with integrated NASA participation. 2. When deemed appropriate by NASA or when NASA crew and NASA assets are deemed above the baseline risk accepted by NASA at the FRR, NASA shall assume leadership of MMT and any or all anomaly resolution activities, with integrated provider participation. 3. Unified decisional authority and mission management that integrates NASA Commercial Crew Program and NASA International Space Station program mission management authority and execution structures.	CCP	ISSP	SOMD	AA	Long term
R.36	Develop and document specific guidelines for how a provider MMT must respond to NOM non-concurrence, and similarly process for how NOM should adjudicate non-concurrence / formal dissent from CCP MMT.	CCP			SOMD	Crewed Flight
R.37	Formalize policy for how NOM is to include or not include inputs from CCP offices and support organizations in readiness for SMMTs.	CCP			SOMD	Crewed Flight
R.38	Create consistency between provider implementations (e.g. NOM CCP MMT polling during provider MMT) of program deliverables.	CCP			SOMD	Long term
R.39	Update CCP, ISSP, and provider documents and FRs to ensure consistency and clarity with programmatic decision authority for near-real-time mission related decisions.	CCP	ISSP		SOMD	Long term
R.40	Create mission specific refresher information to be reviewed by programs and their support organizations just prior to flight, highlighting any residual nuances or differences in the implementation of near-real-time operations.	CCP	ISSP		SOMD	Long term

Table 2: Full list of Starliner Final Report Recommendations

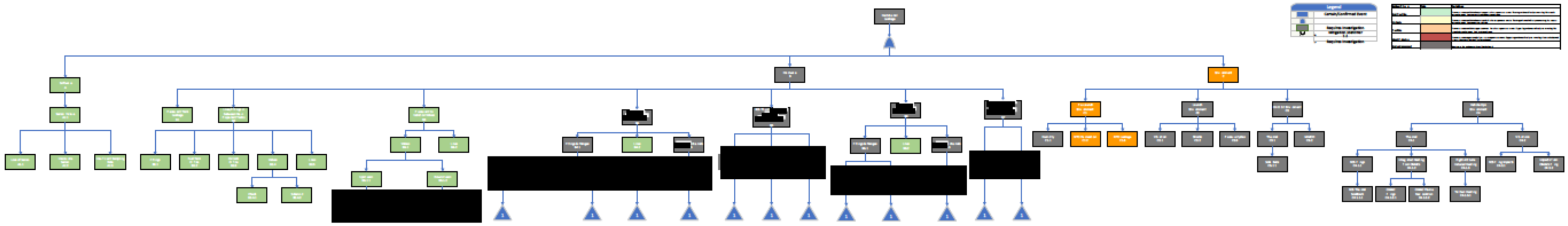
R#	Recommendation Statement	Responsible Orgs			Reporting Org	Recommended Response Time
R.41	Ensure clarity during mission management meetings who has delegated authority to represent the position of various stakeholder organizations, irrespective of more senior leaders being in attendance or asking questions.	CCP	ISSP		SOMD	Long term
R.42	Implement targeted briefings and training sessions for NASA and provider team members on NASA's TA process, expectations, and escalation paths as part of pre-mission preparation.	CCP	ISSP		SOMD	Long term
R.43	All updates need to be broadly communicated via mandatory training for CCP team members.	CCP	ISSP		SOMD	Long term
R.44	Evaluate MMT report structures through all mission phases, giving consideration to the multi-program / multi-MMT construct and decision making, mission execution responsibility, and NASA authority to ensure NASA is operating programmatically unified, even to the potential extent of a NASA Mission Directorate led and integrated activity, and verify all multi-program documentation supports the same authority structure and concept.	All HSF Programs			AA	Long term
R.45	Speak openly to the joint team about leadership accountability, the results of CFT and the path to build in accountability in order to move forward - which can include but not be limited to, concurrence with this report and reclassifying as a Mishap (see R.61).	CCP	ISSP	SOMD	AA	Long term
R.46	Conduct a leadership-led stand down day focused on reflection on the CFT mission, address concerns raised regarding leadership accountability and to primarily focus on building trust across the workforce and moving forward by reframing the open work and objectives.	CCP	ISSP	SOMD	AA	Crewed Flight
R.47	Cultivate a respectful and transparent CCP team culture including direct reports and additional support organizations. Use recommendations in trust, process and authority sections to show progress.	CCP			SOMD	Crewed Flight

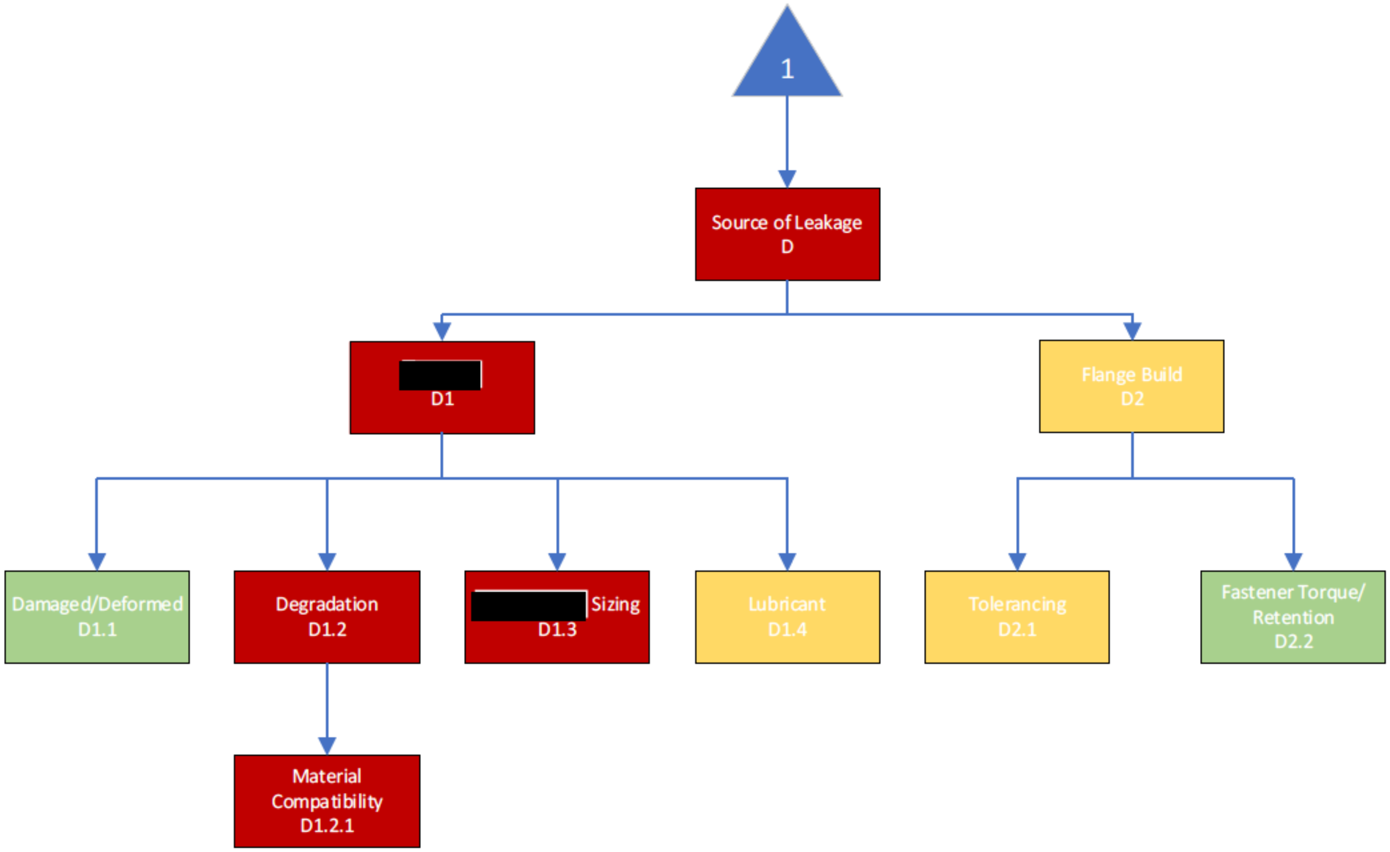
Table 2: Full list of Starliner Final Report Recommendations						
R#	Recommendation Statement	Responsible Orgs			Reporting Org	Recommended Response Time
R.48	Model openly collaborative program to program information exchange between leadership teams including being deliberate to communicate when programs agree or disagree on an approach or issue and provide unified direction for problem solving.	CCP	ISSP		SOMD	Crewed Flight
R.49	Utilizing NASA assets and resources for facilitated discussions, hold a Program Managers forum to communicate program manager lessons learned.	CPMO			AA	Long term
R.50	Establish and immediately implement a strategy to repair trust and strengthen NASA–Boeing partnerships through clear expectations, open accountability, and facilitated team-building sessions. Led by CCP, the plan should begin with leadership and expand to all team members to restore confidence, address past issues, and align on shared values of safety and mission success.	CCP			SOMD	Crewed Flight
R.51	Team leadership to rectify and repair trust across teams	CCP	Boeing		SOMD	Crewed Flight
R.52	Establish and ensure alignment of leadership and teaming expectations around transparency, risk acceptance, and engineering rigor.	CCP			SOMD	Crewed Flight
R.53	Outline how information, processes, and data will be presented, discussed, debated among technical teams to ensure meetings and presentations uphold credibility standards and requirements/metrics to make decisions.	CCP			SOMD	Crewed Flight
R.54	For development vehicle, the provider and NASA must partner in the development and qualification plan of known troublesome systems during the design phase. Make this contractually required. o For Transportation vehicles, this consideration may include Propulsion, Parachutes, Heatshields and H/SI. o For Orbiting vehicles this consideration may include Life Support, MMOD protection, etc.	OP			AA	Long term

Table 2: Full list of Starliner Final Report Recommendations						
R#	**Recommendation Statement**	**Responsible Orgs**			**Reporting Org**	**Recommended Response Time**
R.55	Provide evidence to demonstrate all Starliner subsystems have been re-evaluated for qualification due to missing operational environments during development/initial design phase.	Boeing			CCP	Crewed Flight
R.56	CCP should create/disposition criteria for returning to crewed flight. This should include but is not limited to: • The top-level objectives for Starliner-1 and future tests that must be completed to sufficiently reduce risk to the crew. • A detailed listing of all configuration differences between CFT, Starliner-1, and Starliner-2 and clear risk justification if deltas are identified. • Re-examination of all CFT Flight Test Objectives (FTOs) that were not met, or only partially met, on CFT and determine if these will be met on Starliner-1, or in other ways, prior to Starliner-2. • Identification of any new, critical FTOs that must be achieved on Starliner-1.	CCP	Boeing		SOMD	Crewed Flight
R.57a	Evaluate capability shortfalls with hardware sparing of Batteries, Thruster Valves, Launch Vehicle, etc. Assess ability of Starliner to fulfill contracted missions to ISS. Identify associated technical work to be completed by CCP/Boeing, and where gaps exist implement an action plan to appropriately invest in the Starliner vehicle for the remainder of ISS missions.	CCP	SOMD		SOMD	Crewed Flight
R.57b	Evaluate long term capability shortfalls, overall Human Rating, and sparing for Starliner missions in CLDP. Identify associated technical work to be completed by CCP/Boeing, and where gaps exist and implement an action plan to appropriately invest in the Starliner vehicle to reduce risk for future crewed missions.	SOMD			AA	Long Term

Table 2: Full list of Starliner Final Report Recommendations						
R#	Recommendation Statement	Responsible Orgs			Reporting Org	Recommended Response Time
R.58	Assign Root Cause Analysis (RCA) investigation skill as a required skill set to be maintained and retained within the context of human spaceflight investigations of all types, regardless of classification or specific process called upon for use. Require SMA to build up the required skill set through training and benchmarking and develop a retention plan. This skill set can then be utilized by all NASA programs for various levels of anomaly investigations.	OSMA			AA	Long Term
R.59	For Program Investigations governed by OA-WI-007, establish an effective training protocol for those named to the investigation team, to be completed at assignment to the team.	OSMA			AA	Long Term
R.60	Create a consolidated PIT product repository	OSMA			AA	Long Term
R.61	Given the severity of the event and its alignment with the Type A mishap definition, the PIT recommends that: • The event be formally classified as a Type A mishap. • The event be entered into NMIS to ensure institutional learning and accountability. • The PIT be considered the investigative authority for this mishap, and the report should be considered the final mishap report. 9do not standup another investigation team or an MIB) • The PIT's recommendations follow the formal review, approval, closure, and verification as required under NPR 8621.1D. • In the future, consider separate actions for assigning classification and specifying investigative approach, and depending on the severity/seriousness of the anomaly/investigation consider dedicated full time investigation teams without the need to fulfil the duties of their assigned role during the investigation.	OSMA			AA	SL1

Helium Fault Tree

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D1
Flange Build
D2
Damaged/Deformed
D1.1
Degradation
D1.2
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D1.3
Lubricant
D1.4
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D2.1
Fastener Torque/
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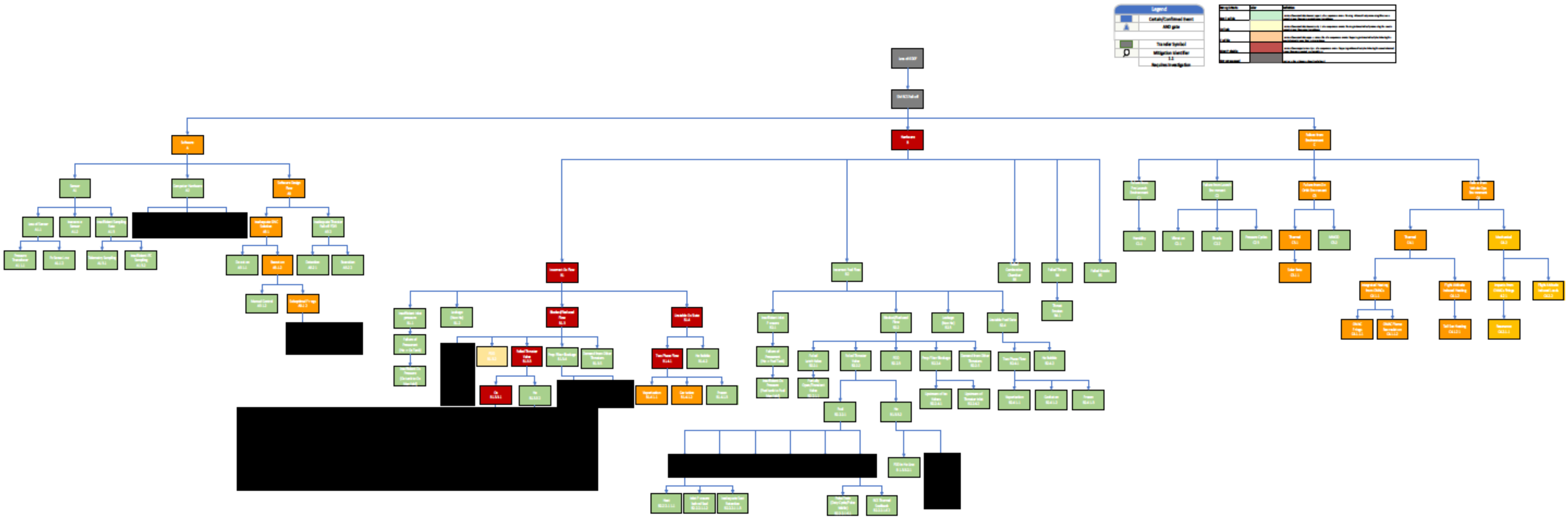
D2.2
Material
Compatibility
D1.2.1

SM RCS Fail-off Fault Tree



Appendix A. NASA Human Factors

Introduction: The NASA Human Factors Analysis and Classification System (NASAHFACS) is a tailored adaptation of the traditional HFACS model, designed specifically to include NASA's unique operational missions and organizational environments. HFACS systematically categorizes the underlying human errors, behaviors and decisions - from acts, to preconditions, to supervision, to organizational influences – enabling a deeper understanding of how and why incidents occur. This multi-layered approach promotes targeted development of mitigation strategies, illuminating opportunities for mishap prevention, a stronger safety culture, and improved performance – both operational and organizational - across the agency.

Background: The PIT Decision-Making (DM)Team conducted interviews which included 66 people from a variety of technical, management and leadership roles throughout NASA and Boeing. The inquiry scope covered a timeframe from CFT launch to CFT return/recovery. Each interview was a semi-structured interview with consistent questions, rankings, and comments under the 5 organizational domains of Organizational Structure, Culture, Communication, Team Dynamics, and Decision-Making. Interviews occurred from April 2025 through July 2025. Mapping of narrative interview evidence into the NASAHFACS framework highlights the presence of human factors. The overall analysis of interview statements considers Preconditions, Supervision and Organizational Tiers. The Acts Tiers is not included given this is a process analysis versus an event analysis as typically found in a traditional HF investigation report.

The Starliner mission delays and uncrewed return were caused by a mix of technical issues as well as human and organizational factors. Most NASA interviewees agreed that returning the crew on Dragon was ultimately the right decision while many Boeing employees disagreed, downplaying the technical risks. These differing risk perspectives persist today. Addressing organizational issues- such as expectations, assumptions, and requirements- offers a critical path forward to preventing future human and organizational factors from exacerbating performance problems and improving overall mission safety.

NASAHFACS: Four hierarchical tiers exist within the NASAHFACS model, each representing a different level of human influence. Three of the four tiers were assessed for their role in the Starliner CFT analysis. The Figure below shows the four NASAHFACS tiers and their associated subcategories highlighted which were found to be present from the interviews.

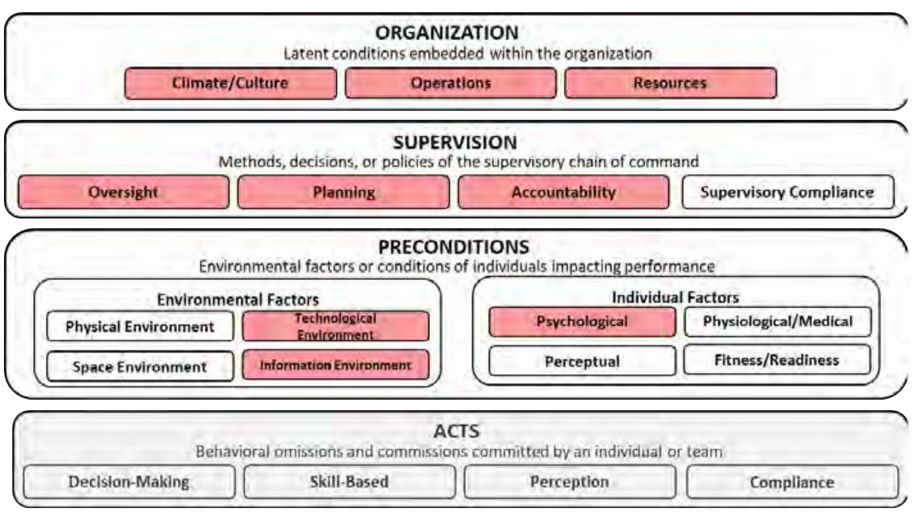


Figure 77: NASAHFACS Tier Descriptions with Subcategories Highlights

CFT PIT Human Factors Analysis

Organizational Tier

The HFACS Organizational Tier encompasses 3 subcategories – Culture/climate, Operations, and Resources. This tier captures the shared organizational attitudes, processes, and resources that impact mission success. PIT interviews revealed numerous examples of deficits (Redlights – RL) in all three Organization categories, as well as successes (Greenlight – GL).

Organizational Climate/Culture. The Organizational Climate-Culture category focuses on systemic influences of culture, climate, and relationships. The culture refers to the long-standing shared attitudes, values, beliefs, or morale that impact operations and/or operational risk. Climate describes the more short-term expectations and behaviors of the group. Contractor relationships, unique to NASAHAFCS, is included to acknowledge the critical effect of commercial parties and the Agency on joint shared assurance on mission implementation and success.

- **Culture** – Differences in cultures were noted in the interviews. Attitudes within Boeing and NASA varied regarding expectations (e.g., testing and timelines). Additionally, different perceptions between NASA CCP and the Technical Authority (TA) became evident. Trust eroded as conflicts increased and went unresolved.
  - (Green Light) Most NASA witnesses remarked that, while "messy", ultimately, NASAs procedures, culture of technical rigor, and valuing crew-life given unknown technical performance, prevailed. "In the end we did the right thing".
- **Climate** – Team decision making, communication, and collaborations were hindered due to poor team dynamics which was the result of heightened stress and decreased morale.
- **Contractor Relations** – While historically challenged, going into the anomaly phase the relationship between NASA and Boeing experienced strain. The degraded relationship between some NASA and Boeing personnel was reportedly exacerbated by strong personalities in meetings.

Organizational Operations: The Organizational Operations category refers to systematic issues within the operations structure and governance which influence operational safety and mission performance. This category includes assessment of how organizational processes, management, training, and those associated deficiencies contribute to risk at the mission or task level.

- **Organizational Structure** ‑ A recurring theme in multiple interviews was the confusion over roles, responsibilities, and decision-making authority. Unstructured meetings contributed to communication breakdowns and a perceived lack of organizational integration between Boeing and NASA further impacted team cohesion.
- **Operational Tempo** ‑ Pressure to work towards decision need dates that were continually pushed out, led the workforce to become chronically fatigued over time. The quantity of meetings also increased after unanticipated anomalies were encountered which made it difficult to get the proper experts to all meetings, further hindering communication and team interaction. One interview used the word chaotic to describe the operational pace for everyone trying to work towards the finishing line of getting the vehicle undocked. This is also related to issues brought up regarding communication of unrealistic launch dates and the consequences (e.g. frustration, fatigue) on the workforce and crew (e.g. morale).
- **Operational Risk Management** ‑ Potential issues identified years prior were not addressed which indicates failure of risk management processes at the organizational level. After Starliner docked to the ISS ongoing circumstances weighing risk became contentions and lengthy. An interview noted the use of "engineering judgement" as a foundation for moving forward without engineering data which indicates an inadequate risk assessment.

- **Program Management and Oversight** - Unclear leadership roles were described across most interviews. A lack of clarity around the decision-making authority further indicated breakdowns at the program management level for both Boeing and NASA. Additional oversight issues included the observation that Boeing appeared to limit inputs from individuals regarding potential issues with the vehicle, thereby controlling additional work and schedule impacts.
    - (Green Light) Personnel changes were made by replacing key individuals who were creating barriers to effective teamwork. This swap out made improvements in relationships by fostering a more composed and cooperative working environment.
- **Publications / Written Guidance** - Witnesses describe a lack of established guidance or protocols for determining who owns specific decision-making capabilities especially during stages of flight and event anomalies (e.g., MIOMP 2110; Appendix C vs Appendix D).
- **Organizational Training** - Interviews indicated there was technical training simulations and coordination efforts however there was a lack of training for how to handle high-risk time-critical anomalies. (e.g., enhanced simulation training for unplanned anomalies)

Organizational Resources: Organizational Resources refers to the availability and management of the physical, personnel, and financial resources provided by an organization to support operations.

- **Personnel** – Witnesses described critical positions as being in short supply. Understaffing of Boeing and NASA personnel was an issue due to various reasons such as personnel being shared between two commercial providers, high workloads, and a limited number of subject matter experts.
- **Funding** – Concern was expressed over the acquisition contract, contract vehicle, and subsequent down-stream effects on personnel, parts, equipment, design, schedule, decision making, meetings size and frequency, authority, relationship between NASA and Boeing, and information required thresholds and deadlines.
- **Material / Parts** – Interviewees acknowledged known hardware issues were accepted prior to launch. Examples were offered where experts demonstrated they didn't fully understand existing technical/system issues (e.g., flying thrusters out of qual).
- **Equipment** – Equipment was identified as a factor during interviews. Examples included organizational decision-making and knowledge related to equipment such as limited Boeing hardware availability, test facility resources, and the pace of hardware testing.
    - (Green Light) One interview highlighted that hardware testing worked well once a clear goal was identified, and the team worked together to execute appropriately.
- **Design** – Questions regarding organizational review and acceptance of the design were raised in several interviews, followed by failed attempts to get more information or dismissal by Boeing.
- **Operational Information** – Interviews cited numerous examples of lack of adequate operational information. This included information requests, the communication/exchange and sharing of technical information between various teams.

Supervision Tier

The Supervision Tier within the NASAHFACS framework addresses how the supervisory chain of command contributes to preparation, training, conditions, and behaviors. The four sub-categories describe how supervisory action – or inaction – introduces "latent" embedded conditions that, when expressed, degrade organizational performance.

Supervision Oversight: The Supervision Oversight category refers to the influence of direct supervision on safety and performance through day-to-day management. Covering a wide range of responsibilities such as modeling, guidance, support, awareness, and interactions with subordinates that ultimately build the quality of relationships between supervisors and personnel. Effective oversight ensures personnel are supported, informed, and aligned with operational and safety goals.

- **Leadership / Modeling / Feedback** – Interviews cited numerous examples of lack of leadership capability to facilitate productive discussions. This was described as a critical deficit in the anomaly resolution process and overall decision-making capabilities.
- **Local Training Issues/Programs** – Interviewees shared that although some training was conducted between NASA and Boeing, including integrated simulation sessions for failure scenarios, many individuals involved in the real-time troubleshooting process had not participated in the original training.
- **Policy** – Multiple interviewees described supervisors displaying a lack of awareness of official guidance regarding who is in charge under anomalous conditions. This lack of awareness and subsequent non-conformance to the policy contributed to uncertainty and frustration.
- **Interpersonal Relations** – Supervisory management of relationships were only prevalent after strained and contentious relationships were seen between some team leads and team members. Supervisors exerted influence over strong personalities to reestablish expectations and resolution of technical conflicts between NASA and Boeing.

Supervisory Planning: Supervisory Planning evaluates how supervisory personnel assess the hazards of an operation and consider associated risk, proficiency, experience, capability, and / or crew make up for the task or mission. Poor planning at the supervisory level compromises mission safety and effectiveness. Effective planning takes into consideration team and individual dynamics, experience, training, readiness, selection, and supervisory behaviors such as observing or thwarting compliance including overall risk assessments and hazard authorization.

- **External Motivation or Supervisory Influence** – NASA technical representatives described decision making as limited by Boeing supervisory influence which dismissed engineering questions at meetings such as the SMMT. An interview noted that Boeing appeared to have a strategy to minimize the number of individuals who are allowed to weigh in on issues during meetings, indicating supervisory influence on individual performance during the mission. "Go fever" was used to describe both NASA CCP and Boeing teams which likely played a role in how supervisors influenced decision making.
- **Risk Assessment** – NASA and Boeing perceive, assess, and tolerate risk differently. This includes different types of risks (e.g., risk to mission vs. risk to life).
- **Authorized Unnecessary Hazard** – Supervisory "go" positions to launch without adequate data suggested fundamental supervisory inadequacies.

Supervisory Accountability: Supervisory Accountability focuses on how supervisors respond to known deficiencies among personnel, equipment, processes, or procedures which influence conditions related to an event. This includes the normalization of deviance where a problem is known but not corrected due to historical methods of operating under such conditions.

- **Personnel Management -** (Green Light) At the onset of issues with communication and team dynamics based on personalities, Boeing and NASA attempted to provide resolution at the management level to move the individuals from leadership roles to support personnel.
- **Operations Management** - Supervisors struggled with complexities and uncertainties of the mission, especially after unexpected anomalies surfaced.

Preconditions Tier

Preconditions are divided into 2 subgroups – Environmental (outside the person) or Individual (within the person). These conditions shape thoughts, behaviors, and interactions of the CFT anomaly. Existing prior to launch that created the conditions all involved needed to deal with. Engineering, safety, program, operators.

