Managing Risk for the James Webb Space Telescope Deployment Mechanisms: Enabling First Light

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SUMMARY and CONCLUSION

The $10 billion James Webb Space Telescope (JWST) is perhaps the most ambitious astronomy mission in NASA history and is the largest and most powerful space science telescope optimized for infrared detection. It is operating in an L2 Orbit about a million miles away from the earth. This will complement and extend the discoveries of the Hubble Space Telescope. It was so big that it had to fold origami – style to fit in the rocket and open in space. Webb's 5-layer tennis court sized sunshield assembly (SSA) protects the telescope from the Sun's thermal radiation enabling instruments to operate about 230 degree C below 0. It relayed the first amazing picture of galaxies to the world on 12 July 2022. Webb's unprecedented infrared sensitivity will peer back in time over 13.5 billion years to see the first galaxies born after the Big Bang.

The complete success of JWST mechanisms deployment after launch was the precursor to the next phase of mirror alignments and mission operations. Complex deployment mechanisms included 344 Single Point Failure (SPF) items involving 178 Non-Explosive Actuators (NEA). The SPF concern was originally tracked by 37 SPF Critical Items Control Plans (CICPs) under JWST's Risk Management Plan. These SPFs were originally considered to be the highest risk contributors based on various engineering assessments including Probabilistic Risk Assessment (PRA). This $10B complex science mission was developed over a period of about 20 years after numerous technical challenges encountered through 2018-19 during Integration and Testing (I&T) [17]. From early 2019 to the day of launch in Dec 2021, the project employed an innovative collaborative Integrated Systems Engineering (IS) process labelled the Enhanced Critical Items Control Plan (eCICP)

The eCICP Verification and Validation (V&V) approach was developed and implemented to address the highest risk SPFs, maximizing confidence to the NASA community that maximum human vigilance and due diligence has been applied for the success of JWST [17]. Finally, the telescope was launched on 25 Dec 2021, and fully commissioned on 12 Jul 2022, accomplishing 100% mission success without any hitch.

The Complexity of JWST [Figure 1] and its deployment can be seen in a YouTube link with 3D graphics details from NASA-GSFC posted in 2018: https://www.youtube.com/watch?v=qysBZZjqTJM