Environmental Preconditions

Technical Environment: When automation or design creates conditions affects the actions of an individual or team and contributes to an event.

- **System Configuration** - SMEs determined thrusters were flown out of qual as a result of misinterpreted test data.

Information Environment: When interactions among individuals, crews, and teams create conditions that influence the preparation and/or performance of the mission.

- **Crew / Team Leadership -** Interviewees often described good communication withing small sub teams, yet difficulty with communication between teams. This led to frustration and delays for required data needed for troubleshooting.
- **Risk assessment during mission -** Interviewees discussed absent/degraded risk assessment in various team determinations (e.g., Boeing, SMMT).
- **Communication -** Numerous communication breakdowns were shared during interviews. Multiple methods and audiences were used during the CFT mission anomaly phase, ranging from small discussion with limited attendance to large scale meetings with open attendance in the hundreds. This aspect of communication styles was also coupled with tendencies to disallow speakers to fully communicate technical concerns which led to frustration and sometimes uncharacteristic behaviors in key stakeholders.
    - (Green Light) Crew communicated list of areas to be addressed which facilitated anomaly resolution and team organization into targeting appropriate items for assessment.
- One person was the single point entry from NASA to Boeing. When others came into the mix Boeing perceived them as new and this contributed to less trust.

Individual Preconditions

Psychological: The category includes emotion, personalities, or attitudes of an individual or team that create conditions affecting performance. Numerous aspects of this category were discussed during interviews. There are three other individual categories not included - Medical, Perceptual, and Fitness - since interviewees did not describe these factors during their interviews.

- **Team dynamics** - While internal team dynamics were often described as productive, cross-team dynamics were described as challenging and problematic. Multiple TA teams experienced frustration communicating with program and partner teams. Teams within the larger team looked at the problem from a different perspective.
- **Emotional state** - Interviewees described situations where individuals reacted to risk/high stress situations during Mission Management Team meetings with emotional outbursts. Frustration effected team dynamics, communication, fatigue and morale.
- **Personality Style** -Interviews noted that strong personalities played a role in degrading the decision-making performance of the team.

- **Mentally exhausted/Fatigued** - Individuals described long hours worked by teams from both NASA and Boeing. This occurred prior to launch and during the mission, increasing individual stress levels and diminishing mental capability during anomaly troubleshooting and decision-making processes.
- **Complacency** - Most NASA interviewees felt Boeing overestimated positive outcomes with insufficient data to support conclusions, were reluctant to get additional testing data and requested hard to get results/transparency. Multiple technical representatives noted acceptance of system anomalies as within risk limits when they were "outside of quals."
- **Expectancy** - Many individuals expressed a mental framework of expecting smooth operations without serious anomalies to occur (again) and to subsequently be working through them. This impacted the preparedness for understanding what decisions would need to be made. TA's were frustrated with Boeing's expectations for the mission to go nominally.
- **Motivation** - (Green Light) Both Boeing and NASA team members appeared to have the drive to "figure this out" and that giving up was not going to be an option. This mitigated some of the distrust at certain points in the resolution phase of the effort regarding how to bring the crew home.

ACTS: Use of the Acts Level is when there's a mishap. In the absence of a specific event, the acts level analysis is not appropriate for this investigation, which is looking at a larger organizational process, with multiple stakeholders, over a period of time.

Summary

The Program Investigation Team (PIT) Decision-making sub-team conducted 66 interviews with people from varying roles and responsibilities involved in Starliner operations. The semi-structured interviews consisted of Likert scores and feedback in 5 general areas: Team Dynamics, Communication, Organizational Structure, Organizational Culture and Decision-Making. Interviewee feedback, when mapped into the NASAHAFCS model, supports the PIT findings and recommendations. All three Organizational categories of Culture, Procedures and Resources, 3 of 4 Supervisory categories (Oversight, Planning, Accountability), and 3 of 8 Preconditions (Technical, Information, and Psychological) were substantially discussed during all interviews.

This investigation uncovered consequential differences in NASA and Boeing assumptions and expectations. While the organizations knowingly differ culturally, contractual requirements within the existing shared assurance approach proved inadequate. The organization faced multiple systemic human factors issues. These vulnerabilities ultimately led to a degradation of trust between the NASA and Boeing organizations, the TA's and CCP, CCP and FOD organizations, and between the CCP and ISS Programs. This factor, as well as the other "red-light" organizational dynamics present elevated risks to the HSF Programs and warrants attention. Moving forward deserves thoughtful and deliberate action at the highest levels of NASA, the Mission Directorates, and the Programs.

Appendix B. Analysis of Likert Scale Survey Data on Team Effectiveness

The following data provides a quantitative analysis of employee perceptions regarding the effectiveness of the joint team's performance of during the Starliner CFT mission, specifically during the mission timeframe beginning with the Flight Readiness Review (FRR) and the return of the Starliner vehicle.

B.1 Methodology Overview

To systematically gather this feedback, a structured survey methodology was employed, utilizing a series of Likert scale questions. This introduction will provide an overview of the Likert scale as a research instrument, including its inherent limitations, its application in this specific context, and a summary of the key statistical findings – including the mean, and mode from the interviews conducted.

Strengths:

- They effectively quantify opinions.
- They are simple for people to understand and answer.
- They provide more nuanced data than a simple 'yes' or 'no'.

Limitations & Considerations:

- **Ordinal vs. Interval Data:** Technically, Likert data is **ordinal** (the responses have a clear order), but we don't know if the psychological distance between a '1' and '2' is the same as between a '5' and '6'. For practical analysis, this data is often treated as **interval** to calculate statistics like the mean.
- **Forced Choice:** This survey used a 6-point scale. With no middle option, respondents were required to lean toward a positive or negative response.
- **Subjectivity:** The term "effectiveness" can mean different things to different people.

B.2 Survey Details

A total of 66 employees were interviewed, 65 of which provided answers to the Likert questions during the course of the interview. Respondents were asked to reflect on their experiences within the joint team during the specified Starliner CFT mission timeframe and rate the effectiveness of five critical operational and cultural components. These areas were selected as key indicators of the team's ability to function cohesively and achieve its objectives under pressure. The five questions posed were:

Survey Questions:

1. On a scale of 1 to 6, how would you rate the effectiveness of the **organizational structure**?
2. On a scale of 1 to 6, how would you rate the effectiveness of the **communication**?
3. On a scale of 1 to 6, how would you rate the effectiveness of the **team dynamics**?
4. On a scale of 1 to 6, how would you rate the effectiveness of the **organizational culture**?
5. On a scale of 1 to 6, how would you rate the effectiveness of the **decision making**?

Rating Scale: 1 (Least Effective) to 6 (Most Effective).

The responses from the 65 interviews were first aggregated and analyzed by affiliation (Boeing, NASA Organizations) and then by interviewee tier, to determine the central tendencies of the data, providing a comprehensive snapshot of the collective sentiment for each of these core areas.

B.3 Summary of Observations

The table below summarizes the **mean** (average score) and the **mode** (most frequent score) for all interviewees. The mathematical midpoint of the scale is 3.5. Figure 1 displays the distribution of positive and negative responses utilizing a diverging stacked bar chart.

Area of Assessment	Mean Score (out of 6)	Mode
Organizational Structure	2.99	2
Communication	3.25	3
Team Dynamics	2.59	2
Organizational Culture	3.00	3
Decision Making	3.30	3

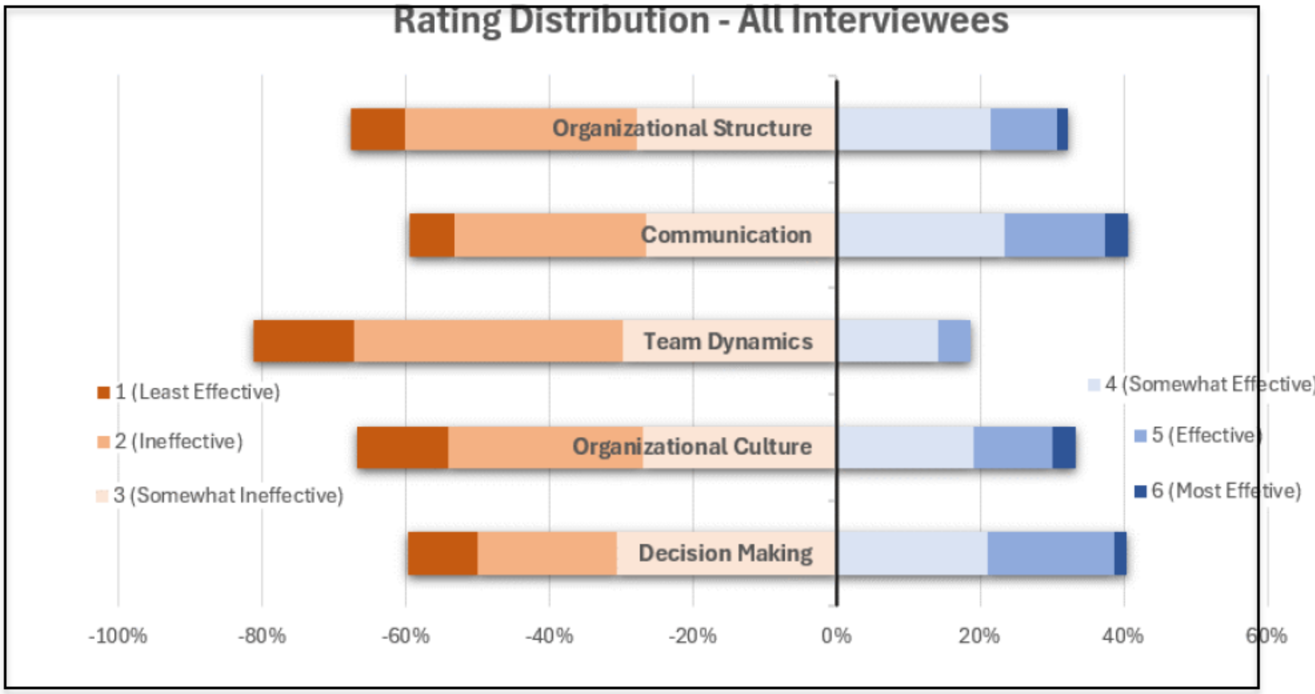


Figure 78: Rating Distribution of All Interviewees

The data from the full team reveals a consistent perception of ineffectiveness across all measured aspects of the joint team's performance. Every category's **mean** score fell below the neutral midpoint of 3.5 on the 6-point scale, indicating that, on average, employees had a negative experience. The analysis of the mode, or most frequent score, reinforces this conclusion and points to specific areas of critical concern.

Key Observations:

Team Dynamics is the most critical issue: With a mean score of 2.59 and 81.25% of respondents rating negatively, Team Dynamics was rated as the least effective area by a significant margin. This low average is strongly supported by its mode of 2 ("ineffective"), which was the most common rating given by respondents. This combination shows a clear consensus that interpersonal and team collaboration was a major pain point during the mission.

Structural and Cultural Weaknesses: Organizational Structure also received low ratings, with a mean of 2.99 and a mode of 2. Like Team Dynamics, this indicates that the team's framework and hierarchy were widely seen as ineffective, not just by a few individuals. Organizational Culture (mean 3.00, and mode 3), was perceived similarly, suggesting the team's shared values and environment were not conducive to success.

Communication and Decision Making were "Less Bad," Not Good: While Decision Making (mean 3.30) and Communication (mean 3.25) were the highest-rated areas, they still fall on the negative side of the scale. Their shared mode of 3 ("Somewhat Ineffective") shows that the most common experience was still negative. These areas weren't strengths; they were simply perceived as less problematic than the core issues of team dynamics and structure.

The following charts will provide a visual breakdown of the distribution of responses for each question sorted by the interviewee's affiliation during the Starliner CFT mission, offering deeper insights into the nuances of the team's perceived effectiveness during the mission.

The following charts will provide a visual breakdown of the distribution of responses for each question sorted by the interviewee's organizational **tier,** during the Starliner CFT mission.

Interviewees were placed into the following organizational tiers and the analysis are presented here to observe differences in perceptions based on level of organization: Agency Leadership, Center Leadership, Board Chair, Board Rep, and Technical Expert.

Legend

- 1 (Least Effective)
- 2 (Ineffective)
- 3 (Somewhat Ineffective)
- 4 (Somewhat Effective)
- 5 (Effective)
- 6 (Most Effetive)

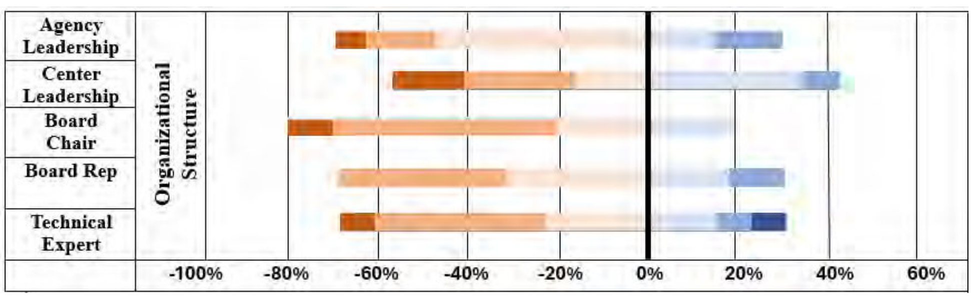


Figure 79: Organizational Structure

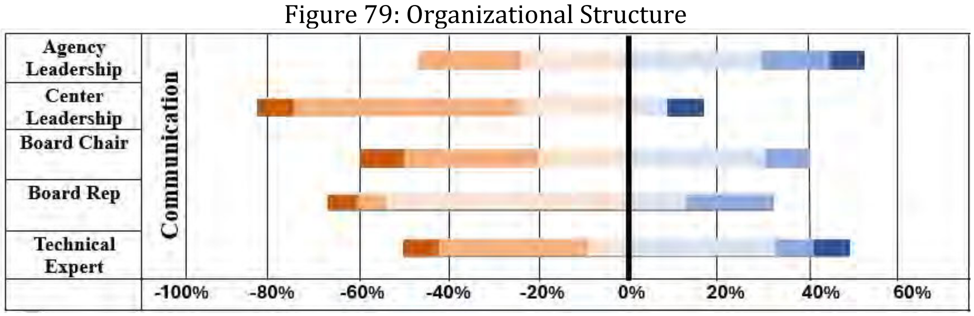


Figure 80: Communication

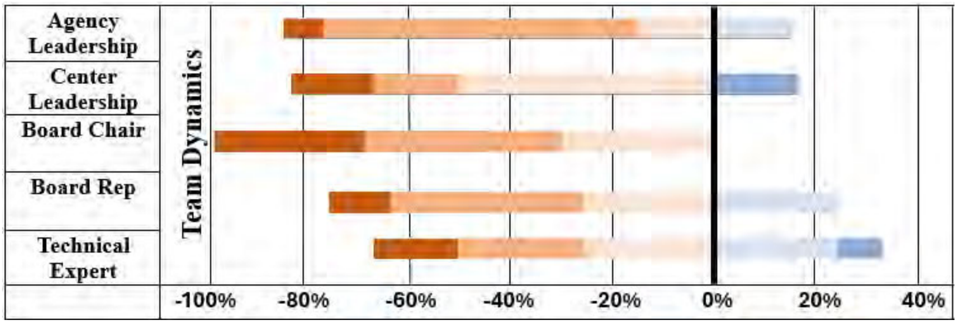


Figure 81: Team Dynamics

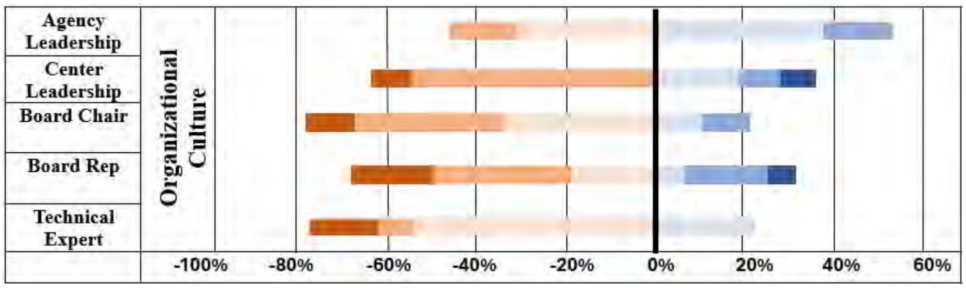


Figure 82: Organizational Culture

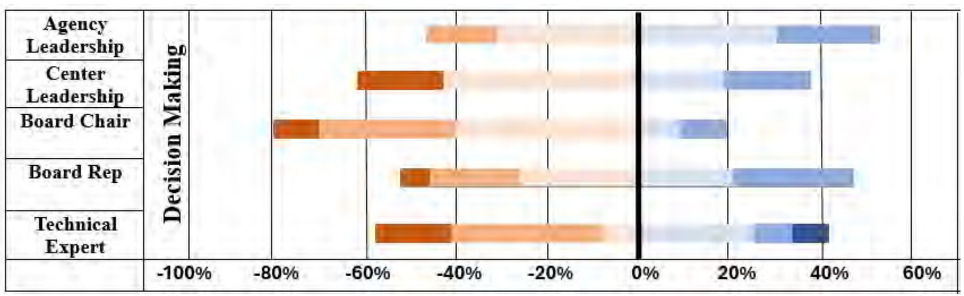


Figure 83: Decision Making

Appendix C. References

[redacted]

Significant Starliner PCBs and Documentation for Prop System

[redacted]

[redacted]

[redacted]

CFT Timeline Links

CFT Meetings from Agency FRR to Launch

[redacted]

[redacted]

CCP Program Control Board Meetings from Launch to Undock

[redacted]

[redacted]

[redacted]

CCP Program Control Board Meetings from Launch to Undock related only to Prop

[redacted]

[redacted]

Starliner Mission Management Team Meetings from Launch to Undock

[redacted]

[redacted]

Starliner CCP ERBs from Go/No-GO to Return

[redacted]

[redacted]

[redacted]

Appendix D. Acronyms, Tables, and Figures

AA	Associate Administrator
AFRR	Agency Flight Readiness Review
ARMO	Agency Risk Management Officer
ATP	Acceptance Test Proceedure
CCDev	Commercial Crew Development
CCP	Commercial Crew Program
CCtCap	Commercial Crew Transportation Capability
CCTS	Commercial Crew Transportation System
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CFT	Crewed Flight Test
CKO	Chief Knowledge Officer
CM	Crew Module
CoFR	Certification of Flight Readiness
CRS	Commercial ReSupply
DDT&E	Design, Development, Test, and Evaluation
DOF	Degrees of Freedom
ECQ	Executive Core Qualifications
EDL	Entry, Descent, and Landing
eRCCA	Enterprise Root Cause/Corrective Action
FDIR	Fault Detection and Isolation Reports
FMC	Flight Management Computer
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FOD	Flight Operations Directorate
FOD	Foreign Object Debris
FORP	Fuel Oxidizer Residual Propellant
FRR	Flight Readiness Review
FSW	Flight Software
FT	Fault Tolerant
GNC	Guidance Navigation and Control
He	Helium
HHP	Human Health Performance
HSF	Human Space Flight
HVCC	High Visibility Close Call
IFA	In-Flight Anomaly
IHS	ISS Hazard System
IMMT	ISS Mission Management Team
IPC	Integrated Propulsion Controller
IRT	Independent Review Team
ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
KOS	Keep-Out Sphere
LEO	Low Earth Orbit
LRC	Langley Research Center

MET	Mission Elapsed Time
MIB	Mishap Investigation Board
MIOMP	Mission Integration and Operations Management Plan
MIP	Mission Implementation Plan
MMH	Monomethyl Hydrazine
MMOD	Micro-Metroid Orbital Debris
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASAHFACS	NASA Human Factors Analysis and Classification System
NESC	NASA Engineering Safety Center
NMIS	NASA Mishap Information System
NOM	NASA Operations Manager
NTO	Nitrogen Tetroxide
OCE	Office of Chief Engineer
OFT	Orbital Flight Test
OMAC	Orbital Manoeuvring and Attitude Control
OP	Office of Procurement
OSB	Outside-of-Board
PCBs	Program Control Boards
PDR	Preliminary Design Review
PIT	Program Investigation Team
PM	Program Manager
RCS	Reaction Control System
RCCA	Root Cause/Corrective Action
SAA	Space Act Agreements
SCE	Spacecraft Chief Engineer
SDRT	Starliner Data Review Team
SM	Service Module
SMC	System Management Computer
SME	Subject Matter Expert
SMMT	Starliner Mission Management Team
SOMD	Space Operations Mission Directorate
SRP	Safety Review Process
STAR	Starliner Test and Anomalies Review
TA	Technical Authority
Therm11a	Thermal Environment
TLYF	Test Like You Fly
UA	Unexplained Anomaly
ULA	United Launch Alliance
UVF	Unverified Failure
WGS	Wideband Global Satcom
WSSH	White Sands Space Harbor
WSTF	White Sands Testing Facility
ZOT	Hot Spot Combustion

Table List:

3. Propulsion System Data
4. Definitions of Key Areas
5. Key Focus Area Effectiveness Ratings

Figures List:

Appendix E. Organizational Trust Plan (Sample)

Goal:

To rebuild and repair trust and confidence between NASA and Boeing teams by establishing clear expectations, open accountability, and shared commitment to safety and mission success—starting with leadership and expanding to all team members.

Objectives:

1. **Restore Confidence** in leadership and team alignment through transparent communication and accountability.
2. **Address Historical Issues** by acknowledging past challenges and misaligned expectations.
3. **Reinforce Shared Values** of safety, integrity, and mission success.
4. **Strengthen Team Partnerships** through structured engagement and facilitated collaboration.

Action Steps:

1. Leadership Engagement (Start Immediately)
- CCP leads the development and execution of the plan.
- Initiate program managers, Technical Authority organizational leaders, and Boeing counterparts.
- Conduct facilitated sessions to openly discuss team challenges
- Express accountability outwardly to show accountability for missteps and seek feedback and input how to repair trust and rebuild confidence across the teams.

2. Teamwide Rollout
- Expand sessions to include other key NASA and Boeing team members.
- Use structured team-building activities to address grievances and rebuild rapport.
- Ensure leadership continues to stay engaged and actively participate in the process to display commitment to continue learning and developing

3. Training & Development
- Implement *Covey's Speed of Trust* course for intact teams.
- Provide coaching and tools to reinforce trust-building behaviors.

4. Communication & Documentation
- Develop and share a written plan outlining expectations, commitments, and partnership principles.
- Reinforce shared values through regular updates and visible leadership support.

5. Timing & Milestones
- Launch plan well before the next major mission milestone.
- Monitor progress and adjust based on feedback and team dynamics.

Expected Outcomes:

- Improved trust and collaboration across NASA–Boeing teams.
- Increased confidence in leadership and team alignment.
- Stronger focus on mission execution and safety.

Appendix F. Investigation Team Chartering Memo

National Aeronautics and Space Administration

Mary W. Jackson NASA Headquarters
Washington, DC 20546-0001

February 14, 2025

Reply to Attn of: Space Operations Mission Directorate

TO: Distribution

FROM: Associate Administrator, Space Operations Mission Directorate

SUBJECT: Transition to Program Investigation Team for Starliner Propulsion Anomalies in International Space Station Proximity

After the initial launch attempt and during the June 2024 Crewed Flight Test (CFT) of Starliner, the spacecraft experienced several Service Module (SM) propulsion system anomalies (i.e. helium leakage and underperforming reaction control engines) that the NASA Commercial Crew Program (CCP) and Boeing teams began investigating immediately after docking during the mission. The investigation was focused on the execution of the remainder of the mission including undocking from the International Space Station (ISS), operations in the proximity of the ISS, execution of the Starliner deorbit burn, SM separation from the Crew Module (CM) following the deorbit burn, and SM disposal with implications to public safety. This in-flight investigation was guided by the high visibility close call approach outlined in NASA Procedural Requirement (NPR) 8621.1D, due to the high visibility of these failures and the potential implications to the ISS/Starliner crew and to public safety.

Prior to launch, a SM propulsion system helium manifold was found to be leaking. Joint NASA and Boeing teams reviewed worst-case loss of helium pressurant capability and concluded the risk of subsequent failures was sufficiently low, and that the capability to complete the mission was sufficient to proceed to launch. After launch, additional helium system leaks were detected in free-flight, as well as post-docking to ISS, resulting in a total of six known manifold leaks in the helium pressurant system. These helium system leaks resulted in a degraded capability for controlling pressurization of propellant during the mission and the heightened potential for an increased risk to control of the spacecraft for return.

An additional anomaly led to five SM Reaction Control System (RCS) thruster fail-offs during the rendezvous and approach to ISS due to overheating of the thrusters. Data reviews in real-time concluded that a loss of redundancy of the thrusters resulted in a temporary loss of Starliner attitude and translational control during the approach within the ISS Approach Ellipsoid, violating the Flight Rule to maintain 6 Degree-of-Freedom control of a spacecraft inside the Approach Ellipsoid. Recovery of the thrusters via ground command hotfires and crew manual flying allowed the Starliner to dock successfully. Uncertainty in the predicted performance of the SM RCS thrusters led to the decision to undock and return Starliner uncrewed.

Following undock, CM thruster hot-fires determined one thruster was failed, causing the CM to perform re-entry in a zero fault tolerant state. The CM prop system provides entry attitude control and loss of redundancy in this system puts safe return of the capsule at risk.

NASA and Boeing have formed several teams to continue to investigate the failures that transpired during the CFT:

1) Boeing and NASA have a combined Testing, Analysis, and Hardware team that is in the process of defining the hardware and software changes and associated qualification testing and analysis required to resume Starliner missions.
2) NASA has instituted a Starliner Tests and Anomalies Review (STAR) team to examine the deficiencies in the NASA certification process all the way back to the early design reviews of the Starliner SM propulsion system.
3) A STAR Senior Review Team consisting of senior leaders across the Agency has been chartered to review the progress of the STAR team, provide feedback and further areas of interest as the team progresses through their investigation.
4) NASA has initiated a data review team to examine the real-time flight data from the previous Orbital Flight Tests to understand why these anomalies were not detected during the post flight reviews for these first two test missions.
5) Boeing has initiated an Enterprise Root Cause Corrective Action (RCCA) team to determine why the Boeing development and testing processes that were utilized for Starliner allowed for these design deficiencies to be present for the CFT. Boeing has also chartered RCCA teams for each In-Flight Anomaly (IFA) under review from the CFT mission.

After discussion with NASA's technical authorities, ISS Program Manager; and Commercial Crew Program Manager, a transition of this work to a NASA independent team was deemed necessary.

In accordance with the ISS Contingency Action Plan (SSP50190); the CCP Mishap Preparedness Contingency Action Plan (CCP-PLN-1010); NASA Procedural Requirement (NPR) 8621.1D; and with the concurrence of the Space Operations Mission Directorate (SOMD), the Programs are convening a Program Investigation Team (PIT) using the ISS program work instruction (OA-WI-007 paragraph 3.1) in response to these events. A cross reference to NPR 8621.1D is included to demonstrate the completeness of this effort to Agency policy.

The scope of the PIT is outlined below, with the intent to examine the anomalies and causal factors and to provide recommendations for future Starliner missions and similar NASA missions going forward. As defined earlier, a review of the anomalies and their causes has continued post flight to provide valuable data and insight to the PIT. The PIT will leverage the work that has already been performed to minimize duplication and preserve limited resources to enable them to proceed more rapidly to their final report.

Ms. Rebecca Wingfield will lead the PIT with a deputy to be named at a later date. The PIT will be a NASA-led activity with Boeing participation. As needed, the primary team members will draw on Agency expertise and perspectives to supplement the team's understanding. The PIT will develop an investigation plan for ISS and CCP for approval with the following elements as appropriate:

1) Team membership
2) Expected scope of the investigation
3) Planned analysis techniques
4) Required resources
5) Schedule
6) Out-briefing plans

The STAR Senior Review Team will remain in place, advising the STAR team until their report is complete. The STAR Senior Review Team is also requested to advise and guide the CFT PIT - meeting periodically with the PIT leadership to review progress and provide advice as to areas of investigation. The STAR Senior Review Team membership may be adjusted as appropriate to assist the CFT PIT - if requested by the Senior Review Team and approved by the SOMD AA. The PIT will provide a monthly interim brief to the SOMD AA and NASA technical authorities until its conclusion. The ISS and CCP program managers will have monthly touch points with the team and will ensure periodic briefings to affected Center Directors. Upon completion of this investigation, which is targeted for no later than May 30, 2025, the PIT will generate a findings report and submit/present it to the Program managers for review prior to final submission to SOMD and other Agency leadership. The scope includes the following:

1) Identify causes and factors that led to the propulsion system in-flight anomalies, including issues from previous flights, programmatic culture, programmatic resources, pre-flight processes, analysis, and test plans that led to a Go for launch with reduced understanding of system capabilities.
2) Develop recommendations for changes to future missions, including certification, processes, procedures, testing, analytical methods, and in-flight operations.
3) Develop a fault tree for the helium leak, SM RCS thruster and CM thruster issues with findings in the final report to include as many of the following items as applicable:
    a. Proximate cause(s)
    b. Intermediate cause(s)
    c. Contributing factors
    d. Organization factors
    e. Observations

f. Recommendations

4) In addition to technical preflight decisions and real-time response factors, assess meeting/team/organization structure, contractor and contractual relationship, effectiveness in team decision making, and any potential cultural barriers or organizational factors that contributed to the findings.

The CCP STAR and OFT data review teams should continue their investigations to a proper conclusion since those teams have already developed several recommendations that can benefit other Programs using a similar fixed price service contact model. Data from these teams will be provided to the PIT to inform the PIT areas of concentration.

The PIT investigation will require support from multiple organizations and should engage resources from various NASA Centers and Boeing as necessary. Please cooperate fully with this investigation and provide any technical data, expertise, or other support to this investigation.

Kenneth
Bowersox

Kenneth D. Bowersox

Enclosure

[redacted]

Appendix A – NPR 8621.1D Cross Reference

NPR8621.1D Section	Included in Proposed HVCC PIT
Chapter 2. Mishap Response, Notification, and Classification	
2.1 Initial Mishap Response	N/A
2.2 Initial Mishap Notifications	N/A
2.3 Post-Mishap Notifications	N/A
Chapter 3. Investigating Authority and Investigation Support	
Selection	
3.1 Appointing Official Determination	✓
3.2 Investigating Authority Member Selection	✓
3.3 Investigating Authority Advisor Selection	Partial: No legal, No PAO, Yes to NSC specialist
3.4 Investigating Authority Consultant Selection	No Non NASA participants
3.5 Appointment Letter Content	✓
Chapter 4. Mishap Investigation Process	
4.1 Mishap Investigation Analysis	✓
4.2 Site Safety and Evidence Preservation and Impoundment	N/A
4.3 Evidence and Fact Gathering	✓
4.4 Findings Determination	✓
4.5 Recommendations Generation.	✓
4.6 Status Reports	✓
4.7 Other Investigation Types	✓ Inclduing real-time decision making
4.8 Mishap Site Release	N/A
Chapter 5. Mishap Investigation Report	
5.1 Mishap Investigation Report Development	✓
5.2 Investigating Authority Release	✓
5.3 Mishap Investigation Report Review, Endorsement, and Approval	✓
5.4 Mishap Investigation Report Distribution	✓
Chapter 6. Post-Investigation Activities*	
6.1 Corrective Action Plan Development	
6.2 Corrective Action Plan Contents	
6.3 Corrective Action Plan Review and Approval	
6.4 Corrective Action Plan Implementation	
6.5 Corrective Action Plan Monitoring and Close Out	
6.6 Lessons Learned Development, Disposition, Submittal, and Approval	
6.7 Investigation Activities Conclusion	
6.8 Evidence Recording and Retention	

* The PIT will provide recommendations and SOMD and CCP will develop an action plan based on available resources

Enclosure

Appendix G. CCP STAR/SDRT Report

- **STAR Investigation Team / SDRT Final Report**
- **CUI STAR Investigation Team and Starliner Data Review Team Lessons Learned Briefing**
- **STAR/SDRT Lessons Learned Presentation**

If you cannot access any of the above links, please enter through NEN > Lessons Learned to allow your NASA certificate to be recognized. Please share as desired within NASA.

Commercial Crew Program
Starliner Tests & Anomalies Review (STAR) Investigation Team
and
Starliner Data Review Team (SDRT)
Report
May 20, 2025

Original signed on 5/20/2025

Dana M. Hutcherson
Chair, STAR Investigation Team
Deputy Manager, Commercial Crew Program

Original signed on 5/20/2025

James H. McMichael
Chair, SDRT
Senior Technical Integration Manager, Commercial Crew Program

Concurred by:

Original signed on 7/15/2025

Joseph "Steve" Stich
Manager, Commercial Crew Program

Starliner Tests & Anomalies Review Investigation Team Report

Commercial Crew Program
Internal Program Investigation

Executive Summary

Background

Jim Free, former NASA Associate Administrator (AA); Ken Bowersox, Space Operations Mission Directorate AA; and Steve Stich, Commercial Crew Program (CCP) Manager commissioned the Starliner Tests and Anomalies Review (STAR) Investigation Team as an internal CCP investigation, led by Dana Hutcherson, that was to identify any lessons learned regarding initial certification approaches that could have prevented propulsion system anomalies experienced during Crew Flight Test (CFT).

[redacted]

Introduction

The purpose of this report is to provide the results of the internal Commercial Crew Program Investigation of Starliner key anomalies identified during CFT.

The team was charged to address such questions during the evaluations and interviews:

- Opportunities for NASA identification of missed failure tolerance assessment and consideration related to deorbit burn impacts in consideration of the helium system within each doghouse
- Opportunities for NASA identification of missed Service Module (SM) Reaction Control System (RCS) thruster qualification gap and the closure of those gaps during thruster qualification timeframe
- Opportunities for NASA identification of inadequately defined SM doghouse thermal environment and the closure of those gaps in the design and qualification timeframe
- Ascertain if these propulsion items were not identified during execution of required propulsion system Preliminary Design Review (PDR) or Critical Design Review (CDR) or subsystem reviews, qualification testing, integrated SM hotfire testing, hazard report reviews and/or certification reviews, post mission reviews, etc.

Results

Findings – notable items uncovered during the documentation and interview process
Recommendations – explicit for Commercial Crew to implement before the next flight, or as practical
Lessons Learned – external value to other NASA Programs

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STAR Investigative Methods

Special Note

The STAR Investigation Team heard many lessons learned from the interviewees that involved the provider and a summary has been provided to the provider. However, the purpose of this investigation was to identify ways that NASA could have prevented the CFT Starliner propulsion anomalies so this report will focus on those NASA related findings.

Evaluation Approach

- Collect historical data
- Interview key members with CCP heritage experience
- Prepare report and share lessons learned

STAR Investigation Team Members

- [redacted]

[redacted]

- [redacted]

[redacted]

[redacted]

- [redacted]

[redacted]

- [redacted]

[redacted]

STAR Senior Review Panel Purpose

The Senior Review Panel will check in with the STAR Investigation Team at regular intervals to provide feedback and further questions to explore during the process. The STAR Investigation Team will share Commercial Crew history, DDT&E/Certification analysis, and findings uncovered during the interview process and report building.

STAR Scope

The STAR Investigation Team (hereafter, STAR) reviewed historical data, interviewed Commercial Crew experts, and provided evaluations to include exploring some of the following items:

- Lifecycle of Boeing propulsion system design
- Shared accountability model including consideration of Boeing outsource of propulsion system to Aerojet Rocketdyne (AR)
- Boeing propulsion CDR and subsystem reviews
  - Early trades and design activities under limitations during Space Act Agreements (SAAs)
- Propulsion resources applied to Boeing and SpaceX by the Program
- Processes for failure tolerance evaluation
- Certification approach (Hazard Report (HR), Verification Closure Notice (VCN), variance, design, and construction standards)
- Phased Safety Review (Hazard Report) process

- Applicable component, propulsion system, and spaceflight utilization knowledge level of personnel
- Review of Boeing propulsion qualification testing
- Boeing SM hotfire testing at White Sands Test Facility (WSTF)
- Independent analysis of propulsion system
- Interdisciplinary system engineering (e.g. doghouse thermal environment)
- Access to Boeing and vendor data

Investigative Process/Timeline

Activity	Draft Timeline
Build Timeline of Events • Contracts/Procurement – Boeing Commercial Crew Integrated Capability (CCiCap), Certification Products Contract (CPC), Commercial Crew Transportation Capability (CCtCap) • Commercial Crew requirements • Boeing DDT&E plus certification for Boeing propulsion systems • Program milestones including SpaceX missions	Start 10/28/24 Finish 11/15/24
Collect Boeing propulsion system data for background information and develop pre-reading material • CPC summaries and technical evaluations, milestone documentation, deliveries, Program Control Boards (PCBs), Directives	Finish 11/15/24
Prepare for Interviews	Finish 11/15/24
Conduct interviews	11/18/24 – 12/18/24 1/7/25 – 1/30/25
STAR Senior Review Panel status meetings	12/5/24; 1/17/25; 2/27/25
Send first draft of causes/themes to review team for recommendations input	1/31/25
Identify key themes and develop report	Through Early March
Brief Senior Review Team, CCP Management, Space Operations Mission Directorate (SOMD) management, Program Investigation Team (PIT), CCP PCB, Aerospace Safety Advisory Panel (ASAP)	2/17/25 – 4/30/25
Prepare outbrief presentations roadshow for lessons learned for other commercially focused programs	April 2025
Release final report	May 2025

Analysis Methods, Processes, and Tools

The team began by collecting historical data.

STAR researched and reviewed:

- CCP requirements and applicable standards related to propulsion
- CCP Boeing SAAs
- CCP Boeing contracts
- Boeing deliverables including all propulsion related variances and dispositions
- Boeing technical reviews including select propulsion related comments, Review Item Dispositions/ Discrepancies (RIDs)
- Boeing milestones
- CCP processes and procedures
- Other Commercial Crew activities concurrently competing with limited resources

STAR built a timeline:

- Boeing SAAs and Contract Milestones
- Boeing Certification Milestones and Formal Reviews
- Other Commercial Crew activities concurrently competing for limited resources

STAR interviewed about 40 key members with Commercial Crew heritage experience from:

- Commercial Crew Program
- Engineering at KSC, JSC, and Marshal Space Flight Center (MSFC)
- S&MA at KSC and JSC
- FOD including Mission Operations and Crew
- ISS Program

Once the interviews were completed, the team documented the results in the final report with findings and recommendations.

Parallel CFT Investigative Efforts

NASA and Boeing formed several teams to continue to investigate the failures that transpired during the CFT.

- Boeing and NASA have a combined testing, analysis, and hardware team that is in the process of defining hardware and software changes along with associated qualification testing and analysis required to resume Starliner missions.
- NASA instituted the STAR Investigation Team to examine the deficiencies in the NASA certification process to include the early design reviews of the Starliner SM propulsion system.
- NASA instituted the Starliner Data Review Team (SDRT) to examine the real-time flight data from previous Orbital Flight Tests to understand why these anomalies were not identified during the post-flight reviews for previous test missions and ground testing.
- NASA chartered the STAR Senior Review Panel consisting of senior leaders across the Agency to review the progress of the STAR and SDRT teams, provide feedback and further areas of interest as the team progressed through their investigation.
- Boeing initiated an enterprise Root Cause Corrective Action (RCCA) team to determine why the Boeing development and testing processes that were utilized for Starliner allowed for these design deficiencies to be present for the CFT. Boeing has also chartered RCCA teams for each In-Flight Anomaly (IFA) under review from the CFT mission.

After discussion with NASA's technical authorities (TAs), ISS Program Manager, and Commercial Crew Program Manager, a transition of this work to a NASA independent team was deemed necessary.

In accordance with the ISS Contingency Action Plan (SSP50190), the CCP Mishap Preparedness Contingency Action Plan (CCP-PLN-1010), NASA Procedural Requirement (NPR) 8621.1D and with the concurrence of the SOMD leadership, the Programs are convening a PIT using the ISS program work instruction (OA-WI-007 paragraph 3.1) in response to these events.

Additional Commercial Crew initiatives:

- CFT lessons learned process (standard operating procedure for each mission)
- IFA review process (standard operating procedure for each mission)
- Engineering review of previously approved certification products

Summary of Boeing Starliner CFT

Event	Result/Comments
Pre-Launch	**Starliner launched with a known small helium leak in an SM RCS isolated to a single RCS thruster port doghouse manifold 2 (P2D2) flange.** Accepted at 2x5 risk based on worst case leak rates of several thrusters, feed the leak analysis, and resulting helium margins.
Launch	**Nominal CFT launch occurred on June 5, 2024**
Day 1 on Orbit	**After achieving a successful orbit five additional small helium leaks were discovered.** Upon leak rate review and reconsideration of helium margins a 'GO' was given to dock with the ISS.
ISS Rendezvous & Proximity Operations	**On approach to ISS, five SM RCS thrusters were de-selected by the flight software due to exceeding fail off performance limits.** All thrusters were immediately hot fire tested by re-selecting but showed signs of degradation. After assessment a 'GO' was given to dock with ISS.
Docking	**Starliner successfully docked with ISS on June 6, 2024.**
Safe Haven	**Starliner was determined to be acceptable based on performance to serve as an emergency egress vehicle from ISS if required on June 7, 2024.**
Mission Testing	**Extensive ground and flight testing was performed during the mission to understand root cause for the helium leaks and the RCS thruster fail offs and potential interrelationships between the two and determine flight worthiness to return crew.** Included two separate docked hot fire tests of the SM RCS where 27 of 28 thrusters were nominal and extensive ground testing at WSTF of a single engine with disassembly and inspection. Note: Gap in RCS qualification for mission profile was identified and considered.
Agency Reviews	**Flight rationale was prepared for both the SM RCS helium and SM RCS thruster anomalies with Boeing's recommendation to undock and return nominally with crew.** NASA did not accept the flight rationale and decided to return Starliner un-crewed.
Undock/Landing	**Starliner undocked, re-entered and landed successfully as predicted on September 6, 2024.**

Boeing's Starliner successfully launched atop a United Launch Alliance Atlas V rocket and reached orbit on June 5, 2024. The Starliner CFT launched with a known small helium leak isolated to thruster P2D2 flange in a SM RCS thruster. Leading up to the launch, the 2x5 risk was accepted based on worst-case leak rates of several thrusters by the Commercial Crew PCB at PCB-24-196[7] on May 23, 2024, with a CFT constraint that lack of 2-fault tolerance for de-orbit be accepted at PCB prior to CFT. That constraint was cleared the following day when Boeing CFT CST-100 risk acceptance for SM system being 1-Fault Tolerant for deorbit was accepted at PCB-24-199[8] on May 24, 2024. A delta Agency Flight Test Readiness Review (FTRR) was held at CoFR-24-028[9] on May 29, 2024, and the poll was unanimous to go for launch with one Commercial Crew CoFR exception, CoFR-24-028-E-1[10], regarding the Boeing CFT SM helium leak management which was subsequently signed on May 31, 2024.

Performance issues were identified in Starliner's SM propulsion system during free flight rendezvous and post docking with the ISS including:

- Five additional small Helium system leaks (three pre-docking and two post-docking).
- Fail offs of five RCS thrusters.
- Operations teams performed a series of hot-fire tests which re-enabled four of the five thrusters. Upon review, a 'Go' was given to dock with the ISS. During ISS rendezvous and proximity operations, five SM RCS thrusters were de-selected by the flight software due to exceeding fail off performance limits. All thrusters were hot fire tested by re-selecting but showed signs of degradation. Starliner successfully docked with ISS on June 6, 2024.

The Starliner Mission Management Team (MMT) meeting at MMT-24-018[11] on June 7, 2024, determined Starliner was acceptable to serve as a safe haven emergency egress vehicle from ISS if required.

While safely docked to station, NASA and Boeing performed extensive ground and flight testing and analysis to evaluate Starliner's performance, understand root cause, and determine flight worthiness to return crew. Testing included two separate docked hot fire tests of the SM RCS where 27 of 28 thrusters performed nominally.

NASA and Boeing

- conducted an extensive fault tree investigation working closely with Boeing's propulsion system suppliers,
- conducted additional in-space hot-fire testing,
- conducted additional ground testing at NASA's WSTF in New Mexico,
- completed additional studies of system fluid and mechanical operations and established probable cause of the helium and RCS thruster failures to better inform performance predictions for the return flight, and
- brought in independent propulsion system experts from across NASA and the Boeing enterprise for an independent assessment of the risk and recommendations on the path forward.

During this time period extensive ground testing of a single engine, including disassembly and inspection, was conducted in conjunction with a review of the original RCS qualification testing in which a gap in RCS qualification for the mission profile was identified.

7 [redacted]
8 [redacted]
9 [redacted]
10 [redacted]
11 [redacted]

Commercial Crew worked with the ISS Program and SpaceX to provide operational flexibility, adjusting the scheduled crewed handover with SpaceX to alleviate schedule pressure and compressed timelines. In the end, the Commercial Crew recommendation to return Starliner uncrewed was presented and unanimously accepted by Agency leadership by the Boeing CFT delta Return Agency FTRR at CoFR-24-035[12] Part 1 on August 24, 2024.

Ultimately, Starliner completed an uncrewed autonomous undocking from the ISS on September 6, 2024, followed by a successful de-orbit, spacecraft separation, descent, landing, and recovery on September 7, 2024. Overall, Starliner performed well across all major systems in the undock, deorbit, and landing sequences. The SM propulsion system performed well. Helium system leaks remained in family requiring no in-flight management and SM thrusters remained healthy. However, the crew module propulsion system experienced a failed RCS thruster. Boeing performed an inspection and began an investigation immediately following recovery of the capsule. NASA was fortunate to have instrumentation and data collection capability that allowed most of the return test flight objectives to be met, even without crew on board. As a result of the extended flight test duration, numerous lessons were documented that will benefit NASA and Boeing in support of future Starliner crew rotation missions.

Post Mission Summary
A number of flight test objectives were completed even though the Starliner spacecraft was return uncrewed.

- CFT Mission Flight Test Objectives (FTOs)
  - FTOs – 347 Total: 311 met, 24 partially met or opportunity objectives, 12 impacted by un-crewed return.
- Completed Preflight Objectives
  - Executed activities involving the crew and critical ground support personnel.
  - Successfully executed astronaut suit-up procedures and transport to pad.
  - Successfully executed crew ingress, hatch closure, and leak checks.
  - Successfully executed critical safety tasks in cabin.
    - Evaluated spacesuit and seat functionality
    - Assessed the in-cabin environment and life support systems
    - Manually armed the Launch Abort System
    - Established effective and reliable in-cabin communication with the crew
  - Gained experience working through prelaunch issues and executing crewed launch scrubs.
- Completed Docked Objectives
  - Starliner successfully completed an autonomous docking.
  - Nominal hatch opening and closing operations essential for visiting vehicles were performed.
  - Configured the spacecraft in and out of quiescent operations.

12 [redacted]

  - Completed critical activities like the transfer of emergency equipment and other cargo.
  - Successfully executed “safe haven” exercises and a real-life demonstration of crew procedures to power up the spacecraft, shelter inside the cabin, and prepare for a possible undocking.
- Significantly more data obtained than originally expected (docked for 3 months vs 10 days).
  - Thermal and power were able to collect data at maximum beta angle and multiple beta cycles.
  - Lessons learned were captured for improvements in build, test, and operations.
  - Model correlation data is being incorporated to reduce uncertainty in predictions.

Commercial Crew Program Background

NASA's Commercial Crew Program was established[13] to facilitate the development of a U.S. commercial crew space transportation capability with the goal of achieving safe, reliable, and cost-effective access to and from LEO and the ISS. From the Program's inception, NASA has remained committed to ensuring that the requirements, standards, and processes for all commercial missions are held to the same safety standards as Government human spaceflight missions. NASA also remains accountable to its International Partners for the safety of crews traveling to and from the ISS on NASA missions pursuant to its international obligations. NASA plans to fulfill these obligations through certification of commercial, crewed transportation systems (CTS), which requires skilled NASA insight in the early crewed missions and continued oversight and surveillance for crewed operational missions. Commercial Crew serves a distinguished role in sharing NASA's human spaceflight expertise with Commercial Providers who strive to develop a CTS, while balancing NASA's responsibility to ensure the safety of its crews.

Commercial Crew leveraged the experiences of the NASA commercial programs, including Commercial Orbital Transportation Services (COTS) / Cargo Resupply Services (CRS) and Launch Services Program (LSP), and led the change in NASA's human spaceflight culture in its approach to managing the program's efforts.

The table below compares Full Time Equivalents (FTEs) for NASA's existing spaceflight programs, demonstrating the efficiencies of CCP.

	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25
Orion	663	662	678	632	593	546	513	495	493	499
SLS	922	959	937	881	875	858	876	772	766	768
EGS	505	524	509	489	520	531	513	483	483	483
Total for 1 CTS	**2,091**	**2,144**	**2,124**	**2,002**	**1,987**	**1,934**	**1,902**	**1,751**	**1,742**	**1,750**
LSP Total	**253**	**264**	**262**	**264**	**271**	**289**	**286**	**277**	**271**	**287**
CCP Total for 2 CTS	**311**	**341**	**339**	**358**	**347**	**340**	**344**	**330**	**324**	**314**

Note: FTEs forecasted for FY25 are provided as end of year projections based on FTE actuals as of April 2025

The Commercial Crew Program was expected to manage development and operations for two crew transportation systems for only 1/6th of the annual FTE of NASA's other human spaceflight program which is collectively working on a single crew transportation system.

CCP - *CCP - Boeing* *Artemis Program*

Figure 84 - CCP vs Artemis Crew Transportation Systems

[13] CCP - The Story of Us https://ccp.nas... ft%20022620%20updated.docx

First, NASA required its CCtCap contractors to integrate and deliver a complete CTS. This important aspect eliminates the need for NASA to perform the complex systems engineering and integration functions for major elements of the CTS, thereby enabling CCP to perform its primary function to oversee contractor performance for crew safety and mission assurance with fewer personnel.

Second, Commercial Crew has accomplished its efforts through a shared assurance model that minimizes overlap of responsibility within NASA by utilizing the most knowledgeable skills to support both oversight and insight activities, while meeting Agency requirements and maintaining necessary checks and balances. NASA implemented the shared assurance model through oversight activities which have been pre-declared through the CCtCap contract. The shared assurance model ensured that checks and balances are in place through clear delegations of authority, while eliminating overlapping efforts.

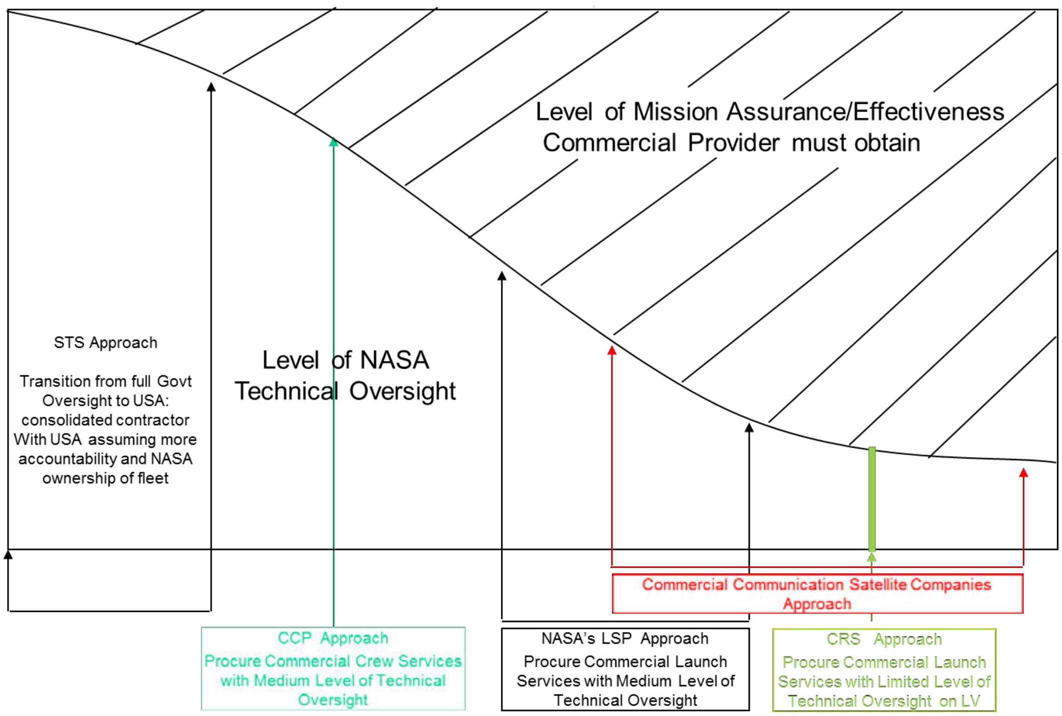


Figure 85 - NASA's Accountability for Mission Success Comparison

Third, Commercial Crew has relied on leveraging best-talent skills, facilities and other resources across the Agency regardless of location (including Cross-Center Supervision). Since inception, Commercial Crew applied a temporal model of FTE utilization across field Centers. The oversight/insight used by Commercial Crew engages technical experts and reach-back from other NASA organizations, resulting in assignment of "best person for the task", which was also successful in LSP, the robotic spacecraft projects, and the COTS/CRS teams.

Commercial Crew leveraged a solid base of expertise from multiple field Centers and has continued an outstanding record in the design, development, test, evaluation (DDT&E) and operation of two crew transportation systems in parallel. Commercial Crew provided the Agency with a single focus for developing commercial crewed transportation capabilities and maximizing the opportunity for industry to operate the systems without dependence on Government assets, all while ensuring compliance with NASA's human rating requirements.

In addition, Commercial Crew rose to meet the Agency's challenge to minimize all resources required for program execution. Commercial Crew helped to develop a new management paradigm that has provided NASA with the desired benefits of consolidated management and streamlined technical and administrative functions for a human spaceflight program.

Staffing a technical workforce adequately to support a two-partner profile has been slightly challenging due to:

- Center ceiling limitations
- Skills mix imbalances or shortages
- Competing resource requirements and
- Commercial Crew schedule conflicts driven by two parallel certifications

Since December 9, 2014, Commercial Crew briefed the NASA Associate Administrator and the APMC on its proposed approach for use of NASA resources and provided quarterly briefings of associated performance at the Baseline Performance Review and Directorate Program Manage Council (DPMC). Commercial Crew also worked across the Agency to optimize use of NASA's current workforce through the annual budget planning process and management briefings by employing:

- Shared Assurance
- Synergy with other programs
- Strong matrixed program support
- Clear communication of insight and oversight responsibilities and
- Minimized Program office footprint and maximized use of technical authorities

NASA's human spaceflight cadre has the unique expertise and talent of those who understand the demands of humans in the spaceflight system, distinguished from those driven by payload or robotic systems in space. Such operational skills related to human spaceflight in LEO are not yet distributed beyond NASA, including to the FAA, DoD or commercial providers in general.

Although certification maintenance is the responsibility of the Commercial Provider, NASA maintains oversight approval authority for any changes to the certification baseline. Alterations to launch vehicles, ground infrastructure, and spacecraft are anticipated to correct anomalies to increase safety and reliability. When any change or set of changes are deemed to affect the baseline established at CTS Certification, NASA will assess the need for a new CTS Certification or, in cases of unacceptable risk, nullify the Commercial Provider's NASA CTS Certification. Consequently, the FTE proposed in the outyears for Commercial Crew must be experts in the existing CTS certified system for timely management of proposed changes prior to crewed flight. NASA's experience with human spaceflight programs has shown that transition of civil service personnel during the critical timeframe from development to operations needs to be carefully planned and managed as we transition from ISS retirement to future commercial LEO destinations.

NASA has in place a Mission Management Team to oversee flight operations and make critical decisions for launch, docking, landing, early return, etc. NASA will ultimately be responsible for crew safety and mission success should there be a serious incident. A skilled team with the proper expertise is required to monitor and assess anomalies and vehicle performance to make the right decision during all aspects of launch, in-flight and recovery operations.

Direction from the Inception of Commercial Crew

NASA has collaborated with commercial companies in the development of critical capabilities necessary for an integrated CCTS. Companies were engaged in multiple ways given the timeframe and strategic needs of NASA and the companies.

Funded SAAs

- Commercial Crew Development (CCDev): NASA provided limited technical assistance focused on the advancement of orbital CCTS initial concepts.
- Commercial Crew Development 2 (CCDev2): NASA provided limited technical assistance focused on advancing orbital CCTS concepts and enabling significant progress on maturing the design and development of all elements of the system.
- Commercial Crew Integrated Capability (CCiCap): NASA provided limited technical assistance focused on enabling significant progress on maturing the design and development of an integrated commercial space transportation system.

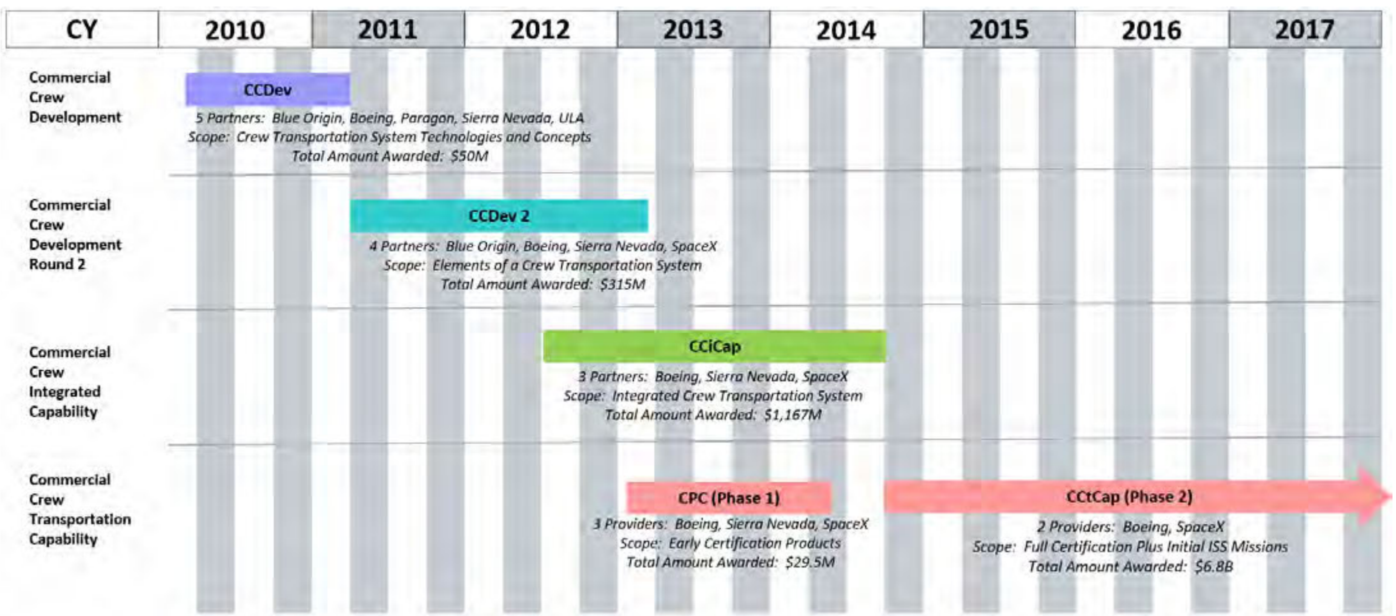


Figure 86 - CCP SAAs and Contracts Timeline

CCP Contracts

In July 2012, NASA approved the "Revised Certification Strategy" for the contract phase.

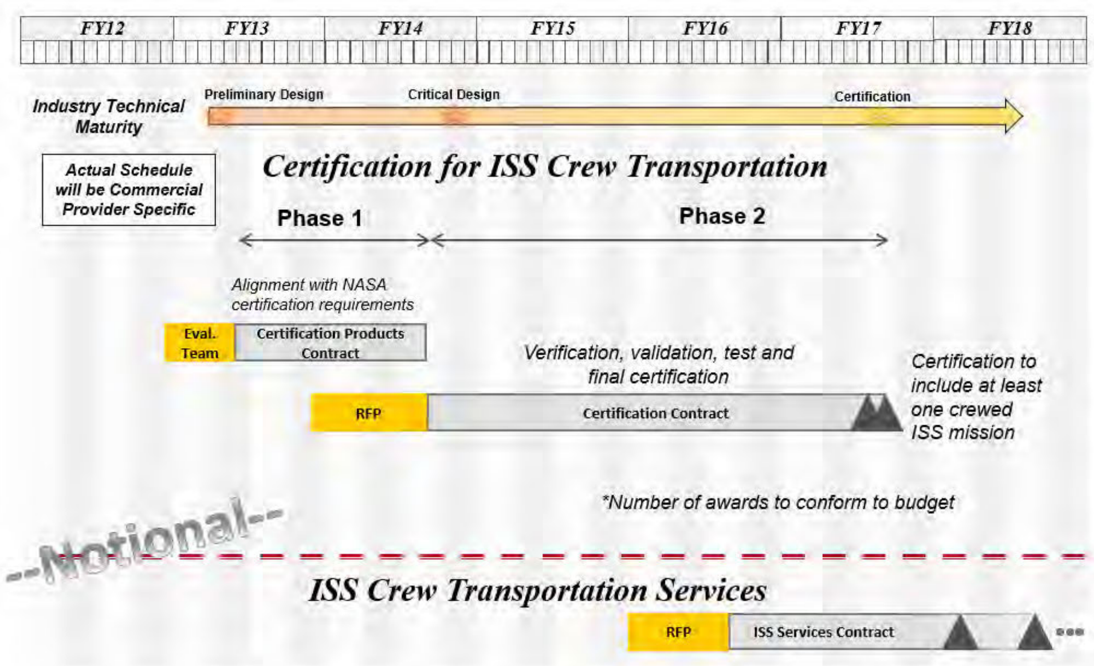


Figure 87 - "Revised Certification Strategy" July 2012

- The Certification Products Contract (CPC) began the initial certification efforts to enable an efficient transition to the CCtCap contract and provide a certified capability for ISS missions.
  - The effort focused on maturation of selected, critical safety, and engineering products including Alternate Standards, Hazard Reports, Verification and Validation Plan, NASA Requirements/Requirement Variances, and Certification Plan.
    - NASA technical assistance slightly increased related to reviewing and maturing technical aspects of design options.
    - Enabled technical interchange about meeting NASA requirements under the contractor's certification approach.
    - Allowed for the review and approval (or partial approval) of mature alternate standards and variances for inclusion in CCtCap.
- The CCtCap acquisition schedule was aligned with CPC final delivery schedule and timeframe for NASA feedback to optimize offeror final proposal revisions.
  - Contract Type: Firm Fixed Price, Performance-Based, with fixed-price Indefinite Delivery/Indefinite Quantity (IDIQ) elements
  - Contract Period: CLIN 001, DDT&E/Certification -- Date of Award through completion of the last required milestone in Attachment J-03, Appendix A

– Develop and certify a CCTS that can provide safe transportation of NASA Crew to the International Space Station (ISS) as soon as possible (goal of NLT 2017)

– The CTS development enabled the purchase, by NASA, of commercial services to meet NASA's ISS crew transportation needs once the capability is certified by the Agency.

Certification Strategy

The Commercial Crew certification approach was different than traditional human spaceflight programs utilizing a risk-based approach[14]:

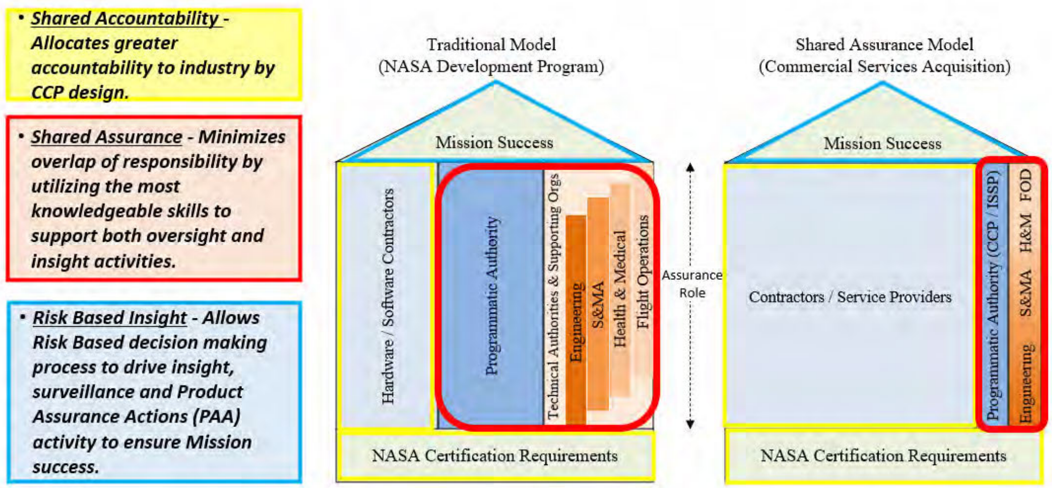


Figure 88 - CCP Shared Accountability Model

- By using a non-traditional approach featuring public partnerships, NASA is facilitating the development of several transportation systems by partnering with commercial companies for human spaceflight services to and from low-Earth orbit and the ISS.
- The key outcome of developing a Commercial Provider based capability is the overall cost effectiveness of the resultant CCTS.
- NASA expected to achieve cost effectiveness through the adoption of several key paradigm changes during the system design and development.[15]
  - Non-traditional contracting approach which enables contractor owned and operated designs
  - Competition via multiple industry providers
  - Mature and stable requirements, managed at a higher level
  - Smart application of design and construction standards
  - Efficient and effective government insight/oversight
  - Lean and agile program management with small footprint
- 1100 Requirements Series:
  - CCT-PLN-1100 *Crew Transportation Plan*

[14] [redacted]

[15] DPMC Presentation – September 14, 2021

[redacted]

- CCT-PLN-1120 *Crew Transportation Technical Management Processes*
- CCT-REQ-1130 *ISS Crew Transportation and Services Requirements*
- CCT-REF-1131 *CCT-REQ-1130 Requirement Interpretation Letters*
- CCT-STD-1140 *Crew Transportation Technical Standards and Design Evaluation Criteria*
- CCT-STD-1150 *Crew Transportation Operations Standards*

- Insight/Oversight Approach
  - Insight
    - Defined as gaining an understanding of the Commercial Provider's requirements and activities and data through watchful observations, inspections, and interactions, without approval or disapproval authority.
  - Oversight/approval
    - Fully engaged NASA technical effort focused on evaluation of contractor's evidence related to NASA product approval.
    - Focused on completion of CTS Certification, requirement satisfaction, VCNs, Variance approval, Hazard Report approval and acceptance of performance milestones for core work and mission task orders through formally submitted contract deliverables.
    - Commercial Crew maintains a streamlined board structure.
    - The Commercial Crew and ISS Programs have established a Joint PCB for joint activities.

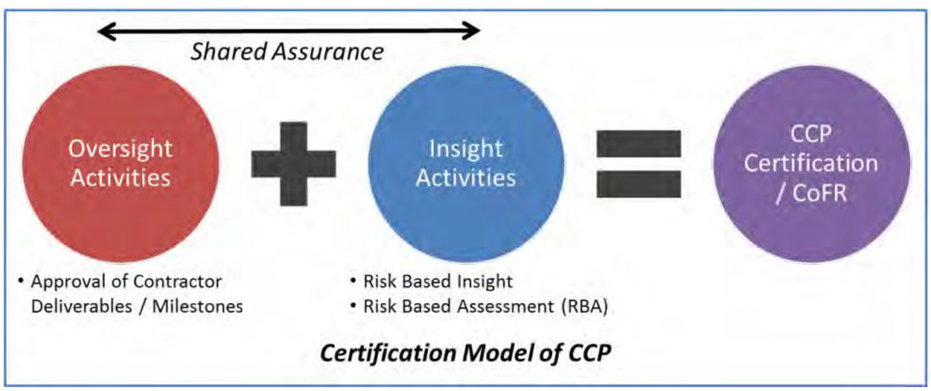


Figure 89 - Certification Model of CCP

- Design certification is the authorization by NASA that the Commercial Provider's CTS design and operations meets NASA's requirements.
  - Commercial Provider is responsible for developing and executing its plan for certifying a CTS for its own use.
  - Commercial Crew, with the ISS Program, substantiate the Commercial Provider's certification assertion to ensure compliance with NASA requirements and NASA crew safety.

- CoFR is the authorization by NASA that grants the use of Test-specific/Mission-specific Commercial Provider's CTS hardware (HW), software (SW), and Operations team to transport NASA crew to and from the ISS.
  - Commercial Provider is responsible for developing and executing its plan for certifying a CTS for flight readiness.
  - Commercial Crew, with ISS Program, substantiate Commercial Provider's CoFR assertion to ensure compliance with NASA requirements and NASA crew safety.

Commercial Crew Metrics and Decision Structure

Commercial Crew PCB Topics – 2010-2024 (includes joint ISS PCB topics)

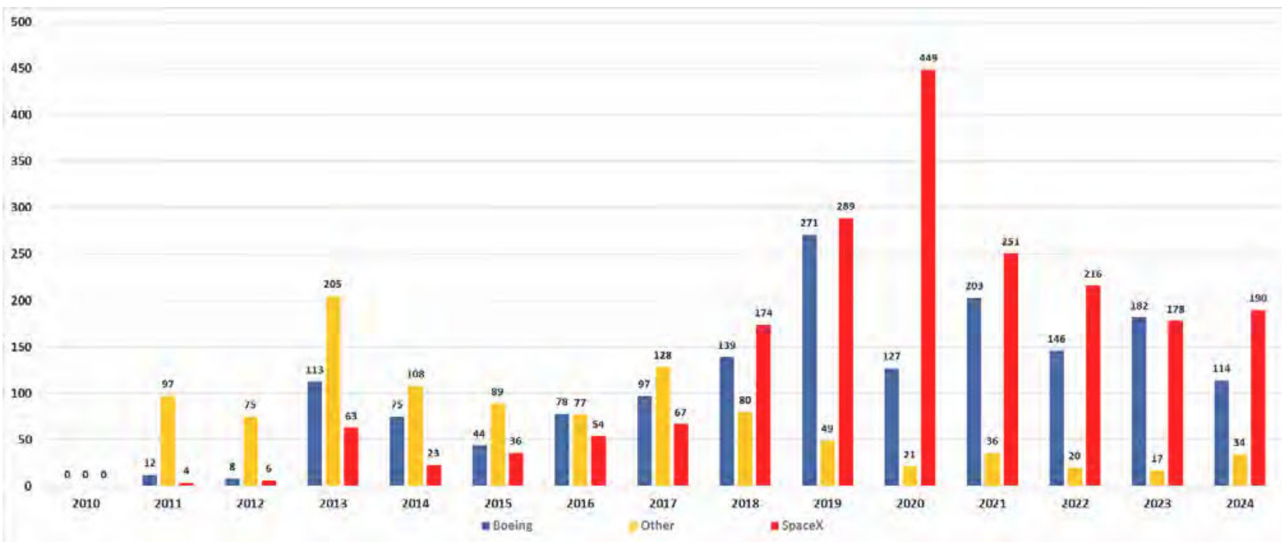


Figure 90 - Commercial Crew PCB Topics – 2010-2024

The PCB is the approval authority for establishing Program technical requirements, documents, schedule, safety, and risk acceptance and for any changes thereto. It also has the final assessment of the Commercial Providers' progress at Performance Milestone Reviews, manages the Government's investment risk, and determines success or actions needed to mitigate or accept identified gaps. The PCB approves contract change requests and any new internal agreements with other NASA programs, institutional offices, and external agencies.

The PCB is responsible for the approval of the following:

- Applicable programmatic documents that require the Program Manager's signature
- Baselining or revising applicable Data Requirement Deliverables (DRDs) per the *CCtCap DRD Review Process* (CCT-P-3040)
- Baselining or revising requirements/verifications, exceptions, deviations, or waivers to Program requirements
- Adjudication of issues affecting crew health and safety, and mission success
- Changes to Program baseline schedule milestones
- CCTS design, development, test, and certification issues
- CoFR recommendations

- New agreements or changes to existing agreements and contracts
- Milestone approval and direction for associated payment
- Risk assessments of the CCTS and approval of any risk above baseline
- Evaluation of design analyses and safety assessments
- Milestone readiness and closeout for Commercial Providers' technical reviews
- Other items as determined by the PCB Chair

Commercial Crew CPC Letters and CCtCap Directives – 2010-2024

Figure 91 - CPC Letters and CCtCap Directives – 2010-2024

A Commercial Crew Program Directive is the mechanism for transmitting management or board direction to the Program, supporting organizations, and Commercial Providers in the conduct of the CCP during the CCtCap era. A CPC letter was the mechanism for transmitting DRD decisions to the Commercial Providers during the CPC era. The CCP Manager or any Commercial Crew organization can identify the need for a directive. Directives require the Program Manager's signature. Directives for ISS (i-Requirements) designated in CCT-REQ-1130 are integrated and therefore additionally require the ISS Program Manager's signature, delegate, or reference to the ISS approval documentation. Directives are required for approval of risk acceptances and closures, unexplained anomalies, in-flight anomaly (IFA) closures, certain DRDs, unallocated future expenses, and all variances and alternate standards except Category II Material Usage Agreements (CAT II MUAs).

Commercial Crew Total Boards and Panels – 2010-2024

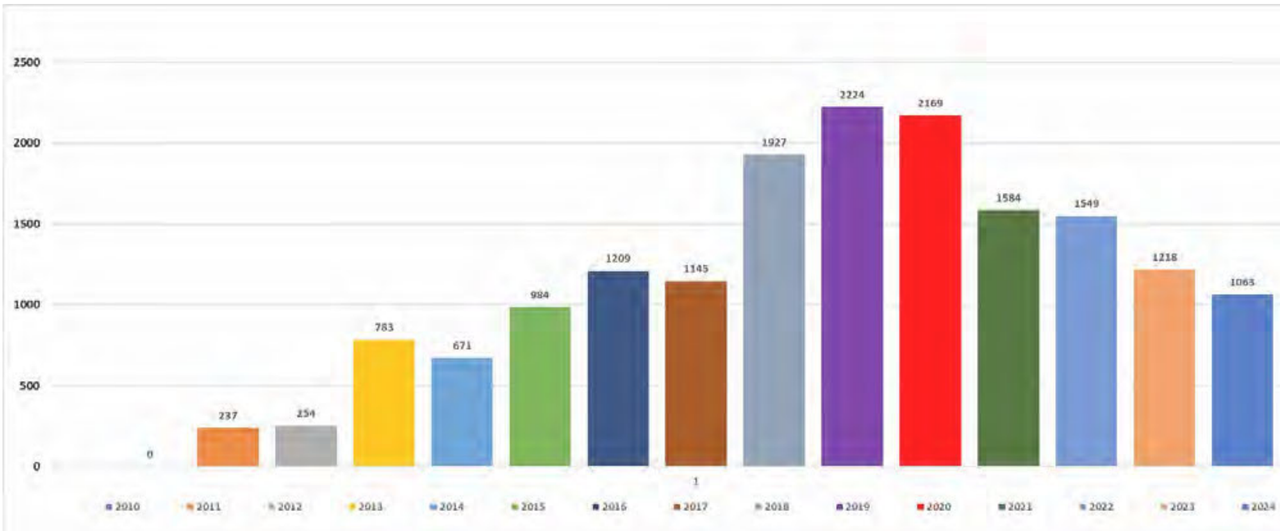


Figure 92 - CCP Total Boards and Panels – 2010-2024

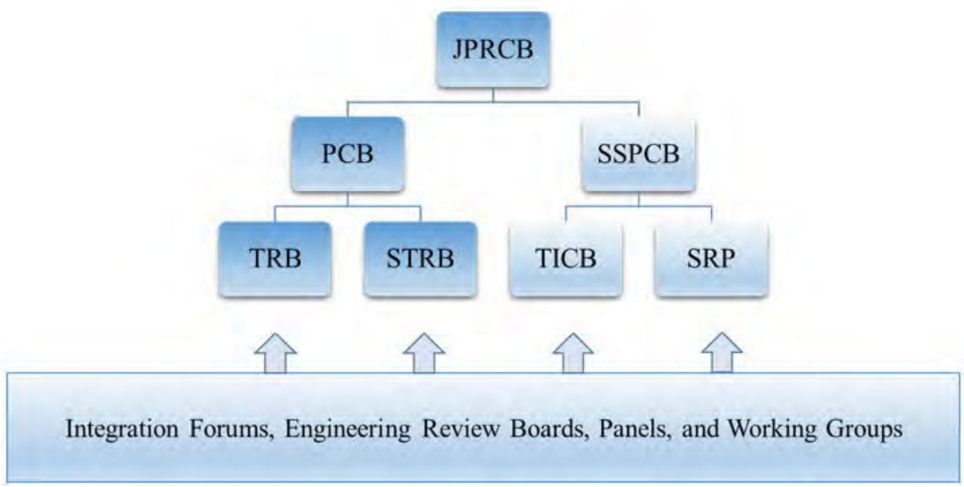


Figure 93 - CCP Board Structure

Descriptions of the Lower Boards

The Technical Review Board (TRB) supports the PCB with the technical management, systems engineering, and integration for Program requirements which have not been delegated to the Commercial Crew Safety Technical Review Board (STRB). The TRB is the mechanism that TAs and supporting organizations utilize to obtain technical decisions for Commercial Crew. The TRB will meet jointly with ISS Technical Integration Control Board (TICB) when requirements and risk issues impact both Programs.

The STRB supports the PCB with the technical management, systems engineering, and integration for designated Program safety requirements. The STRB provides review and oversight of delegated safety and technical requirements, activities, and safety products associated with ground and flight safety of a CCP CTS by assessing safety and/or technical risk issues. The STRB is the mechanism that TAs and supporting organizations utilize to obtain safety related decisions for Commercial Crew. The STRB is responsible for review and approval of the Ground, Launch Vehicle, Spacecraft, and Landing/Recovery hazard analyses, along with all integrated hazard analysis and supporting documentation. The STRB works in coordination with the ISS Safety Review Panel (SRP) where safety and technical risk issues impact both programs. For safety topics affecting both programs, a single integrated review process for CCP STRB and ISS SRP is implemented to review and approve integrated safety risk issues.

The ISS-CCP Joint Program Requirements Control Board (JPRCB) is responsible for the approval of joint program documentation, agreements, processes, and milestones and/or the final disposition of joint technical and programmatic issues and changes.

The Verification and Validation (V&V) Panel supports the Program Boards by offering guidance on the planning and execution of CCT-REQ-1130 verifications and system validations and assessments of risk in the verification and validation methods, activities, and schedule.

Program organizations utilize forums to review and discuss significant technical topics, integrate across the organization, and formulate joint office/stakeholder positions for office decisions or Program Boards and Panels agenda items.

After Agency Flight Readiness Review (FRR) for each mission, PCB meetings will be held to close any open items from approved CoFR exceptions. The purpose of these PCBs is also to report on the status of any open work and actions from the Agency FRR prior to the Commercial Provider's Launch Readiness Review (LRR). After the LRR, each of the Commercial Provider's Mission Management Team, the Dragon MMT (DMMT) chaired by SpaceX and Starliner MMT (SMMT) chaired by Boeing, are established, and operate until after crew handover to NASA post-landing. Any open items from the Commercial Provider LRR will be addressed at the SMMT/DMMT and elevated to the agency if required.

The Commercial Crew Mission Management Team (MMT) is the mechanism that Technical Authorities and supporting organizations interface with to obtain technical decisions for CCP during real-time mission operations as defined in the Crew Transportation Plan. The DMMT and SMMT is the decision-making body, respectively, responsible for programmatic trades and decisions associated with launch countdown, in-flight activities, landing, and recovery. NASA CCP has a voting member (NASA Operations Manager (NOM)) on both teams according to the specific plans of each Commercial Provider and maintains its authority to approve acceptance of any risk to crew safety, vehicle safety, and mission success above the nominal baseline as defined by the Agency FRR. The NOM receives input from the Commercial Crew MMT members.

Commercial Crew Timelines

Overall Commercial Crew Timeline of Events

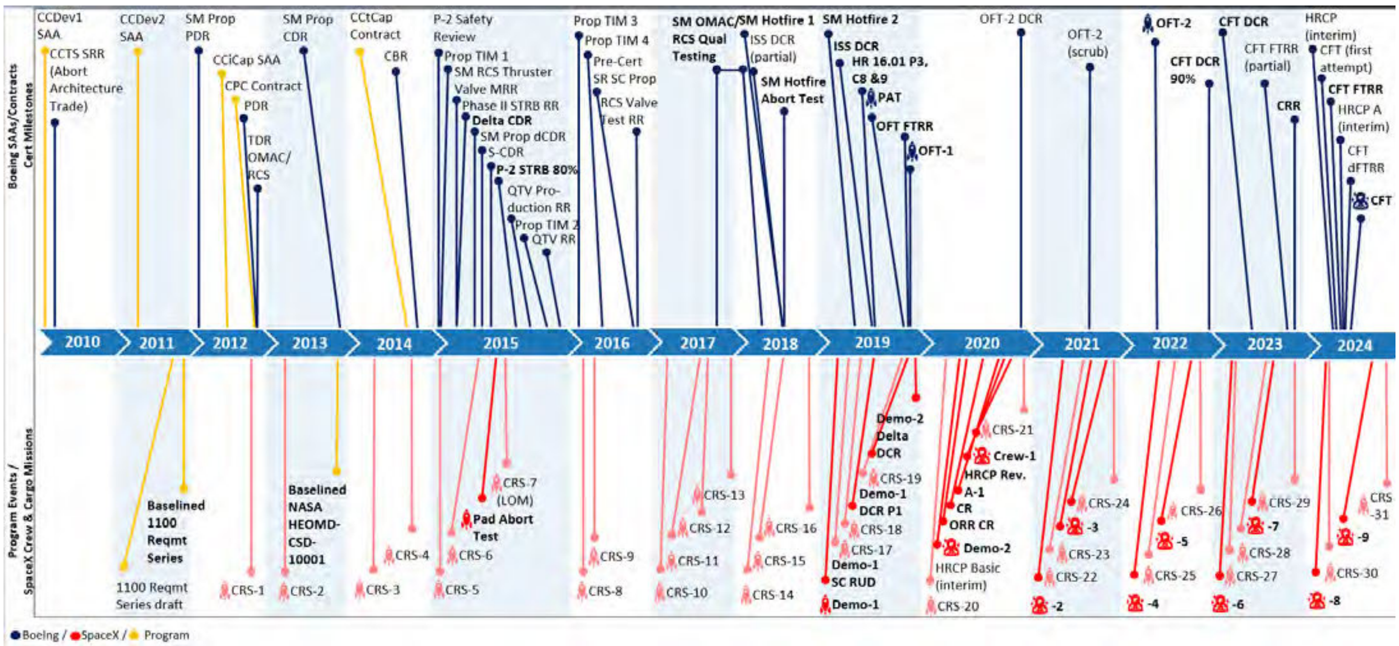


Figure 94 - Commercial Crew Timeline of Events

To accurately trace back to ‘full on implementation’ it is critical to understand the timeline for Boeing design decisions vs. NASA engineering capacity to influence and assess these decisions. NASA requirements, Boeing’s tailoring of requirements, how components actually functioned and were tested versus Boeing early design decisions must also be considered. Add to this Boeing’s limited ability to see specific supplier information and limited flight experience ensured significant discovery was inevitable.

Timeline observations for Starliner:

- 2010 - CCDev1 SAA awarded
- 2011 - CCDev2 SAA awarded
- 2012 - SM Propulsion System PDR
- 2012 - CCiCap SAA awarded
- 2013 - SM Propulsion System CDR
- 2014 - CCtCap contract awarded
- 2015 - dCDR
- 2015 - SM Propulsion System dCDR
- 2017 - 2018 - SM Orbital Maneuvering Attitude Control (OMAC) and SM RCS qualification testing
- 2019 - SM Hotfire 2.0
- 2019 - OFT-1 Launch
- 2021 - OFT-2 (First Attempt)
- 2022 - OFT-2 Launch
- 2024 - CFT (First Attempt)

- 2024 - CFT Launch

Focused CFT SM Propulsion Anomalies Timeline

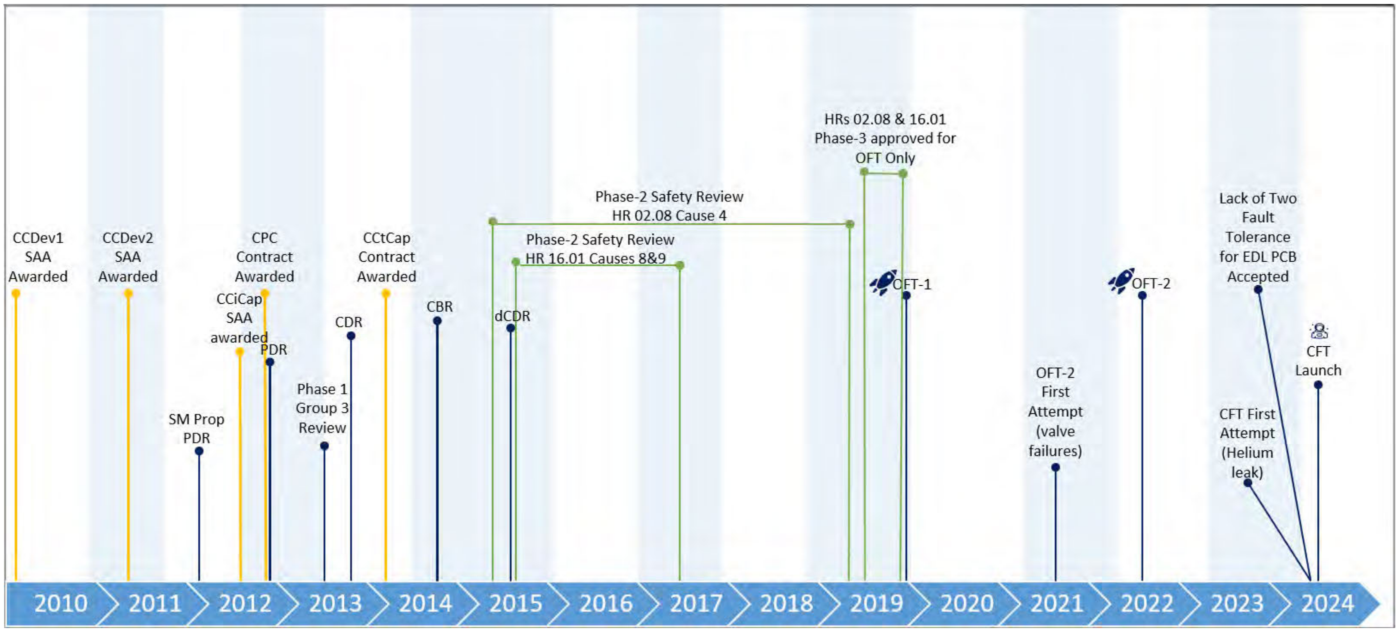


Figure 95 - Focused CFT SM Propulsion Anomalies Timeline

General Findings

After interviewing approximately 40 NASA CCP experts with various experience working with Starliner since inception of the Commercial Crew Program, the STAR team uncovered several general findings. Although these items were not a direct focus of this investigation, they were contributing factors for the root causes of the technical issues investigated.

- Critical designs were set prior to CCtCap, with limited government interaction.
- Resources and skills were not adequate during key design activities prior to contract award.
- Resources and skills were stressed during flight tests and operations resulting in competition between near term flights and resolving long term issues.
- NASA staffing plans post-award were not tailored for each provider's schedule and culture, with limited dedicated teams for each provider.
- The rigor in resolving issues identified by NASA during design reviews was less than expected.
- At the beginning of CCtCap, the focus was on SpaceX human spaceflight design maturity, with a preconceived notion that Boeing was more experienced in human spaceflight.
- CCP Requirements were adequate, but there was no spacecraft propulsion standard to provide guidance on qualification testing.
- NASA was unwilling to enforce the contract terms on Boeing due to prior cost and schedule over-runs and the potential consequence of enforcement.
- Shared Accountability Model did not operate as planned. The burden was on NASA to prove it was unsafe.
- Supplier contracts put in place early in CCtCap for lot/lifetime buys of hardware design resulted in hardware propagation across numerous vehicles and increased impacts for change implementation.
- Qualification tests had shortcomings.
- Lack of spare hardware available impacted ability to conduct testing when technical/performance questions arose.
- Supplier design/build data access constraints led to insight challenges.
- Suppliers' build quality/variability issues were hard to exonerate for the SMs.
- Unrealistic launch dates influenced Boeing design and build decision making.

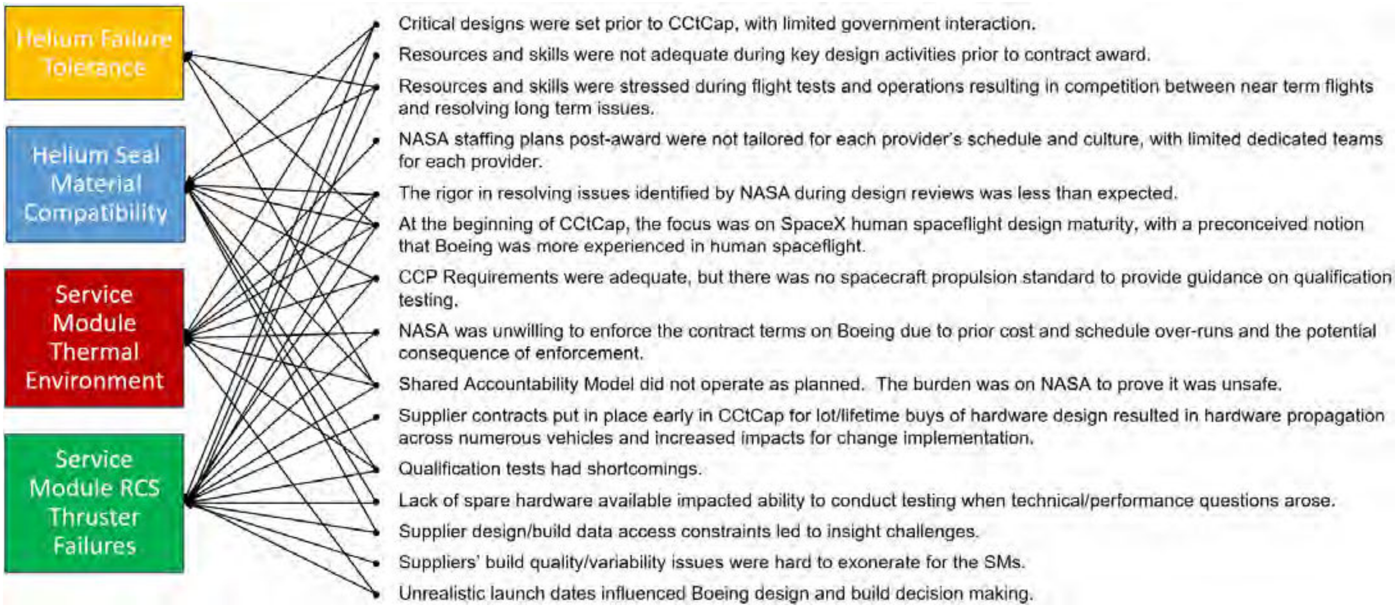


Figure 96 - STAR General Findings Matrix

General Findings

During the SAA phase, design decisions and implementation were proceeding with a "light" engineering touch. By the time NASA requirements were understood, the timeline was not realistic for implementing new designs. Through CCtCap, NASA was finally able to see and approve Boeing's early decisions pertaining to NASA products and expectations for performance as they related to NASA crew.

Acquisition Strategy & Contracts

- SAA Phase (2010 – 2014)
  - Commercial Crew used Space Act Agreements (SAA) in the early years calling for industry partners to develop crew transportation capabilities, requirements, and to perform tests to verify, validate and mature component and integrated designs.
  - Guidance on SAA interaction limited NASA technical direction and feedback during preliminary and critical design reviews, limiting comments and suggestions on design trades and requirement compliance.
  - Guidance stated only to "provide feedback containing the Commercial Partner's internal plans or requirements versus what the Commercial Partner did to meet the milestone criteria". Guidance was given to "not provide technical opinions or suggestions of what design solutions are acceptable or preferred, as that was concluded to potentially lead to misunderstanding of NASA-specific forward directions".
- CCtCap (2014 – present)
  - Limited technical interaction culture mandated by the SAAs approach remained in the early contract phase

- At the start of CCtCap, Boeing's main focus was to finalize designs to award supplier contracts, relying on design reviews held prior to contract initiation.
- The Certification Baseline Review (CBR), the first milestone on contract, focused on processes and management plans to allow funding release mitigating impacts of contract delays due to Sierra Nevada protest. The CBR did not meet the expected intention to level set the Commercial Provider's technical baseline for DDT&E at contract start.
- The Delta Certification Design Review (dCDR), held after contract award, was a missed opportunity to resolve known design issues identified in the SAAs and CPC.

- Schedules
  - Unrealistic schedules resulted in unneeded schedule pressures, likely resulting in early design and implementation trades made for perceived upcoming missions.
  - Noted more focus on OFT (OFT-1 and OFT-2 anomalies and resolution) without an ability to look ahead to the crewed test flight.
  - Schedules often drove what was accepted as use-as-is to not impact schedules versus what should have been fixed to improve the spacecraft.
- Insight
  - Insight data was difficult to access, constrained to select NASA personnel, and further constrained by component/system supplier limited insight.
  - Insight data may have been available, requested by other NASA personnel or Boeing, but took time to find and often utilized critical engineering resources to collect.
  - Approval of the oversight documents was granted but insight data was often needed to cover the gaps in deliverables.
  - Contractor insight data access was not executed as required in contract or the insight plan provided in Boeing deliverables. Further, NASA did not enforce the Insight clause. See Appendix F.
  - The shared accountability approach was inconsistently applied and for some systems did not work as planned. NASA incorrectly assumed the Commercial Providers to levy requirements and testing on their suppliers. The Commercial Provider focused on meeting contractual requirement language resulting in insufficient demonstration across the components/system and ground/flight.

Communication and Interaction

- Relationships and Culture
  - There was a preconceived notion that Boeing was more experienced in design and development of human space transportation systems and NASA had a false sense of security with their system design and component selection ability based on significant demonstration of successful experience and relationships spanning human spaceflight.
  - The NASA to Boeing relationships and interactions were limited to the Commercial Provider's contract requirement definition.

  - NASA felt the need to "prove it's unsafe," or "prove that it will fail" vs. Boeing providing the verification evidence sufficient to conclude “proving it's safe”. Application of that approach facilitated a culture with the shared belief that if there was a chance to succeed, there was no reason to stop or change direction.
  - Comments and suggestions were not adequately considered, incorporated into products, or explored sufficiently. NASA relationships with Boeing became strained, resulting in reduced communication and technical feedback.
- Resources and Priorities
  - CCP is comprised of exceptionally talented and dedicated personnel.
  - Through the interview process, the team did not observe any withholding of opinions or assessments.
  - There was no evidence of concerns not being surfaced during flight readiness discussions prior to CFT. Hindsight allows a different perspective and results in a different conclusion when flight performance highlights missed opportunities in the early design phases.
  - NASA was understaffed, at contract award, supporting two Commercial Providers at a critical juncture, when the support teams were also struggling with priorities (steep learning curve for new personnel on the program).
  - NASA staffing profile, with limited personnel dedicated to each provider, was not tailored to address provider plans, readiness, or culture (one size fits all approach) resulting in resources shifting to the highest priority at the time (e.g., Commercial Provider closest to flight).
  - NASA staff was oversubscribed with limited amount of time to integrate across multiple systems. (e.g., Integration between propulsion hardware and thermal expertise disconnected until CFT).
  - NASA had limited system level understanding to inform proper risk-based assessments, possibly limited knowledge in integrated testing expertise.
  - Personnel turnover in key areas could have impacted handover during certification efforts for Starliner (e.g. STRB chairs).
  - Resources were a challenge for NASA and the Commercial Provider due to multiple factors, including subcontractor layers, leaving little time to "be curious".

Requirements

- CCP developed a good set of requirements, including design and construction standards. The CCP 1100 series of requirements were deliberately written at a higher-level, leaving room for provider innovation but there was also room for incorrect/inadequate interpretation by the providers.
  - Specifically, for spacecraft propulsion, there was no specific design and construction standard(s) levied on this complex system which encompasses propulsion qualification and testing at system or subsystem levels.
- CCP did not ensure adequate flow down of NASA requirements and design and construction standards to Boeing’s specifications or the flow down of those to Boeing suppliers’ verifications.

- Component and subsystem specifications were developed before mission designs were complete.
  - For example, the AR specification includes mission timeline and representative duty cycles but doesn't have the real mission duty cycle.

- Materials compatibility requirements were not well defined for hypergols. Boeing chose to conduct analysis versus tests and were generally implemented after encountering internal corrosion problems.

Design, Testing, & Hardware Build

- Key design decisions were made before CCtCap, with limited government interaction observing PDR/CDR. The basic architecture was set in 2010, evolved slightly through PDR and CDR. Once on contract, it was difficult to implement changes impactful to the design architecture codified via contract.
- Component level PDR/CDRs were conducted without Boeing or NASA.
- Multiple corrosion and contamination issues were observed during hardware builds at suppliers throughout the life of the Program.
- SM hardware anomalies resulted in most likely causes, where root cause was often not fully resolved due to SM disposal.
- Heritage hardware was used as justification to reduce testing but did not appropriately assess operating environments and duty cycles.
- Hardware was largely designed for procurement planning before contract award, with little room for change after contract award.
- Instrumentation had room for improvement to adequately capture thruster temperature, usable pressure chamber data, and data rates.
- The propulsion qualification testing lacked a flight-like approach. Boeing did not document test like you fly (TLYF) or test as you operate (TAYO) exceptions for component level testing and mission phase testing was not executed. This was not captured as a requirement violation in the Verification and Validation Plan.

Recommendations and Lessons Learned

Recommendations

- Consider dedicated resources for critical systems per provider.
- Qualification testing campaign should be augmented, TLYF.
- Consider hardware spares availability.
- Insight access should be provided across the NASA/Boeing teams.
- Suppliers build quality/variability insight should be rectified.
- “Use as is” dispositions should only be considered after exhausting options for hardware changes.
- Increase the rigor in evaluating UAs by investing in more hardware testing to validate fault tree closure rationale.
- Co-develop schedule assessments to drive achievable schedules and to ensure that risk-based decisions can be driven by credible inputs.
- Ensure Commercial Providers take ownership in preparing the acceptance rationale and providing verification evidence.
- Revisit the perception that NASA technical team often felt forced to "prove it's unsafe," or "prove that it will fail", when there was insufficient verification evidence provided to “prove that it's safe”.
- Consider bringing in high level expertise from outside of the Program to evaluate critical anomaly resolutions.

Lessons Learned

- Identify key system level expertise in high-risk areas to endorse critical design decisioning.
- All spaceflight programs should incorporate the soon-to-be released NASA propulsion standard and TLYF principles.
- Increase awareness of agreements with major subcontractors and suppliers and how requirements are flowed down and verified.
- Closely investigate the use of legacy hardware designs with alternate applications.
- Prioritize detailed component level data and NASA involvement in design reviews (e.g., propulsion components).
- Require adequate hardware and system level integrated testing, with a solid understanding of validation testing plans early.
- Consider adequate hardware spares availability for subsequent anomaly resolutions.
- Critical Design Reviews as a part of the Certification Strategy should be performed under contract where direct feedback and success criteria can be achieved.
- Ensure the technical teams have readily available access to appropriate insight data.

Helium System Issues

Helium System Failure Tolerance

Issue

After the first CFT launch attempt, it was realized by the NASA and Boeing teams that the Starliner SM propulsion system was not two failure tolerant for deorbit. Boeing and NASA did not identify the issue during the phased safety review process when the applicable Hazard Report cause and control strategy was developed.

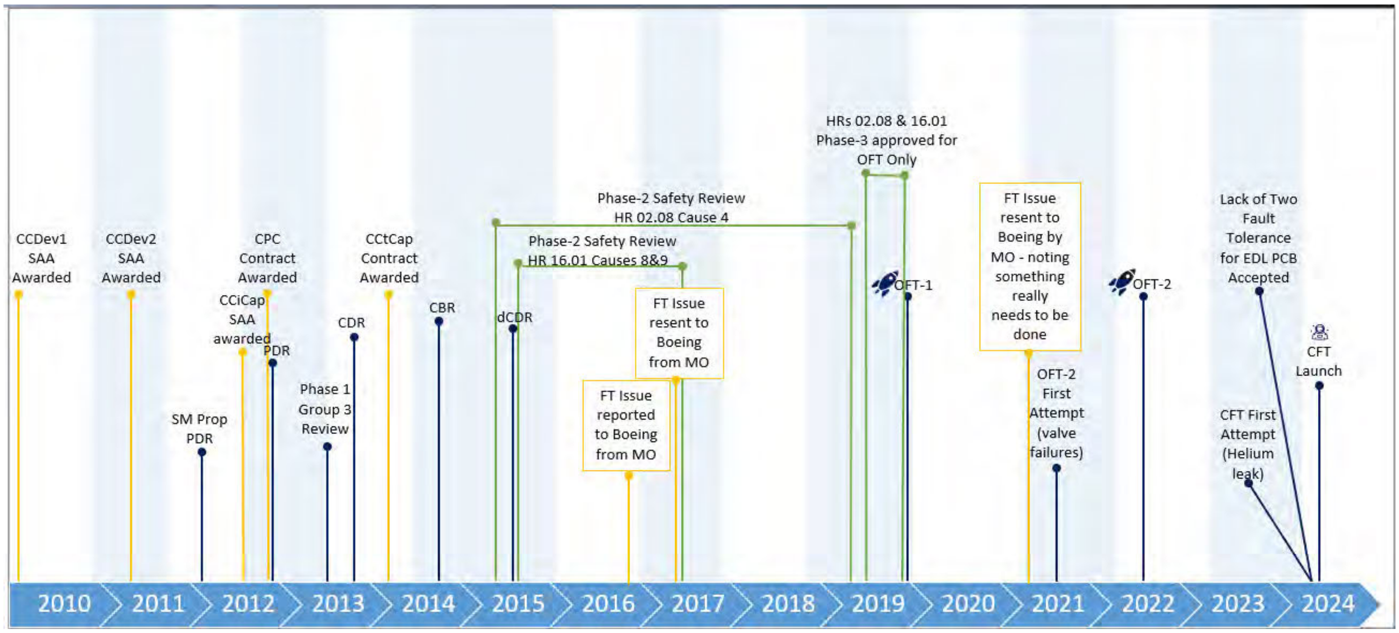


Figure 97 - Focused CFT SM Propulsion Anomalies Timeline with Correspondence

Background

The Boeing SM propulsions system PDR[16] was held January 9-10, 2012, under CCDev2. At that time, the helium pressurant system had three helium manifolds per doghouse. By Critical Design Review[17] on 11/19-21/2013 the system had evolved to two helium manifolds per doghouse. The pressurant system has remained largely the same since then. The change to a two helium manifold design created the failure tolerance issue.

The Phase II safety review[18] for CCTS-02.08 and CCTS-16.01 began in Feb of 2015 and finished in late 2019. The review did not identify the failure tolerance issues or flag the Helium seal material choice as a hazard cause for leakage of the pressurant.

16 [redacted]

17 [redacted]

18 [redacted]

CCTS-02.08 - Rev 02/08/19[19] Cause 4 Control 7 addresses failure tolerance due to leakage of pressurant, but it focuses on CCTS-VR-0029 SM propulsion abort pressurization leg fault tolerance. That variance addressed the lack of failure tolerance of the [redacted]. The doghouse [redacted] that were identified as a failure tolerance issue during CFT are in a different downstream location of the [redacted]. The HR's focus on the CCTS-VR-0029 may have contributed to missing the lack of 2 FT in the downstream doghouse [redacted].

CCTS-16.01 – Rev: 05/01/2017[20] Cause 1 discusses Helium failure tolerance just after control 10. It acknowledges that delivery of helium to individual thrusters is zero failure tolerant and points to Causes 8 (for attitude control) and 9 (for translation) as the location in the report that covers how the system level redundancy achieves functional Failure Tolerance.

CCTS-16.01 Cause 9 Control 1 states the system is 2 FT to the loss of translational maneuvering capability, including any combination of [redacted]. It is not clear how Boeing or the STRB assessed the failure tolerance of the pressurant system with combinations of manifold failures. A rigorous [redacted] assessment of the pressurant system should have identified the failure tolerance issue with a common RCS and OMAC helium manifold before approving a phase II hazard report.

The phase III safety review of CCTS-16.01 should have been another opportunity to identify the failure tolerance issue. The expectation is the Commercial Providers are the experts in their systems and will bring forward a complete picture of their systems and any requirement variances, including shortfalls in failure tolerance. CCTS-16.01 Cause 9 control 1 verifications. Verification 1a should have identified the failure tolerance issue. That verification did not change in the OFT, OFT-2, or CFT applicable report causes. Boeing submitted that verification closure and NASA approved the verification even though the documents referenced in the verification were not sufficient to verify the hazard control.

Verification 1a refers to attachment 2 and the Guidance Navigation and Control (GN&C) CDR as a verification. Attachment 2 references Table 2 and Table 3, for translational control authority. The information in Attachment 2 is not sufficient to demonstrate that the system is 2 FT.

Verification 1a also refers to the GN&C CDR[21]. This section does not address failure tolerance other than to assess stability requirements. The verification artifacts pointed to by verification 1a do not verify the hazard control. It is unclear how Boeing approved the verification or how the STRB was able to verify their work.

In November of 2016, an FOD Mission Operations employee supporting the Starliner team identified the failure tolerance problem and sent an email[22] to Boeing's engineering leadership discussing the issue and potential resolutions. That employee again followed up on that email in May of 2017, resending that issue to the same distribution. That employee sent a third follow up email in April of 2021, noting that "This has been languishing for some time now, and we really need to do something with it."

19 [redacted]

20 [redacted]

21 [redacted]

22 [redacted]

Boeing engineers and engineering managers were notified that there was a failure tolerance issue prior to the OFT test flights. This issue was not communicated to NASA FOD Safety, NASA Safety, NASA Engineering, or Commercial Crew Program personnel. It is unclear whether Boeing engineering communicated this issue to Boeing safety personnel. The STAR Team believed this was a missed opportunity to identify the failure tolerance issue earlier in the design phase perhaps due to competing priorities and limited resources.

Findings

- CCP did not perform a sufficient Phase I safety review.
- Rigorous channelization of the helium pressure system was not performed as part of the phased safety reviews.
- Focus of channelization that was performed was the hypergolic propellant system, not the helium pressurant system.
- Quantity of helium available to support ascent aborts led many to consider a leakage impacting nominal operations, including SM disposal, as a non-credible failure scenario.
- CCTS-16.01 Cause 9 Verification 1a – The artifacts referenced do not verify the Hazard Control's assertion that the system was 2 FT.
- Boeing submitted CCTS-16.01 Cause 9 Verification 1a for approval with incomplete verification evidence.
- NASA approved CCTS-16.01 with incomplete verification evidence for Cause 9 verification 1a.
- Failure tolerance concern was raised to Boeing several times but was not addressed.
- Early on, the Boeing/Mission Operations (MO) ground rules and relationship with NASA created an environment where MO employees were discouraged from sharing key information with other NASA organizations (CCP Safety, FOD Safety, STRB). All communication was to go through Boeing.

Recommendations

- Implement a more rigorous process for NASA assessing Boeing HR verifications.
- Work with Boeing to improve the process Boeing uses to verify HR controls and their process for providing HR control data to NASA.
- Ensure that safety concerns identified by the FOD Mission Operations team are communicated to Boeing and NASA.

Lessons Learned

- Performing a timely (in line with PDR) Phase I safety review is essential to identify hazards in a timeframe where design changes are able to be implemented to mitigate confirmed hazards.
- Rigorous channelization is important to accomplish early in a design cycle.
- Leaning into "commercial practices" does not mean that documentation shouldn't be clear and available. One core part of CCP's success has been clear access to the data needed to make risk informed decisions. STRB verifications data is another example of that importance.
- HR control verifications need an appropriate level of rigor and awareness.

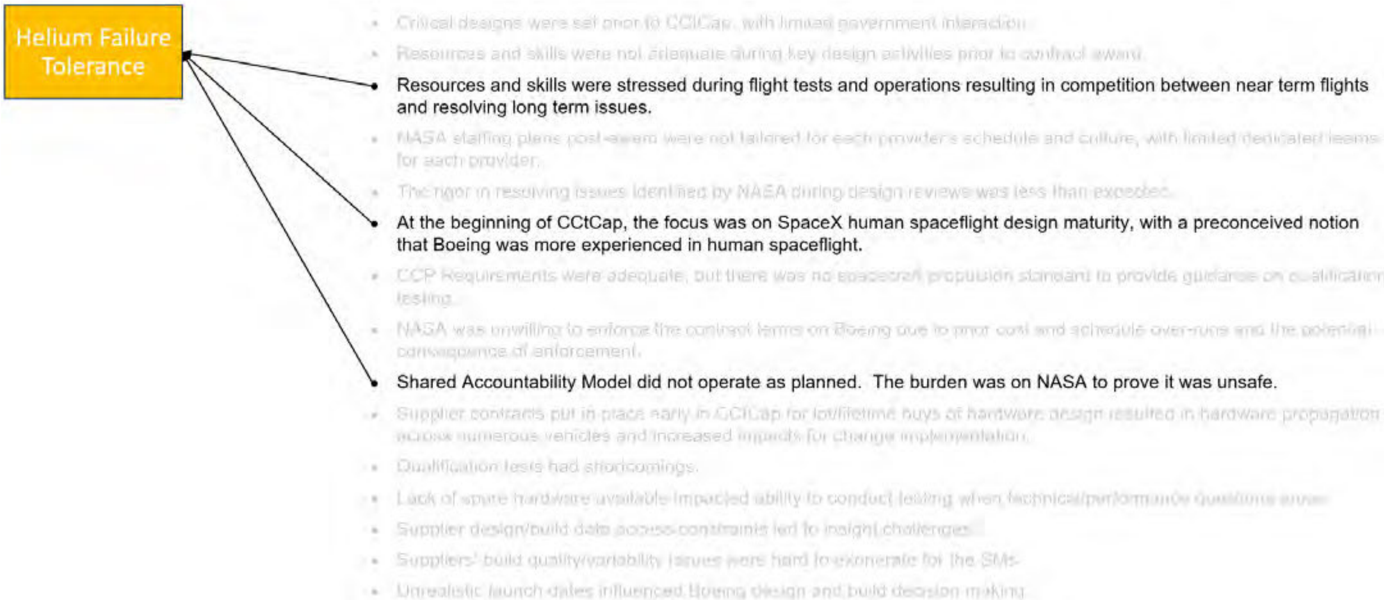


Figure 98 - General Findings Matrix - Helium FT

Helium Seal Material Compatibility

Issue

The SM propulsion system is designed with [redacted] flanges that are not compatible with Nitrogen Tetroxide (NTO) which contributed to the helium leaks seen on CFT.

Background

The Boeing SM propulsions system PDR[23] was held January 9-10, 2012, under CCDev2. The helium pressurant system at the time specified [redacted] that would be compatible with NTO. By Critical Design Review[24] on 11/19-21/2013 the system had evolved to only having a [redacted] interface. The [redacted] seal material was not identified in the CDR charts.

The overall system design didn't change much at delta Critical Design Review[25] in 6/23-26/2015. NASA did submit one RID that is relevant to material compatibility. RID 194 - Fluid Compatibility per NASA-STD-6001 Test 15 only addresses short term exposure. No mention on how long term compatibility (210 days) will be addressed.

The RID was answered with a presentation[26] highlighting a review of published papers and other data sources on the effects on individual materials. Flight specific or assembled component testing was not performed.

CCTS-02.08 - Rev 02/08/19[27] Cause 1 Control 13a references CCTS-16.01 for material compatibility. CCTS-16.01 – Rev: 05/01/2017[28] Cause 1 Control 24 specifies that the Helium system components are not compatible with hypers and references back to CCTS-02.08 again. Leaks at the RCS thruster mating flange were not looked at critically as a credible failure.

CCTS-02.08 - Rev 02/08/19 cause 5 control 3 says the seals are assessed for compatibility and states this limits permeation through soft goods, but the environment isn't quantified and the control 3 verifications reference back to CCTS-16.01 again.

The CCTS-16.01 Cause 3 (OMAC) and Cause 4 (RCS) Controls referenced from CCTS-02.08 Cause 5 control/verification set 3 all reference that materials are selected per Boeings approved alternate standard DCC1-00020-01F[29]. Section 4.1.3 from that document lists the material selection requirements including short, and long term testing that is required to simulate worst-case use environments. Long term materials tests in the flight like configuration were not performed. The helium seals were assumed to not be in an NTO environment, permeation was not considered a part of the worst case use environment.

A helium leak was identified during the OFT-2 flight but an IFA was not declared. The issues was closed out at a Boeing Prime Material Review Board (PMRB) without elevating to a NASA board.

Findings

23 [redacted]
24 [redacted]
25 [redacted]
26 [redacted]
27 [redacted]
28 [redacted]
29 [redacted]

- Materials testing at the assembled component level was not required per standard (NASA 6016 or Boeing Alt Standard). Individual material testing does not always capture integrated effects.
- It was assumed that the RCS flange helium O-ring would not be exposed to NTO even though it was on a common flange with fuel, oxidizer, and helium.
- SM hotfire ground test hardware was not torn down and inspected. When parts of the test article were later disassembled, after CFT, the O-rings were disintegrated.
- The environment created as a result of hypergol permeation was not investigated, understood, or quantified. HR control just said, “limits permeation”.
- Helium O-ring was not assessed for hypergol compatibility.
- NASA did not have insight into helium O-ring material selection. It was not included in CDR and even post CFT launch there was uncertainty on what specific material remained.
- CCTS-02.08 and CCTS-16.01 repeatedly reference back and forth to each other overcomplicating the picture of where and how controls were verified.

Recommendations

- Perform component level materials compatibility testing for seal materials ensuring that materials are tested in flight-like configuration with enveloping gases/liquid exposure, enveloping environments, and for enveloping exposure durations including margin.

Lessons Learned

- Tear down test articles and inspect them post-test within a timeframe that does not invalidate inspection results.
- Strengthen materials compatibility requirements for hypergol exposure. There is no substitute for long term exposure testing. In the absence of suitable environmental testing a Material Usage Agreement (MUA) is required to assess gaps.
- Propulsion system components that are exposed to hypergolic propellants (including permeation through seals) should be required to have long term hypergolic exposure testing as an assembled component with encompassing environments applied. Material coupon testing is insufficient.

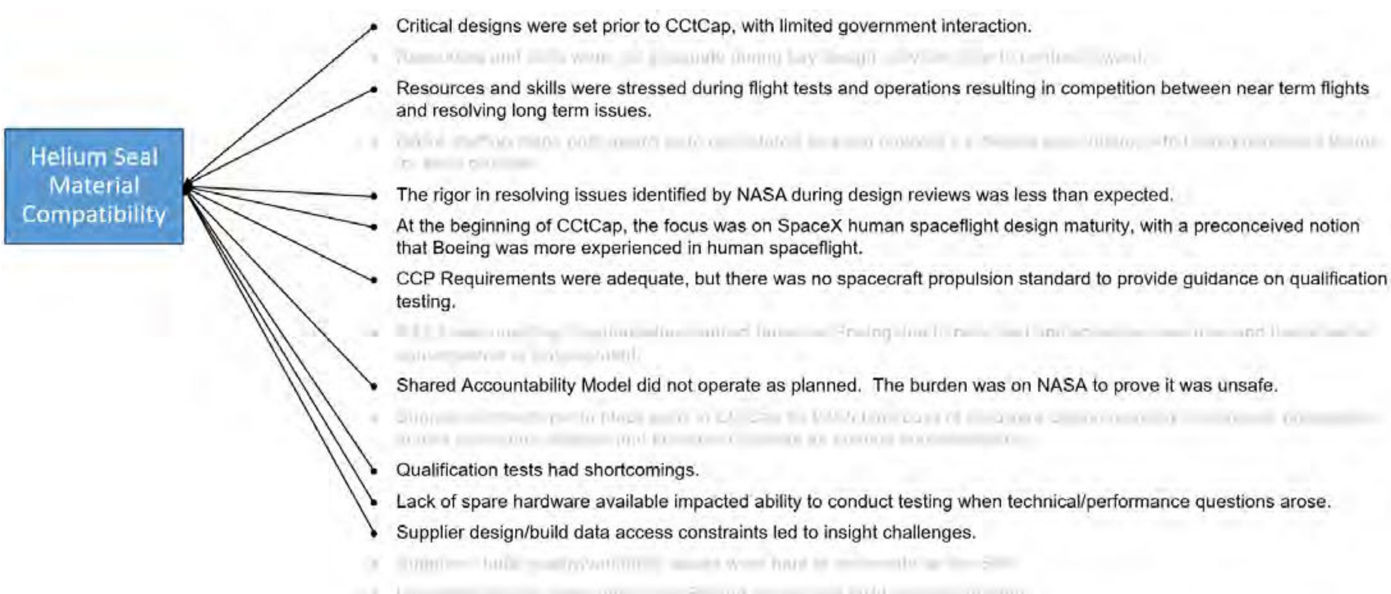


Figure 99 - General Findings Matrix - Helium Seal Material Compatibility

SM Doghouse Thermal Issue

Issue

During CFT, extreme Reaction Control System (RCS) injector temperatures were observed and multiple SM RCS jets failed during the approach to ISS leading to loss of 6-degrees of freedom (DOF) control.

Background

Unexpected heating of the SM RCS thrusters, leading to thruster failures, was observed on the OFT-1 and OFT-2 flight tests but the hardware failure modes and temperature capability/tolerance of the hardware components was not explored through additional ground testing, except for the pressure transducers and valve solenoids. The fact that higher temperatures were resulting in deformation of the RCS thruster internal soft-goods was not understood until ground testing was performed during CFT.

The thermal environment understanding of the SM propulsion system dog houses during powered flight was primarily based on analytical models. The most complete model was developed by AR and included the heating effects of the OMAC and RCS thrusters firing. Boeing also had a thermal model for the SM which included a simplified model of the doghouses, but that was intended to address quiescent operations and did not include heating from firing the thrusters. The AR thermal model was validated for limited jet firing histories, as it was primarily intended to evaluate the temperature performance of the propellant tank and line heaters when the propulsion system was docked/quiescent. The ability to maintain propellant temperatures above their minimum acceptance temperatures, as well as the commodity freezing point during the long quiescent period docked at ISS, while using minimal electrical power, was a primary design challenge for the AR team and was the focus of ground and flight test objectives. The key aspects of that design challenge during quiescent operations were validated through thermal vacuum testing on the ground and flight instrumentation.

The vehicle instrumentation within the SM doghouses was limited in the number of instruments and data rate. Instrumentation was primarily intended to validate cold performance or intended to support quiescent operations. Additionally, the flight vehicle's thermal instrumentation locations did not coincide with the locations of the ground test instrumentation during thruster testing and the extrapolation of the thermal environments between the as-tested and in-flight locations was not validated in ground testing.

Prior to OFT, NASA engineering evaluated the issues with the qualification testing of the SM propulsion system thrusters and noted that the results of the ground testing did not fully satisfy verification expectations for flight representative usage/induced environmental conditions. However, NASA engineering recommended proceeding with the OFT flight as they assessed that "low risk exists for all mission phases" and proposed that the data obtained from that flight be used to validate the acceptability of the thrusters for the eventual CFT (PCB-19-383[30]).

During OFT-1, ten SM RCS thrusters failed off during the brief, unsuccessful test flight. The ten failed thrusters included six of the eight aft-facing thrusters. The extremely rapid SM RCS jet firings which occurred early in OFT-1 led to the number of jet firings being far in excess of the qualification levels and resulted in RCS failure annunciations by Fault Detection, Isolation, and Recovery (FDIR). These rapid jet firings also led to thruster heating far in excess of qualification test levels. Of the ten thrusters that failed off in flight, nine were shown to

30 [redacted]

be due to transducer failures triggering FDIR and one thruster had a transducer failure and another hard failure that caused the thruster to remain inoperative after the other thrusters were re-enabled. The hard failure was believed to be due to the valve solenoid overheating. The limited RCS "hard" failures experienced during OFT-1 led to a false belief that the thruster hardware was very robust for exposure to high temperatures, except for the transducers and solenoids (PCB-20-404[31]). This belief persisted until the ground testing results were available during CFT.

During OFT-2, two of the eight aft-facing SM RCS thrusters (B1A3 and S2A2) failed off during the approach to the ISS. These two thrusters were reselected and performed during the de-orbit burn. One RCS thruster (S1A1) experienced a single FDIR failure during ISS approach and subsequently failed during the de-orbit burn. Two of the three failed jets had fuel injector temperatures observed at or above [redacted] F in telemetry and (S1A1 and B1A3) and the four thrusters with the highest oxidizer injector temperatures were aft-facing (including the three mentioned above). The heating related fault tree block (3.1.7 Hot Valve/Injector) was identified as a contributing factor for the B1A3 and S1A1 failures, but not the S2A2 failures because that injector temperature never exceeded [redacted] F. "Seat swelling was considered (reducing propellant flow) but since flow is controlled by trim orifice and injector, seat swell contribution to resistance change would be negligible" but the high injector temperature was theorized to result in NTO bubble formation. The corrective action identified to mitigate the risk of further failures on CFT was a Mission Data Load (MDL) change to the [redacted] to reduce the potential for "false" failures due to the limitations of the thruster chamber pressure sensor sample rate. [*OFT-2 SM RCS Jet Fail-off, Non-conformance #NCR015432W, Francisco Fusco, 15 December 2022*[32]]

OMAC thruster heat soak-back into SM RCS jet hardware was observed on OFT-2, but was not deemed to be as significant as the heating produced by firing the RCS jets. [*RCS thruster injector temperatures during soakback appear to have exceeded temps observed during qual, OFT-2-76, Francisco Fusco, 13 March 2023*[33]]

Findings

- Driving thermal design concern for the SM doghouses was maintaining propulsion system temperatures using heaters during quiescent operations (i.e., the cold cases).
- The AR thermal model was validated for quiescent operations by ground testing.
- The AR thermal model included the effects of jet firings, but these effects were not validated by ground testing.
- NASA engineering submitted a Boeing RID (B-RID) comment during a propulsion system design review in the SAA timeframe that the AR thermal model was immature. B-RID comment was withdrawn to be discussed at a later technical interchange meeting (TIM). No evidence of resolution was found.
- Boeing thermal model did not include the effects of jet firings before CFT.
- RCS thruster testing configuration was not flight-like as it did not reflect the insulative properties of the doghouse assembly and included active cooling to reduce the turn-around time between tests.

31 [redacted]
32 [redacted]
33 [redacted]

- SM hot fire test was not intended to evaluate the thermal environment within the doghouse. Test article did not include all the OMAC and RCS thrusters, nor were the few RCS thrusters that were included in the test article fired for flight-like durations.
- Flight instrumentation locations for thermal sensors were limited and different than the locations for RCS thruster ground testing.
- Explicit FTOs exist for determining the local Crew Module (CM) thruster thermal environments, but there were not analogous FTOs for the SM thrusters or the doghouse.
- OFT-1 and OFT-2 IFA investigations noted high temperatures were measured at the RCS thruster injectors.
- OFT-1 and OFT-2 IFA investigations did not include ground testing of doghouses assemblies or RCS thrusters to better understand the thermal environment during OMAC or RCS thruster firings (or soak back heating after firings).
- Unexplained Anomaly (UA) and fault tree dispositions for SM RCS thruster IFAs were not validated through subsequent ground testing.
- Thermal and propulsion disciplines were not well integrated before CFT.

Recommendations

- Conduct ground testing of the SM doghouses in their flight configuration to validate the thermal models when the OMAC and RCS jets are firing.
- Update AR and Boeing thermal models as needed based on the ground test results.
- Update the SM doghouse thermal environments as needed based on the updated thermal models and ground testing.
- Re-certify SM RCS thrusters and other hardware within the doghouses for the revised thermal environments.
- Increase the number of in-flight thermal measurements within the doghouse on the Starliner-1 SM and validate the updated thermal environments through formal Flight Test Objectives.

Lessons Learned

- Document the limitations of vehicle thermal models for both hot and cold cases.
- Invest in ground testing to validate critical models, particularly when flight experience or IFAs show that induced environments are exceeding pre-flight expectations.
- Ensure FTOs address hot and cold cases for propulsion systems.

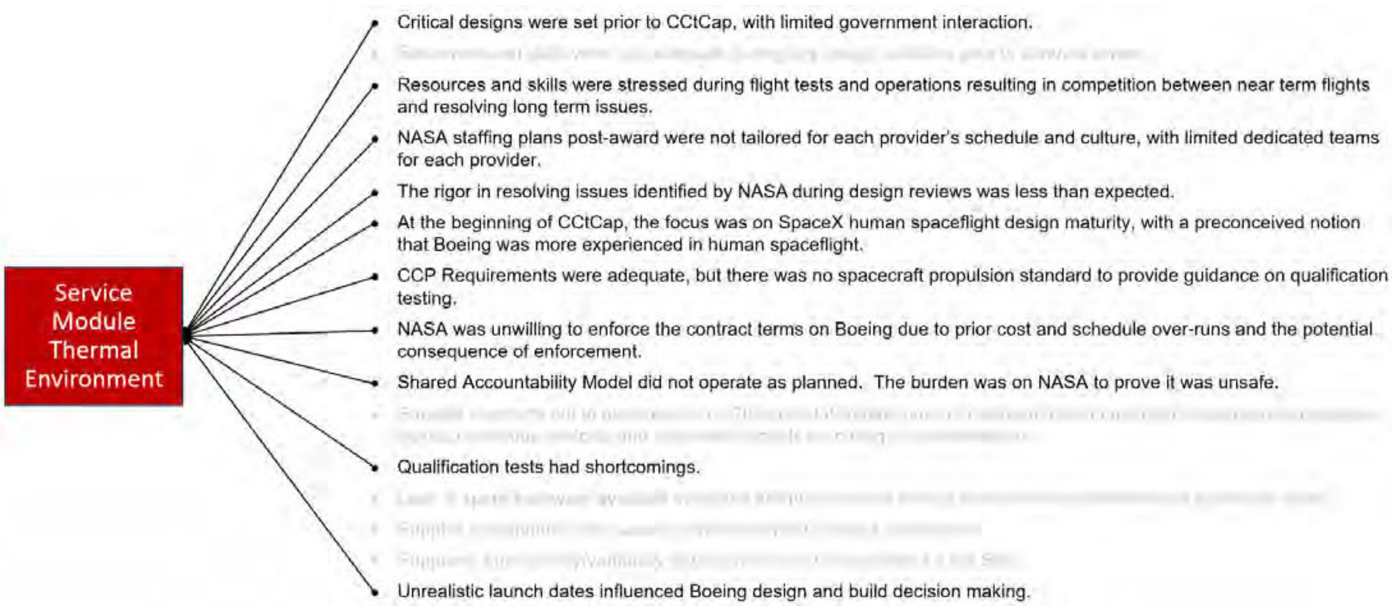


Figure 100 - General Findings Matrix - SM Thermal Environment

SM RCS / OMAC Thruster Failures

Issue

During CFT, extreme RCS injector temperatures were observed and multiple SM RCS jets failed during the approach to ISS leading to loss of 6-DOF control. Ground testing and tear-down of the RCS thruster identified that there was deformation of the Teflon RCS poppet seal occurring.

Background

SM RCS thruster failures were observed on the OFT-1 and OFT-2 flight tests but the hardware failure modes were not explored through additional ground testing, except for the pressure transducers and valve solenoids. That higher temperatures were resulting in deformation of the internal soft-goods of the RCS thrusters was not understood until ground testing was performed after additional failures were observed during the Starliner approach to the ISS during the CFT.

The CCTS-16.01 Cause 4 (RCS) Controls reference that materials are selected per Boeings approved alternate standard DCC1-00020-01F[34]. Section 4.1.3 from that document lists the material selection requirements including short, and long term testing that is required to simulate worst-case use environments. Long term materials tests in the flight like configuration were not performed.

The vehicle instrumentation within the SM doghouses was limited in the number of instruments and data rate. The primary indicator of thruster failures were the chamber pressure measurements which has a [redacted] data rate.

Prior to OFT, NASA engineering evaluated the issues with the qualification testing of the SM propulsion system thrusters and noted that the results of the ground testing did not fully satisfy verification expectations for flight representative usage/induced environmental conditions. However, NASA engineering recommended proceeding with the OFT flight as they assessed that "low risk exists for all mission phases" and proposed that we use the data obtained from that flight to validate the acceptability of the thrusters for the eventual CFT (PCB-19-383[35]).

During OFT-1, ten SM RCS thrusters failed off during the brief, unsuccessful test flight. The ten failed thrusters included six of the eight aft-facing thrusters. The extremely rapid SM RCS jet firings which occurred early in OFT-1 led to the number of jet firings being far in excess of the qualification levels and resulted in RCS failure annunciations by FDIR. These rapid jet firings also led to thruster heating far in excess of qualification test levels. Of the ten thrusters that failed off in flight, nine were shown to be due to pressure transducer failures triggering FDIR and one thruster that had a transducer failure and some other hard failure that caused the thruster to remain inoperative after the other thrusters were re-enabled. The hard failure was believed to be due to the valve solenoid overheating. The limited RCS "hard" failures experienced during OFT-1 led to a false belief that the thruster hardware was very robust for exposure to high temperatures, except for the transducers and solenoids (PCB-20-404[36]). This belief persisted until the ground testing results were available during CFT.

During OFT-2, two of the eight aft-facing SM RCS thrusters (B1A3 and S2A2) failed off during the approach to the ISS. These two thrusters were reselected and performed during the de-orbit burn. One RCS thruster (S1A1) experienced a single FDIR failure during ISS approach and subsequently failed during the de-orbit burn. Two of

34 [redacted]
35 [redacted]
36 [redacted]

the three failed jets had fuel injector temperatures observed at or above [redacted] F in telemetry and (S1A1 and B1A3) and the four thrusters with the highest oxidizer injector temperatures were aft facing (including the three mentioned above). The heating related fault tree block (3.1.7 Hot Valve/Injector) was identified as a contributing factor for the B1A3 and S1A1 failures, but not the S2A2 failures because that injector temperature never exceeded [redacted] F during ISS approach. "Seat swelling was considered (reducing propellant flow) but since flow is controlled by trim orifice and injector, seat swell contribution to resistance change would be negligible" but the high injector temperature was theorized to result in NTO bubble formation. The corrective action identified to mitigate the risk of further failures on CFT was a Mission Data Load (MDL) change to the Flight Management Computer (FMC) persistency to reduce the potential for "false" failures due to the limitations of the thruster chamber pressure sensor sample rate. [*OFT-2 SM RCS Jet Fail-off, Non-conformance #NCR015432W, Francisco Fusco, 15 December 2022*[37]]

OMAC thruster heat soak-back into SM RCS jet hardware was observed on OFT-2; but was not deemed to be as significant as the heating produced by firing the RCS jets. [*RCS thruster injector temperatures during soak back appear to have exceeded temps observed during qual, OFT-2-76, Francisco Fusco, 13 March 2023*[38]]

Findings

- Design details and the internal configuration of the RCS thruster valves was not fully documented in data deliverables to NASA, nor was it readily accessible to NASA engineers as insight data.
- Orbit insertions and ISS approach trajectories were not fully defined and the resulting RCS thruster duty cycles were not fully understood when the thruster qualification testing was defined and performed.
- RCS thruster testing configuration was not flight-like as it did not reflect the actual duty cycles predicted for CFT.
- RCS thruster testing configuration was not flight-like as it did not include the insulative properties of the doghouse assembly and included active cooling to reduce the turn-around time between tests.
- Limitations in flight measurements and data rates made troubleshooting of the RCS thrusters very difficult.
- The extremely high usage rate of the RCS thrusters over-heating the pressure transducers on OFT-1 was attributed to be the cause of the numerous failures identified by FDIR.
- RCS thruster performance after thruster re-selection on OFT-1 gave the Boeing and NASA team a false sense of thruster capability/robustness.
- OFT-1 and OFT-2 IFA investigations noted higher than expected temperatures were measured at the RCS thruster injectors.
- MUAs were not generated for the RCS thruster soft goods.
- Only flight hardware assigned to subsequent flights was available for testing during the flight test program.
- NASA didn't foresee the poppet extrusion problem, even though it was a known failure mode and identified on the OFT-2 fault tree but was closed as a noncredible scenario.
- For OFT-2, NASA and Boeing didn't have the tools to measure thrust degradation (simply treated thrusters as failed or operational).

37 [redacted]

38 [redacted]

- OFT-1 and OFT-2 IFA investigations did not include ground testing and tear-down of doghouse assemblies or RCS thrusters to better understand the impacts of the thermal environment on the hardware and soft goods.
- UA and fault tree dispositions for SM RCS thruster IFAs were not validated through subsequent ground testing.

Recommendations

- Conduct ground testing of the SM RCS thrusters in their flight configuration to validate the most likely failure cause(s) and RCCA fault tree closures.
- Conduct ground testing of the SM RCS thrusters in their flight configuration to re-qualify the propulsion system for the anticipated thruster usage and induced environments.
- Conduct tear-down and inspection of ground test articles within a timeframe that does not invalidate inspection results to understand any changes/damage resulting from the updated qualification test program.
- Generate MUAs for the RCS thruster soft goods and hardware, as needed, to address material compatibility and revised thermal environments.
- Increase the data rate of chamber pressure measurements on the Starliner-1 RCS thrusters.

Lessons Learned

- Ensure NASA has insight to critical component design details even if that hardware is produced at sub-tier suppliers.
- Integrated testing of the propulsion system in a flight like configuration is an essential element of system verification and validation.
- Validation of induced environments through ground and flight testing is also essential.
- Invest in ground testing to re-qualify propulsion system hardware, particularly when updated trajectory design maturity, flight experience, or IFAs show that anticipated usage and induced environments are exceeding pre-flight projections.
- Tear down and inspect ground test hardware to ensure that impacts upon soft goods are understood for both commodity exposure and combined environments testing.

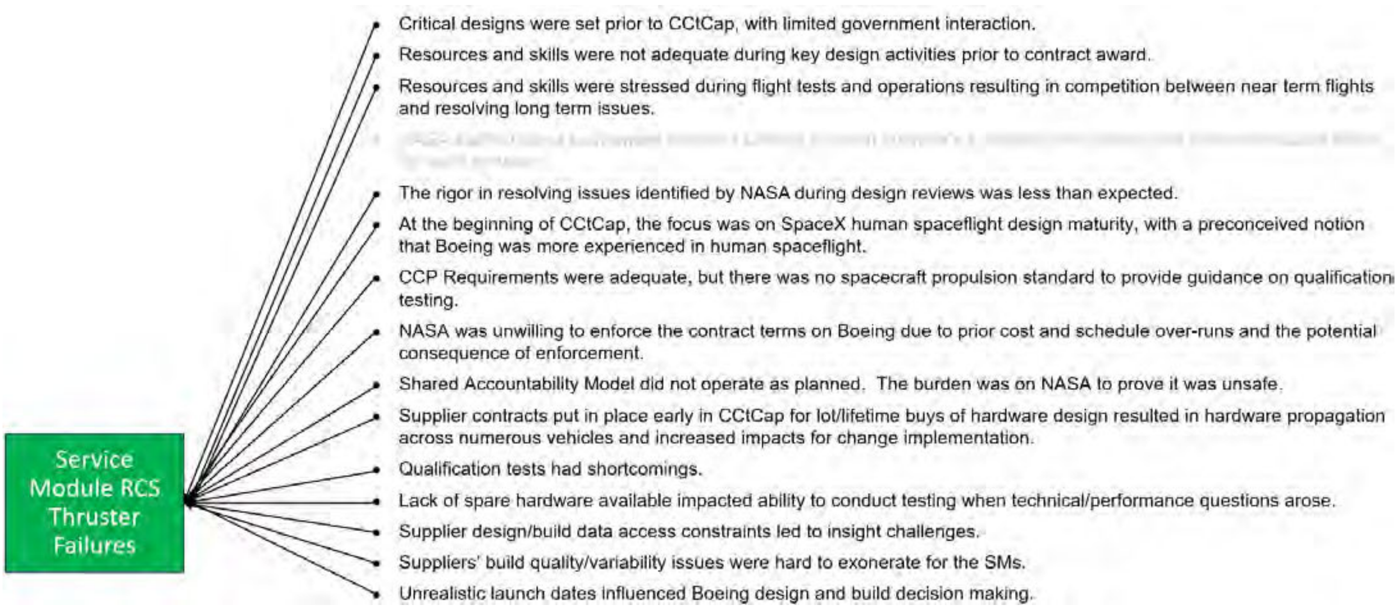


Figure 101 - General Findings Matrix - SM RCS Thruster Failures

The Starliner Data Review Team Report
SDRT Members

- [redacted]

  [redacted]
- [redacted]

[redacted]

- [redacted]

[redacted]

- [redacted]
- [redacted]

[redacted]

SDRT Scope

The SDRT focused primarily on the SM RCS thruster failures and reviewed available data for this failure across the OFT-1, OFT-2, and CFT missions. The primary goal of this sub-team was to look for data or opportunities where issues with the SM RCS thrusters might have been uncovered in previous missions. The team was interested in the fault-tree analysis process used in all missions, specifically as insight to help determine if the current CFT fault-tree analysis is robust and has reached the true root cause of CFT anomalies. In addition to reviewing data, the team interviewed eight technical experts covering propulsion, operations, and thermal disciplines.

OFT-1 Mission (12/20/2019 – 12/22/2019)

During the OFT-1 mission, the Mission Elapsed Time (MET) which was supposed to be latched at L-0 (launch) was incorrectly latched in place at L-10:23:53 (an error in the coding). This led to the Starliner spacecraft believing that it was over 10 hours into the mission at launch. Following spacecraft separation with the Atlas V launch vehicle, Starliner is programmed to execute maneuvers tied to the mission timer. With the incorrect time set, the Starliner attempted to perform incorrect maneuvers. These incorrect maneuvers led to excessive firing of the SM RCS Thrusters (but no OMAC firings), well outside of the qualified usage duty cycle, total pulse count, and total firing time. As the STAR team noted, this led to excessive propellant usage and 10 thruster failures, nine of which were attributed to high pressure sensor temperatures and one which was attributed to high solenoid temperature.

Findings

- The Boeing/NASA teams did not consider the 10 failures experienced on CFT to be “thruster failures”. They attributed the issue to over-use and pressure transducer and solenoid failures due to over-heating.
- If anything, the team gained extra confidence in the robustness of the thrusters because they continued to work even though significantly stressed outside expected usage. Boeing noted in a PCB presentation “OFT MET Anomaly demonstrated robustness of RCS thruster design despite long duration of excessive usage” [*SM RCS Thruster Failures during OFT,* [redacted] *17 July 2020*[39]].
- This “smoking gun” of the MET anomaly was immediately adopted as the only issue. Because of this conclusion, that the thrusters were used incorrectly, the fault tree developed was not extensive or robust. It consisted of 3 legs, with 21 total failure modes and sub-modes, reference *Figure 102*.

[redacted]

Figure 102 - OFT-1 SM RCS Thruster Fault Tree

- At the completion of OFT-1, additional thruster testing was proposed, but not pursued. Team members went as far as preparing a draft test request for the NASA White Sands Test Facility (WSTF). However, based on interviews with the experts involved at that time, the testing was dropped because it was believed there was no need to test thrusters in a usage profile like OFT-1 actual usage, as this was not representative and known to be well outside qualification limits.
- The teams noted that high duty cycle usage of the thrusters was potentially damaging, “Post-OFT, Team has been sensitized to SM RCS Jet high-pulse usage events” [*SM RCS Thruster Failures during OFT,* [redacted],

[39] [redacted]

17 July 2020[40]]. However, no changes in SM RCS usage were adopted. There were some changes made to OMAC usage during the deorbit burn, but not SM RCS. Again, the issue was attributed to MET anomaly over-use.

- Solenoid and pressure transducer failures could have potentially masked poppet swelling issues. However, the rapid thruster recovery of OFT-1 leads most technical experts to conclude poppet swell did not occur, or at least was not limiting thruster performance.

Recommendations

- Examine the fault-tree analysis performed by Boeing and determine if it is detailed and robust and that blocks are closed using objective evidence and not merely statements that are presented as factual without supporting data.

Lessons Learned

- Fault-tree analysis can be compromised by the team finding a "smoking gun" that is quickly determined to be root cause. It is human nature to focus on the obvious, at the expense of other potential issues. Requiring full and objective evidence that has been reviewed by independent technical experts for any fault-tree block closure is critical.
- While the root cause of the OFT-1 failures is likely tied to the MET anomaly, this mission presented an opportunity to identify a weakness of the SM RCS thrusters, that they are susceptible to failure due to overheating. Teams should consider extending learning from the actual failures to be more generic, along the lines of "What does this failure show us and are we sure the system does not have a weakness not previously identified?"

[40] [redacted]

OFT-2 Mission (5/19/2022 – 5/25/2022)

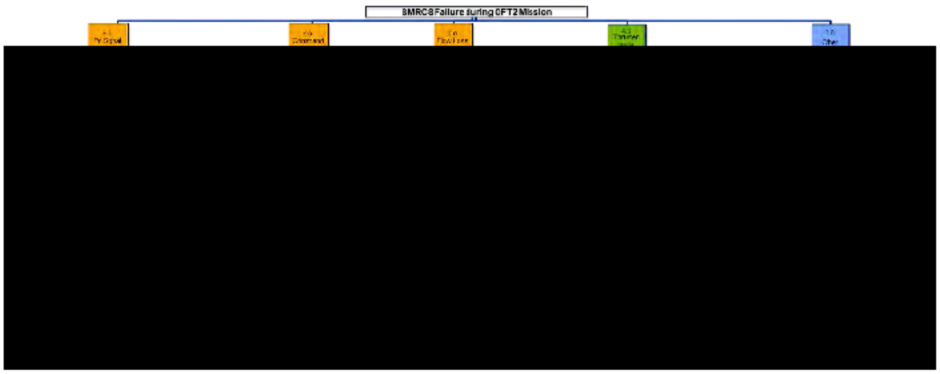
The SM propulsion system uses a Fault Detection, Isolation, and Recovery (FDIR) scheme where it checks for thruster chamber pressure as an indicator of thruster status. Any chamber pressure less than 110 pounds per square inch absolute (psia) is considered "off" or degraded by FDIR. Any pressure above this limit and the thruster is considered to be "on". The Integrated Propulsion Controller (IPC) and the Flight Management Computer (FMC) use these measurements to determine if the thruster is on when it has been commanded off (thruster failed on) or off when commanded on (thruster failed off). For the OFT-2 mission, the persistence, or the number of failed thruster flags required for the FMC to remove a thruster from the availability table was set to two. This means that the IPC had to detect low chamber pressure readings and set the "failed off flag" twice for the FMC to read on the data bus.

There are a variety of data rates in use throughout the Boeing [redacted]. For example, the [redacted]). One major issue that has been identified, and persisted through CFT, is that the propulsion system data is only sent via telemetry to the ground at [redacted] per sample. This can make it difficult to understand exactly how the [redacted] pressure are performing. In addition, the count of flags set comes through telemetry at [redacted]).

Three thrusters failed during the mission, by exceeding the FDIR persistence limit. In analyzing the actual data rates and pressure data sampling, the teams concluded that the thrusters were being shut down by FDIR that was "missing" chamber pressure measurements.

Findings

- False FDIR fail-off occurred due to [redacted] settings. The FDIR captures "false" low chamber pressure readings and counts as "strikes". The [redacted] required to remove the thruster from the usage table.
- The thrusters recovered quickly, and effects of seat separation were expected to be permanent and weren't considered due to SM thruster recovery.
- Seat swelling was considered as a failure mode, and as the STAR team has already noted, a Boeing presentation (ERB-23-0005) had a slide where the first bullet stated, "Seat swelling was considered (reducing propellant flow), but since flow is controlled by trim orifice and injector, seat swell contribution to resistance change would be negligible". When this presentation went to the next management briefing (JPRCB-23-002), that bullet had been removed from the slide. The experts interviewed by the SDRT did not recall that specific bullet and could not explain why it had been removed.
- FDIR was identified as root cause of the thruster shutdown. Like OFT-1, this became the "smoking gun" for the OFT-2 mission. While the OFT-2 fault tree was more robust than OFT-1, with 5 legs and 83 failure modes and sub-modes (*Figure 103*), once again many fault tree blocks closed without rigorous objective data.



[redacted]

Figure 103 - OFT-2 SM RCS Thruster Fault Tree

- Several presentations make the statement that should this type of "failure" be seen again, the solution is to disable FDIR, because the thrusters are fine. Like OFT-1, these failures were not considered thruster failures, but were considered misapplication of FDIR.
- In OFT-2, it is not possible to assign root cause, but poppet seat swelling cannot be ruled out as a cause of failure.

Recommendations

The recommendations coming from OFT-2 are like those listed above for OFT-1; focus on ensuring the fault tree analysis and evidence provided are robust and objective.

Lessons Learned

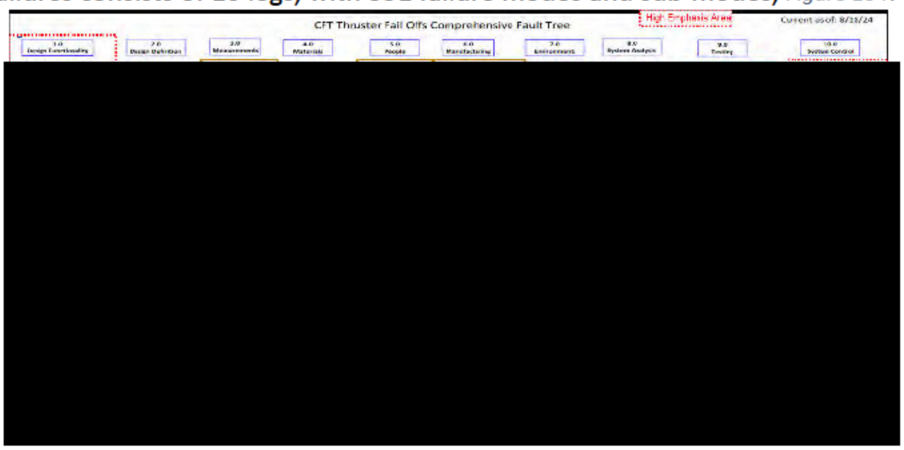
- Fault-tree analysis can be compromised by the team finding a "smoking gun" that is quickly determined to be root cause.
- The team seemed to be focusing on solutions that did not involve hardware changes. Changes to FDIR persistence from two to five "flags set" was an easy, quick solution that could be implemented in software.
- FDIR shutdown of thrusters masked any opportunities for additional learning, immediately becoming the focus of the failure investigation.

CFT Mission (6/5/2024 – 9/6/2024)

During the CFT mission, five SM RCS thrusters failed. Four of these thrusters were recovered after some time and hot fired to allow for continued usage in the mission. One thruster, B1A3 was never recovered. During the mission, investigation and testing at WSTF uncovered that the thruster valve Teflon poppet seat could swell given exposure to NTO and high temperatures. In addition, higher than expected temperatures of the NTO propellant supply lines could have also been an issue, as bubbles entrained in the higher temperature NTO can disrupt thruster performance.

Findings

- Poppet seat swelling was identified as the proximate cause of failures based on extensive WSTF testing.
- The fault tree process at the completion of CFT, which is still ongoing as of this writing, is much more disciplined and much more in-depth and comprehensive than previous missions. The fault tree generated for the CFT failures consists of 10 legs, with 351 failure modes and sub-modes, *Figure 104*.



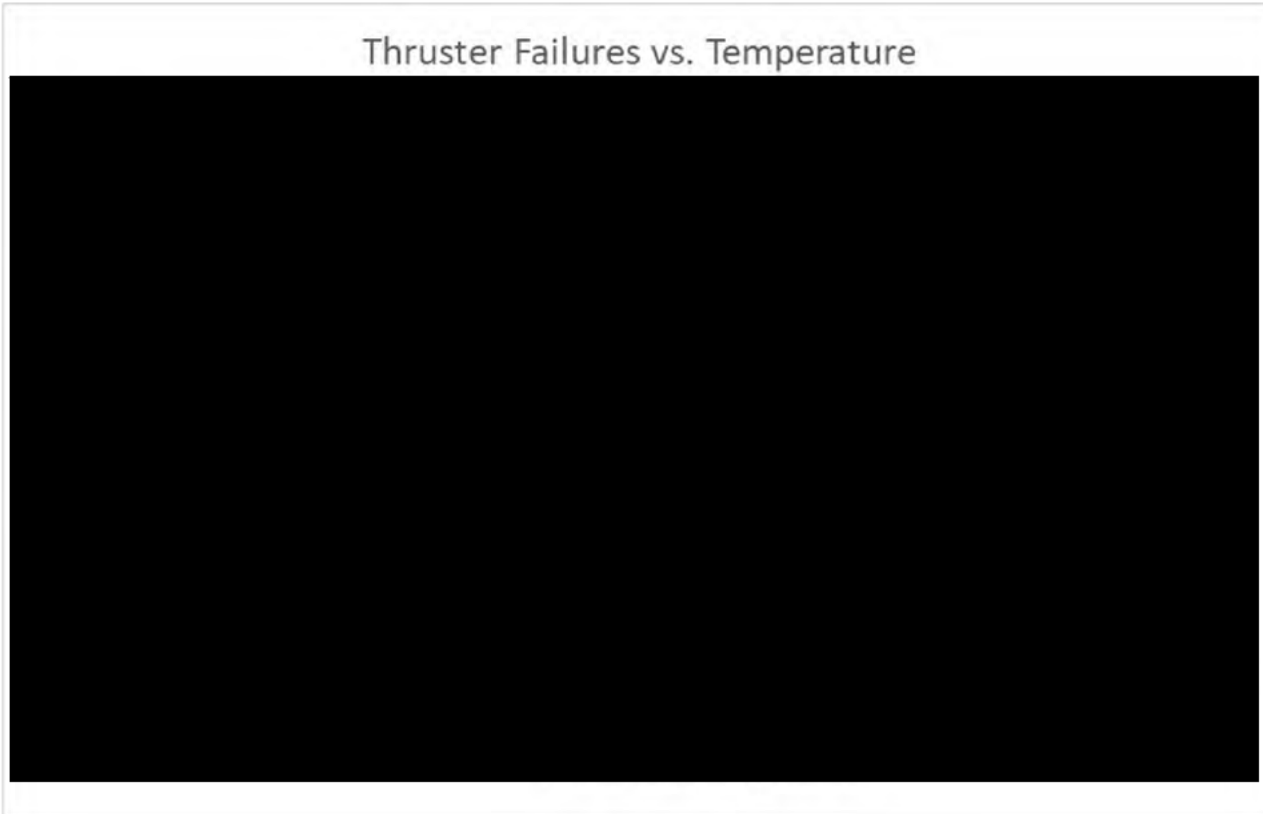
[redacted]

Figure 104 - CFT SM RCS Thruster Fault Tree

- Thruster temperatures seen on CFT were cooler than those found during OFT-1, but several were higher than OFT-2. While there is inconclusive evidence, this is believed to have occurred for two reasons. First, manual piloting was included as a flight test objective on CFT. This piloting caused more jet firings than previously seen on OFT-2 and could have led to elevated temperatures. Also, as FDIR persistence was increased from two to five after OFT-2, that change likely led to thrusters not being de-selected as quickly in the CFT mission. In effect, the change in FDIR persistence allowed the thrusters to continue to operate longer and heat more. The maximum NTO valve temperatures for each mission, each thruster is shown in *Figure 105*.

[redacted]

- SM RCS thruster failure is a multi-variable event as previously discussed. Temperature is not the only cause of failure. Thrusters got much hotter during OFT-1 than CFT, and yet continued to operate. Temperature of thrusters at failure are shown in *Figure 106*. As shown below, six of the thrusters that failed in OFT-1 did so at significantly higher temperatures than failures seen in OFT-2 and CFT.



[redacted]

Figure 106 - Thruster Failure Count by Temperature

- Low data rate ([redacted] continued to make diagnosis of thruster issues difficult. The team developed improved tools to determine thruster performance based on spacecraft reaction. However, multi-axis firings with multiple jets still made it difficult to diagnose based on inability to capture chamber pressures.

Recommendations

- Improve the data rate for critical parameters either through changes to current architecture, or additional data measuring and recording systems.
- Continue to refine the tools necessary to ascertain thruster performance based on vehicle reaction, independent of thruster chamber pressure measurements.
- With many variables playing into thruster failures, and history showing failures as low as approximately [redacted] F, it is critical to ensure that thermal environment changes and improvements planned for the next mission demonstrate significant margin. There is uncertainty as to where the actual failure temperature is, so margin is required to limit the chance of thruster failure.

Lessons Learned

- Manual control can introduce an unconstrained demand on any system. It is not possible to effectively envelope the amount and manner in which a human pilot will operate a system. Given this difficulty in enveloping human behavior, software systems should be used to create “keep out zones” that ensure human commands do not call for a system to operate outside of its qualified environment.

Systemic / Programmatic Issues

There are many issues that have been identified by the SDRT that apply across all the missions reviewed.

Findings

- Poppet seat swell is an historically documented and known issue for this type of thruster. Many examples of Teflon poppet seat swelling were identified by the NASA propulsion team and reviewed by the SDRT. These include:
  - A Gemini attitude control anomaly investigation from 1967 makes the statement: "Known causes of performance degradation included: NTO vaporization, thermal distortion, Teflon valve seat swelling, NTO flow decay, etc. The high temperature critical part of the TCA valve is the Teflon (FEP) seat, which, if subjected to high temperature, may swell. If excessive, this swelling could restrict propellant flow."
  - Shuttle Auxiliary Power Unit (HOPE-X Program) in 2000 had acceptance testing (ATP) failure with this exact failure mode, poppet seat swelling. This finding is particularly interesting because it occurred after the poppet seat had only been exposed to water (not NTO) at ambient temperatures (not elevated temperatures). In other words, Teflon poppet seats of this geometry can demonstrate swelling without propellant or high temperature exposure. This valve was also built by MOOG, the Starliner propulsion system valve manufacturer.
  - Wideband Global Satcom (WGS) failure investigation found "The pressure data of the WGS anomaly pointed to a reduction in oxidizer flow and thus the focus turned to swelling of the Teflon in the valve".
  - Mars 71 Anomaly investigation found "Seat deformation was exacerbated by high soak back temperatures and exposure to propellants. NTO softened the seat more than MMH."
  - An American Institute of Aeronautics and Astronautics paper (AIAA-2000-3549) states "…both model and experimental data shows that PTFE seal extrusion can be caused by thermal cycling alone, without the intervening influence of oxidizer. Furthermore, thermal extrusion is accompanied by gap formation".
- Early in development, Commercial Crew and Commercial Partners implemented a review process and participants created Review Item Discrepancies (RIDs). Unfortunately, major RIDs created by NASA during reviews were combined with Boeing generated RIDs.
  - The Boeing RIDs did not have the same depth/required actions as the original NASA RID, and Boeing RID closure only needed "acceptance" from the Boeing author.
  - During the design review cycle, several RIDs were submitted that identified concerns or issues regarding the SM prop doghouse thermal environments. These were then combined with Boeing RIDs that did not have a clear, documented closure.
- There are a number of requirement sets that are applicable to development of the propulsion system. However, many requirement gaps remain.
  - SMC-S-016 is applicable but lacks sufficient details on qualification hot fire testing and does not enforce a requirement for this type of test.
  - NASA-STD-5012 also lacks specificity on qualification hot fire testing.

- NASA-STD-6001 is an applicable material specification, and it specifies selection of fluid compatible materials (e.g., NTO). However, it lacks sufficient details on material selection and interactions.
- SMC-S-025 is a propulsion system-level requirement set, but states it is not applicable to small engines like the SM RCS thrusters.

- Integrated doghouse thermal qualification testing was never baselined. OFT-1 was planned to provide thermal qualification of the doghouse.
- Throughout the Starliner development phases, the propulsion thermal model maturity was a concern, as it lagged the overall SM propulsion system design maturity. In other words, the propulsion system design was finalized before thermal analysis was completed.
  - Thermal model maturity was a concern from the first SM propulsion system level design review.
  - Boeing was behind schedule throughout the design process. Data was not at a commensurate level of maturity indicated at multiple reviews.
  - Boeing did not effectively communicate SM propulsion system duty cycles or planned usage to the propulsion system designer, AR.
  - Thermal concerns were never raised to NASA mission planning meetings to discuss alternatives to reduce RCS heating. Thruster usage and mission parameters were not coordinated with the propulsion system provider, AR.
- Thruster performance is a complex, multi-variable issue.
  - It is an inter-related combination of temperature, duty cycle, total cycles, total firing time, OMAC usage, valve poppet seat geometry, valve poppet stroke clearance, etc.
  - Testing any one aspect, or maybe even a few of these together may not lead to a true solution with margin.

Recommendations

- Given this multi-variable problem, a robust delta-qualification test program will be required. Temperature alone, while important, is not the only parameter of interest to be enveloped during testing.
- Lessons learned within individual companies, as well as across the spaceflight industry, are not well captured or consulted during new hardware builds. CCP should work to implement a robust lesson learned process to be flowed to Commercial Providers.
- Special attention must be paid to thermal models and their certification/validation. Models must be reliable and predict environments conservatively to ensure design selections based on their output are appropriate.

Lesson Learned

- Lesson learned within individual companies as well as across the spaceflight industry are not well captured or consulted during new hardware builds. NASA should work to implement a robust lesson learned process to be flowed to Commercial Partners/Providers.
- Disposition of all RIDs needs to be approved by the author and reviewed at a PCB or equivalent forum to ensure that all concerned parties concur the issues identified have been adequately addressed.

- Building a propulsion system based solely on high-level component requirements is insufficient and misses interactions/integrated effects between hardware and the usage environment. Requirements by themselves are insufficient to cover design specific solutions.
- Spacecraft missions cannot be enveloping of all possible flight environments and scenarios and flight test is not an acceptable substitute for a robust ground test program.
- Thermal models and thruster usage were not adequately integrated between Boeing and their propulsion system designer, AR. The SM RCS thrusters were considered to be "Off the shelf" hardware, but the actual usage environment was never compared to historical usage to understand if these thrusters were suitable for the Starliner planned usage profiles.

STAR Senior Review Panel

Senior Review Panel Members

- [redacted]

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STAR Senior Review Panel Summary

To: [redacted]

From: Star Senior Review Panel

Date: 4/29/2025

Subject: STAR Senior Review Panel Peer Review Closeout

[redacted]

Per the STAR Senior Review Panel charter, the panel has participated in recurring peer reviews of the STAR team products. This includes an overview of the data collection process early on, including interview feedback. It also included interim products that organized the feedback, findings, and recommendations around themes, as well as the final written narrative integrating the STAR final product. These peer review efforts were conducted over a series of meetings on approximately a monthly cadence beginning in December 2024 and concluding with the review of final report in April. The senior panel members remained constant during this effort, though not all members were present at every interaction. The panel members were:

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

Through monthly meetings, the Review Panel had the opportunity to see some of the details of the STAR team interviews, from which the final STAR team conclusions were drawn. The STAR team interview data revealed a number of themes that were not considered in-scope for the STAR team investigation, which the Review Panel found to be important themes to include as NASA looks at how to best incorporate the lessons of the Starliner CFT mission.

NASA and Boeing launched several concurrent investigations associated with CFT, and the STAR Investigation itself was fairly limited in scope. The stated intent of agency leadership was to launch a parallel investigation into the organizational factors that influenced the outcome of CFT, which has been transitioned to a Program Investigation Team and currently on-going as this STAR investigation comes to a close. The Review Panel will remain intact to advise the CFT PIT as they complete their investigation.

Though the STAR investigation focused tightly on Starliner service module propulsion system issues, a number of the findings, recommendations and lessons learned provided by the STAR investigation are general in nature. The Review Team recommends that CCP and Boeing apply those recommendations and lessons beyond Starliner's propulsion system in an effort to gain the greatest value from this investigation, reduce the potential of finding similar issues in other Starliner systems in future flights and provide maximum value to the agency across our portfolio of development and operations.

In reviewing the data and results of the STAR investigation, several themes come into focus that the Review Team considered in a broader context.

- The interview data from the STAR investigation revealed a number of organizational and cultural aspects of decision-making, briefly touched on in the General Findings section of this report. These items of interest influenced the final outcome of CFT. The Review Panel finds merit in further detailed investigation of those themes.
- Many of the STAR investigation recommendations require a greater investment of personnel and/or hardware in the form of greater insight and communication during product development, review/approval of supply chains and sparing strategies, as well as a dedicated focus on flight-like hardware test campaigns. The Review Panel observes that currently a number of Starliner test topics are making their way to the Commercial Crew Program Control Board, each with the same challenges: limitations on available hardware and test facilities that would limit the ability to run flight-like tests. The Review Panel agrees with the STAR Investigation Team recommendations but finds that Commercial Crew needs to address how to change decision-making processes going forward when called on to navigate similar challenges, now and in the future. Otherwise, the lessons of CFT will be lost.
- A final theme centers on the idea that NASA requires two, independent providers for crew access to LEO. This redundant capability requirement produced an over-constrained system;

two providers were selected for Commercial Crew contracts and NASA required that both be successful. Resource constraints (and perhaps in the case of Starliner an over-reliance on the promise of heritage hardware and software), and the requirement of success ultimately led to a smaller effort in testing, reduction in design iteration and erosion in the norms of flight rationale and standards for risk acceptance. If every provider must be successful and NASA is unwilling or unable to fund improvements, and enforce, or alter contracts to ensure success, it is inevitable that standards will lower, increasing the chances of failure.

It is the Review Panel's overall assessment that the STAR investigation did a commendable and thorough self-analysis with its given limited scope. Their recommendations are stated as, "explicit for Commercial Crew to implement before the next flight, or as practical" which the Review Panel endorses. The Review Panel finds that the Commercial Crew Program should develop and share a post-investigation implementation plan and timetable to ensure subsequent Starliner missions benefit from the CFT experience. The Review Panel encourages that the lessons learned be shared with other NASA Program/project managers widely and immediately, in order for them to make any applicable and necessary changes. Lastly, the Review Panel looks to the PIT to explore the themes stated above.

Conclusions

STAR Summary

Commercial Crew accepted risks in the SM propulsion system and the CM propulsion system that were not fully understood prior to CFT. These risks included variances to requirements and unexplained anomalies from the previous flight tests. There were no unstated technical concerns among the NASA team during the commit to flight process, but there was a shared underestimation of the likelihood of future thruster failures.

Improvements to Commercial Partner/Provider interaction early in design phase could have enhanced the technical capability.

SDRT Summary

There were many opportunities to find system susceptibility to elevated temperature and high duty cycle usage. In both the OFT-1 and OFT-2 missions, a fundamental and seemingly clear "root cause" was found and all team effort and energy was focused on resolving those issues (MET anomaly and FDIR). These believed root causes masked the opportunity to learn from how the hardware behaved when operated at the edge of the envelope. Additional testing to explore these higher temperature operating conditions could have led to finding of the poppet swell issue prior to the CFT mission.

Of course, hindsight is always 20/20 vision, and cost and schedule realities make it difficult to go far beyond the "clear" root cause. Teams should evaluate what other impacts failures have had on hardware to help mitigate undiscovered issues moving forward.

Appendix A
Acronyms

Acronym	Definition
AA	Associate Administrator
AR	Aerojet Rocketdyne
ASAP	Aerospace Safety Advisory Panel
ATP	Acceptance Testing
B-RID	Boeing Review Item Disposition / Discrepancy
CAT	Category
CBR	Certification Baseline Review
CCDev	Commercial Crew Development
CCDev2	Commercial Crew Development (Round 2)
CCiCap	Commercial Crew Integrated Capability
CCP	Commercial Crew Program
CCtCap	Commercial Crew Transportation Capability
CCTS	Commercial Crew Transportation System
CDR	Critical Design Review
CFT	Crew Test Flight
CM	Crew Module
CPC	Certification Products Contract
CoFR	Certificate of Flight Readiness
COTS	Commercial Orbital Transportation Services
CRS	Cargo Resupply Services
dCDR	delta Certification Design Review
DDTE	Design, Development, Test, and Evaluation

DMMT	Dragon Mission Management Team
DOF	Degree of Freedom
DRD	Data Requirement Deliverable
EDL	Entry, Descent, and Landing
FDIR	Fault Detection, Isolation, and Recovery
FMC	Flight Management Computer
FOD	Flight Operations Directorate
FTE	Full Time Equivalent
FTO	Flight Test Objective
FTRR	Flight Test Readiness Review
GMO	Ground and Mission Operations
GN&C	Guidance Navigation and Control
HEOMD	Human Exploration and Operations Mission Directorate (retired)
HH&P	Human Health and Performance
HR	Hazard Report
HQ	Headquarters
HW	Hardware
Hz	Hertz
IDIQ	Indefinite Delivery/Indefinite Quantity
IFA	In-Flight Anomaly
IPC	Integrated Propulsion Controller
ISS	International Space Station
JSC	Johnson Space Center
JPRCB	Joint Program Requirements Control Board

KSC	Kennedy Space Center
LEO	Low Earth Orbit
LRR	Launch Readiness Review
LSP	Launch Services Program
MDL	Mission Data Load
MET	Mission Elapsed Time
MHz	Megahertz
MIUL	MIUL = Materials Identification and Usage List
MM&I	Mission Management and Integration
MMT	Mission Management Team
MO	Mission Operations
MRR	Manufacturing Readiness Review
msec	Millisecond
MSFC	Marshall Space Flight Center
MUA	Material Usage Agreement
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering Safety Center
NOM	NASA Operations Manager
NTO	Nitrogen Tetroxide
OFT	Orbital Test Flight
OMAC	Orbital Maneuvering and Altitude Control
P2D2	Port Doghouse Manifold 2
PC&I	Program Control and Integration
PCB	Program Control Board

PDR	Preliminary Design Review
PIT	Partner Integration Team
PMRB	Prime Material Review Board
PSIA	Pounds per Square Inch Absolute
RCCA	Root Cause Corrective Action
RCS	Reaction Control System
RID	Review Item Disposition / Discrepancy
S&MA	Safety and Mission Assurance
SAA	Space Act Agreement
SC	Spacecraft
SDRT	Starliner Data Review Team
SE&I	Systems Engineering and Integration
SEB	Source Evaluation Board
SM	Service Module
SMMT	Starliner Mission Management Team
SOMD	Space Operations Mission Directorate
SRP	Safety Review Panel
STAR	Starliner Tests and Anomalies Review
STRB	Safety Technical Review Board
SW	Software
TA	Technical Authority
TDR	Technical Design Review
ThOR	Thermal Operations and Resources
TICB	Technical Integration Control Board (ISS)

TIM	Technical Integration Meeting
TLYF	Test Like You Fly
TAYO	Test as You Operate
TRB	Technical Review Board
UA	Unexplained Anomaly
V&V	Verification and Validation
VCN	Verification Closure Notice
WGS	Wideband Global Satcom
WSTF	White Sands Test Facility

Appendix B
Interviews
Summary of Interviewees

- Programmatic:
  - Program Managers and Deputies (former and current)
  - CCtCap Source Evaluation Board members
  - CCP Office Managers and Deputies
  - Spacecraft Propulsion Leads and Experts (former and current)
  - Safety Technical Review Panel Chairs (former and current)
  - Certification Manager (former)
  - Verification and Validation Panel Chair (former)
- Flight Operations Directorate:
  - Starliner Crew (current and future)
  - Flight Directors (former and current)
  - Mission Operations
  - JTT Chair
- Engineering:
  - Chief Engineers
  - Spacecraft Leads
  - Spacecraft Valve Experts
  - Spacecraft Thermal Experts
- S&MA
  - Chief Safety Officers (former and current)

STAR Interview Questions

Support Posture:

- When did you support CCP and what was your role working with Boeing?
- Was CCP your primary responsibility? Boeing CCP? What percentage of time were you spending on CCP (Boeing CCP)?
- Did you participate in mission support and/or flight following?
- Referencing the timeline in the pre-read materials, are there any observations you would like to share?

CCP Programmatic:

- Please describe your understanding of the insight/oversight philosophies during your involvement through the CCP lifecycle (SAAs, CPC, CCtCap) and Program leadership.
- Due to the limitations governed under this SAAs, did this prevent NASA from providing feedback needed to influence the design?
- If in CCP prior to CCtCap, what was your perspective of Boeing and SpaceX ability to implement certification of a human space transportation system?
- Do you believe that the CCP 1130 requirements were adequate?
- Do you believe that the CCP design and construction standards were adequate?
- Do you believe that the CCiCap and/or CCtCap deliverable requirements were adequate?
- Do you believe that the CCtCap insight data deliverables were adequate?
- Do you believe that your team had sufficient expertise and resources to perform your insight and oversight roles on CCtCap?

SM Propulsion Certification:

- Did you believe that the SM propulsion system hazards were adequately understood prior to CFT? (not looking for 20/20 hindsight)
- Describe the NASA review level of hazard verifications throughout the process.
- Did you believe that the SM propulsion system software, including FDIR, was adequately understood prior to CFT? (not looking for 20/20 hindsight)
- Did you believe that the SM propulsion system environments (thermal, loads, etc.) were adequately understood prior to CFT? (not looking for 20/20 hindsight)
- Did you believe that the SM propulsion system hardware design was adequately understood prior to CFT? (not looking for 20/20 hindsight)
- Did you believe that the SM propulsion system performance was accurately modelled prior to CFT? (not looking for 20/20 hindsight)
- Did you believe that the risks of the SM propulsion system were accurately characterized prior to CFT? (not looking for 20/20 hindsight)

- Did you believe that the OFT 1 & OFT 2 IFAs on the SM propulsion system were adequately resolved prior to CFT? (not looking for 20/20 hindsight)
- In your opinion, were the SM propulsion system designs finalized too early/late?
- Did we have adequate reviews prior to the design implementation?
- Did we have sufficient ability to effect change on the design process?
- Was the Program governance for shared accountability, and requirements flow down, adequately applied to Boeing outsourcing of prop system to Aerojet Rocketdyne and their suppliers for DDT&E?
- Do you believe the team focused on the right products to evaluate certification or should we have had different priorities? (Phased Safety Review, VCNs, Variances)
- Do you believe there were prop system decisions made due to unrealistic schedules during DDT&E?

Qualification Testing:

- Did you participate in or evaluate the prop system qual testing?
- Did you review any of the subsystem qual specifications from Aerojet and suppliers?
- With hindsight knowledge, what would you have changed in the qual testing to prevent the anomalies uncovered during CFT?
- Did the team consider doghouse qual testing?
- Did we have adequate instrumentation in the test flights to validate qual or flight environments?

M&P Specific Questions (used for small subset of interviews):

- Was M&P involved in the prop system design reviews under CCiCap? Were there any significant findings/comments?
- How does the MIUL/MUA process cover the SL-1 prop system components from AJR? What about their suppliers, such as Moog?
- A summary of the MIUL/MUA progress came forward to the PCB before OFT. Why wasn't there a subsequent briefing for the other test FLTs?
- Did we receive MUAs prior to CFT for the [redacted] Helium O-ring within the RCS thruster flange or the Teflon poppet seal within the RCS thruster? If so, what category MUAs were they?
- Did we require Hypergol exposure testing for soft goods within the SL-1 prop system, particularly for the RCS portion of the system? If not, why did we continue allowing analysis in lieu of testing after earlier compatibility issues with both providers?

Closing:

- Do you have any comments that you would like to make?

SDRT Interview Questions

Background of the SDRT:

- The SDRT charter is to examine the detailed data from OFT / OFT-2 / CFT and focus on how anomalies from the previous missions were resolved or accepted for continued flight. The main goal was to understand what data the teams reviewed, what conclusions were drawn, what data might now be looked at with perfect hindsight in a different light, and probably most importantly, is the CFT data being looked at correctly or is there something else that should be considered in regard to CFT?

Background:

- Tell about your experience with Starliner, which missions you supported directly, and current role for Boeing missions.

OFT Mission (12/20/2019 – 12/22/2019):

Focusing on the SM RCS thrusters, it appears (to the SDRT) that the high duty cycle / overuse of the thrusters led to temperatures beyond qual that caused pressure transducer shift / failures, solenoid failures, and thruster shutdown. The "root cause" was determined to be the MET anomaly / thruster use outside of expectations and qual and that "fixing the MET anomaly would eliminate future failures".

- What was the Anomalous OI Burn / Mission Elapsed Time (MET) anomaly and what do you think was affected?
    a. Were there any discussions at the lower, working team levels with Boeing that weren't added to future charts for Program level meetings?
    b. Do you think the MET anomaly concealed any deeper, fundamental issues with the thrusters and / or did the team write off thruster issues as being solely caused by this anomaly?
- Were lessons learned from the flight and the method of anomaly resolution thorough?
- What post-flight proceedings address root cause of the failed thrusters? Do you recall the origin of the fault tree and internal discussions of its elements?
- What agreements were made on corrective actions or additional testing for OFT-2?
    a. There are specific references to "Recommend ground testing of RCS thrusters to assess impact of OFT duty cycle on Pc sensor operation. Was any additional testing completed post-OFT to better characterize thruster performance and temperatures or improve thermal models?

- Reference: "Offline Action 2 - Recommend ground testing of RCS thrusters to assess impact of OFT duty cycle on Pc sensor operation"

b. There were also notes that the team was now "sensitized to high jet pulse usage" – were any changes made to reduce the number of jet firings / increase pulse durations?

OFT-2 Mission (5/19/2022 – 5/25/2022):

For this mission, the SDRT would summarize the outcome of this investigations and changes made to be that data rates, and thruster ramp-on rates, the root cause of failures was believed to be FDIR failures or "strikes". Increasing persistence on the number of strikes required to fail a thruster was believed to have eliminated the "nuisance" faults and thruster shutdown.

- Is this an accurate understanding of the issue, or how would you characterize the failures and actions to mitigate?
- Were there any similarities to the OFT-1 failures discussed at this time?
- With current hindsight (and not trying to point any fingers), do you think the OFT-2 failures were / could have been from higher than expected thruster temperatures, similar to CFT?
- After the first OFT-2 launch attempt, when the team discovered oxidizer valve issues, did the team discuss or expand review of oxidizer compatibility with other components outside the valves?
    a. Was this a missed opportunity to find oxidizer compatibility issues?
- Did the fault tree change from OFT and was the RCCA approach different?
    a. Was there new data presented or discussed that wasn't considered during OFT-1?
    b. Was there any discussion of integrated Doghouse testing after this mission?
- In regard to OFT-2 IFA (OFT2-76), S1A1 exceeded qual thermal limits. (PCB-23-053) [redacted] thermal environment, but did not use propellants in their testing.
    a. Do you remember any specifics from this test?
    b. Was this documented as a TAYO exception at the time?
- For the SM RCS IFA closures, the ERB charts had a statement under [redacted] was considered but since the flow is [redacted] to flow resistance would be minimal. Was there an analysis from AR or Boeing that was used to make this statement?

CFT Mission (6/5/2024 – 9/6/2024):

For CFT, it seems that poppet swell was discovered from the WSTF testing conducted and has become the leading candidate for root cause. Elevated temperatures beyond qual levels created an environment where NTO bubble / boiling was occurring and the high temperatures also created elevated back-pressure behind the poppet seat and softened the Teflon as well.

- Is this an accurate understanding of the issue, or how would you characterize the failures?
- Looking at the peak temperatures seen in CFT, it seems that they are somewhat higher than OFT-2 and cooler than OFT-1. What do you think caused the temperatures to be elevated in CFT?
- CFT had issues and some new / modified steps to finish propellant loading. Is there any chance and / or any way that changes to the prop loading procedures subjected the poppet seals to a "new" environment?
    a. Higher pressure differential / higher levels of vacuum / more time at pressure and opportunity for NTO to get behind the seat?

Summary

- Are there any other issues that you think are important to understand the similarities / differences between these three missions, as they relate to RCS thruster failures?
    a. What didn't we ask you that you think we should have?
- Do you think the process for analyzing the failure, determining likely root cause, and working toward resolution is better today?
    a. Maybe specifically, do you think the failure investigation process was thorough, or is there a possibility the team "latched on to" the first / most recognizable cause?
    b. Do you think our current process will get to an accurate root cause and lead to testing and analysis that will prevent failures in future missions?

Appendix C
Relevant Links

[redacted]

[redacted]

SDRT Document / Presentation Review and Notes

[redacted]

[redacted]

Appendix E

SSP 30599, Rev. F Safety Review Process

Phase	Timing	General Safety Effort Required to Support Review	Purpose of Review
I	Preliminary Design Review	Develop safety analysis/assessment report to reflect the preliminary design: Define hazards. Define hazard causes. Evaluate action for eliminating, reducing, or controlling hazards. Identify approach for safety verification. Prepare a description of ground, assembly, maintenance, and nominal operations. Determine compliance with SSP 50021 and SSP 51700 requirements.	Assess preliminary design against SSP 50021 and SSP 51700 requirements. Evaluate preliminary hazard controls and safety verification methods. Identify interface hazards and requirement inconsistencies.
II	Critical Design Review	Refine and expand safety analysis/assessment report: Evaluate interfaces and mission (for ground) operations procedures, plans, and timeline. Update hazard descriptions, causes, and controls. Finalize test plans, analysis procedures, or inspections for safety verification. Finalize description of ground, assembly, maintenance, and nominal scenarios. Determine compliance with SSP 50021 and SSP 51700 requirements.	Assess final design against SSP 50021 and SSP 51700 requirements. Identify potential non-compliances. Concur on specific hazard controls and safety verification methods.
III	Prior to processing <END ITEMS> for launch	Complete safety analysis. For safety review panel, complete all significant safety verification test, analyses, and/or inspections. Open standard safety verification items are documented on the SVTL. Submittal of flight safety certificate (ISS_OE_906) to the safety review panel. For Ground – Submittal of GSRP Safety Certification Letter to KSC Operations	Approval of final safety assessment. Resolve non-compliances Identify and resolve open safety items. Certificate of Ground Safety Compliance

Post phase III activities	Verification Complete	Close open VTL items. Assess real time changes	Support ISS Safety CoFR endorsement

Appendix F
Raw Timeline Data
<Above the Year Timeline>

Boeing SAAs/Contracts/Boeing Milestones	**Launch/Board Date/Signed**
CCDev1 SAAs (5)	1/30/2010
CCTS SRR (Abort Architecture Trade)	3/4-5/2010
CCDev2 SAAs (4)	4/4/2011
SM Prop PDR	1/9-10/2012
CCiCap SAAs (3)	7/31/2012
CPC Contracts (3)	12/5/2012
PDR	12/2012
TDR OMAC/RCS	12/2012
SM Prop CDR	12/9/2013
CCtCap Contracts (2)	9/16/2014
CBR	11/21/2014
P-2 Safety Review	1/13/2015
Prop TIM 1	1/15/2015
SM RCS Thruster Valve MRR	3/16/2015
Phase II STRB RR	3/16/2015
Delta CDR	**5/6/2015**
SM Prop dCDR	6/2015
S-CDR	7/6/2015
P-2 STRB 80%	**7/17/2015**
QTV Production RR	8/10/2015
Prop TIM 2	10/29/2015
QTV RR	12/4/2015
Prop TIM 3	1/28/2016
Prop TIM 4	4/22/2016
Pre-Cert SR SC Prop	10/2016
RCS Valve Test RR	11/29/2016
SM OMAC/RCS Qual Testing	**10/2017 – 3/2018**
SM Hotfire 1	**6/2/2018**
ISS DCR (partial)	6/25/2018
SM Hot Fire Abort Test	**6/25/2018**

SM Hotfire 2	**5/9/2019**
ISS DCR	**6/20/2019**
HR 16.01 P3, C 8&9	**7/22/2019**
PAT	**11/4/2019**
OFT FTRR	**12/13/2019**
OFT-1	**12/20/2019**
OFT-2 DCR	12/18/2020
OFT-2 (scrub)	8/4/2021
OFT-2	**5/19/2022**
CFT DCR 90%	**12/15/2022**
CFT DCR	**6/7/2023**
CFT FTRR (partial)	11/29/2023
CRR	**11/30/2023**
HRCP (interim)	4/25/2024
CFT FTRR	**4/25/2024**
CFT (first attempt)	5/6/2024
HRCP A (interim)	5/29/2024
CFT dFTRR	**5/29/2024**
CFT	**6/5/2024**

<Below the Year Timeline>

Events/Documents/SpaceX Missions	Launch/Board Date/Signed
1100 Requirement Series draft	9/2011
Baselined 1100 Requirement Series	**12/2011**
CRS-1	10/7/2012
CRS-2	3/1/2013
Baselined NASA HEOMD-CSD-10001	**11/17/2013**
CRS-3	4/18/2014
CRS-4	9/21/2014
CRS-5	1/10/15
CRS-6	4/14/2015
Pad Abort Test	**5/6/2015**
CRS-7 (LOM)	6/28/2015
CRS-8	4/8/2016
CRS-9	7/18/2016

CRS-10	2/19/2017
CRS-11	6/3/2017
CRS-12	8/14/2017
CRS-13	12/15/2017
CRS-14	4/2/2018
CRS-15	6/29/2018
CRS-16	12/5/2018
Demo-1	**3/2/2019**
• **Demo-1 SC RUD**	**4/20/2019**
CRS-17	5/4/2019
CRS-18	7/25/2019
• **Demo-2 DCR Part 1**	**11/15/2019**
CRS-19	12/5/2019
• **Demo-2 Delta DCR**	**12/16/2019**
CRS-20	3/6/2020
• HRCP Basic (interim)	5/22/2020
Demo-2	**5/30/2020**
• **ORR CR**	**7/24/2020**
• **CR**	**9/3/2020**
• **HRCP Rev. A-1**	**11/10/2020**
Crew-1	**11/16/2020**
CRS-21	12/6/2020
Crew-2	**4/23/2021**
CRS-22	6/3/2021
CRS-23	8/29/2021
Crew-3	**11/10/2021**
CRS-24	12/21/2021
Crew-4	**4/27/2022**
CRS-25	7/14/2022
Crew-5	**10/5/2022**
CRS-26	11/26/2022
Crew-6	**3/2/2023**
CRS-27	3/14/2023
CRS-28	6/5/2023
Crew-7	**8/26/2023**
CRS-29	11/9/2023
Crew-8	**3/3/2024**
CRS-30	3/21/2024

Crew-9	**9/28/2024**
CRS-31	11/4/2024

Key:

Gold – NASA

Blue – Boeing

Red – SpaceX

Appendix G
Commercial Crew Transportation Capabilities Contracts (excerpt from RFP-public domain)
H.15 GOVERNMENT INSIGHT

(a) Introduction

(1) Government insight provides NASA Commercial Crew Program (CCP) and ISS Program Management an understanding of the Contractor's activities to assess the status, critical paths, and risk associated with successfully completing contract requirements, achieving final certification, and successfully completing Post Certification Missions. Government insight will include: Insight, Quality Assurance function, and Joint Test Team (JTT) participation as defined below.

(2) Government insight is defined as gaining an understanding of the Contractor's activities and data through an effective working relationship, inspections and interactions, without approval or disapproval authority, and provides information for the eventual certification approval.

(i) This clause describes the intended primary working-level interface between the Contractor and the Government during execution of this contract. It is intended to facilitate an exchange of information adequate for nominal activities.

(ii) The Government reserves the right to implement remedies for nonconforming services or work. These remedies are described in clause E.2 52.246-4 *Inspection of Services and Research and Development Work - Fixed-Price (Deviation)*.

(3) The Contractor shall ensure the Government has insight, into all subcontractors and suppliers performing or supporting any critical work associated with this contract.

(4) Details of the Contractor's approach to insight to accomplish items (a)(1), (a)(2) and (a)(3) above shall be implemented in accordance with **DRD 001 Insight Implementation Plan.**

(b) Notification
The Contractor shall notify the Commercial Crew Program designee of technical meetings, control boards, reviews, tests, and areas identified for Government Quality Assurance associated with certification and Post Certification Mission activities in the mutually agreed timeframe to permit meaningful Government participation through the entire event, in accordance with **DRD 001 Insight Implementation Plan**.

(c) Access

(1) The Contractor shall provide the Government and its support services contractor(s), under suitable protective conditions, access to all Contractor activities associated with certification and Post Certification Mission activities under this contract. Activities include, but are not limited to CCT-PLN-1100, *Crew Transportation Plan,* Appendix C, *Insight Areas*.

(2) The Contractor shall provide the Government and its support services contractor access to all data used in performance of this contract, including but not limited to, data associated with areas of insight identified in CCT-PLN-1100 Appendix C and supporting data/information, and administrative and management information with the exception of financial information; and any other information, not used in performance of the contract, related to the Crew Transportation System (CTS) design, production, and operations to include technical data, supporting data/information, and administrative and management information with the exception of financial information.

(3) At a minimum, access to data is the ability for Government and its support services contractor personnel, both remotely and on-site at the Contractor's facilities, to locate and review all data (as defined in (4) directly below) in a useable and readable format.

(4) The Government may use the data to which it has access under this provision solely for the purposes specified in paragraph (a)(1).

(5) The Contractor shall provide office space co-located on-site, badging, furniture, telephones, and use of easily accessible fax, data lines, and copy machines, for full-time and temporary Government personnel and its support services contractor performing insight activities, in accordance with **DRD 001 Insight Implementation Plan**.

(d) Joint Test Team Activities

(1) The JTT-related activities will be Contractor-led (reference CCT-PLN-1120, *Crew Transportation Technical Processes,* Section 5.3, *Flight Test*), and shall include active and steady state Government participation both on site and remotely. The Contractor shall accommodate Government personnel who will provide embedded insight during the activities identified in (d) (2). Government JTT members will not provide direction to Contractor personnel on design changes or procedures, or any other aspect of CTS development, production, or operation. Government JTT members provide insight only, and will not approve or disapprove any aspect of the Contractor's CTS design or performance of the contract. Any action(s) taken by the Contractor in response to any direction given by any person other than the Contracting Officer shall be at the Contractor's risk. The

JTT will provide a formal, unambiguous, programmatic structure for Government operationally focused input to the Contractor. In addition, the Government lead on the JTT will provide integrated, consolidated operations insight to the CCP. By its structure, the JTT will prevent unintended, informal Government inputs to the Contractor. To the maximum extent possible, the JTT will work together and strive to resolve operational issues at the lowest level.

(2) The Government's JTT insight activities will focus on qualitative assessments of crew operational interfaces with the vehicle and human-in-the-loop assessments of operational suitability. These assessments will include, but are not limited to vehicle handling qualities, situational awareness, workload and operational complexity, usability, cockpit layout, displays and controls, and flight crew suits. In addition, insight will occur through participation during the planning and build up phase of ground testing (e.g., simulator training and evaluations, mockup demonstrations, etc.), during test flights, and during the post-test flight evaluation process. Insight gained through integrated operations assessments will ultimately feed into NASA's verification approval decisions (before test flight) and validation approval decisions (post test flight).

(e) Government Quality Assurance (GQA) Functions

(1) The Government will perform the following quality assurance functions: Product Examination, Process Witnessing, Record Review, Surveillance, and Audit.

(2) GQA functions will be performed for all safety-critical items/processes/products identified by a risk based analysis (RBA). An RBA is an iterative analysis based on a comprehensive understanding of the design, development, testing, critical manufacturing / assembly processes, and operations used to identify areas of risk. The Contractor shall support the RBA, by providing technical expertise, as required. The definition of safety critical is found in CCT-REQ-1130, *ISS Crew Transportation and Services Requirements Document,* and SSP 50808, *ISS to Commercial Orbital Transportation Services (COTS) Interface Requirements Document (IRD)*.

(f) Result of Insight

(1) Insight should result in an effective working relationship between the Government and the Contractor leading to a NASA certification of the Contractor's CTS. Should insight and/or JTT participation identify non-compliance with CCT-REQ-1130, CCT-PLN-1120, and/or SSP 50808; the terms and conditions of the contract; or a difference in interpretation of test results; or disagreement with the Contractor's technical approach; the Government insight team will elevate the issue through the appropriate CCP boards. Through an effective, functioning relationship, the Government

and Contractor should strive to resolve issues at the lowest working level and minimize issues elevated to program boards. Program boards will disposition recommendations in a timely manner and provide oversight resolution if necessary. Resulting board decisions and direction will be transmitted to the Contractor through the Contracting Officer. If disposition results in a requirement change, the change clause (I.2, FAR 52.243-1, *Changes-Fixed Price*) would take effect. If the Contractor and Contracting Officer disagree on whether the board disposition provided is within the requirements of the contract, the disputes clause (I.2, FAR 52-233-1, *Disputes-Alternate I*) is applicable.

(2) The data generated as a result of Government insight may be used, modified, reproduced, released, performed, displayed, or disclosed within the Government and its support service contractors under suitable protected conditions. The Government may not, without written permission of the Contractor, release or disclose the data outside the Government, except as otherwise required by law, use the technical data for manufacture, or authorize the technical data to be used by a party outside the Government.

(g) Contractor Responsibility

Notwithstanding the insight set forth in this Clause, the Contractor assumes full performance responsibility as set forth in this contract. The Government's insight or JTT participation under this clause shall not be construed as authorization, endorsement or approval of milestones, certification or final acceptance or rejection of Post Certification Mission success.

(End of Clause)

Appendix I. Senior Review Panel Response to Investigation Team Report

December 31, 2025

Space Ops Mission Directorate AA,

A Senior Review Panel has participated in SOMD's Program Investigation Team (PIT). The PIT was chartered to investigate the technical, organizational, and cultural contributors to the anomalies occurring during the CST-100 Starliner Crewed Flight Test (CFT).

Review Panel members were:

[redacted]

This panel has participated regularly with the PIT, including an overview of the investigation process, review of interim products and findings, and providing feedback along the way. The PIT Final Report on CFT is a comprehensive and sobering assessment of the technical, organizational, and cultural challenges that impacted the mission. While the technical cause investigation continues, the recommendations related to culture and organization which can drive technical outcomes are both necessary and timely. Our panel endorses the PIT methodology and recommendations as actionable.

This panel would advise SOMD to adjudicate all 61 recommendations proactively and transparently, and to use this as an opportunity to examine areas which might benefit from change. A plan for the "road to" the next Starliner missions, both uncrewed and crewed, and a spacecraft certification plan that allows for incorporating learning from the investigations are not yet in place. The lack of these plans raises concerns that the lessons from CFT will not be incorporated in the spacecraft and operations associated with follow-on missions. A thorough SOMD review and action plan for the recommendations is warranted.

The panel also supports "that the event be retroactively classified as a Type A mishap and that PIT report serve as the final mishap investigation report." In doing so, this adds the rigor and communication that events like this deserve and ensure archiving for the benefit of lessons and learned for future missions.

The PIT Final Report is a vital document that captures the complexity of integrating commercial systems into human spaceflight. It balances technical rigor with organizational introspection and offers actionable recommendations. The lessons from CFT must be institutionalized—not only within NASA and Boeing but across the broader commercial spaceflight ecosystem. Safety, transparency, and accountability must remain paramount, especially as NASA continues to rely on commercial partners for crewed missions. The panel encourages SOMD to promptly distribute the report, at a minimum, to the NASA Administrator, the Associate Administrator, Mission Director AAs, center directors, human spaceflight program managers and Tech Authorities.

This concludes the Senior Review Panel activities, although panel members will stay engaged from our respective domains.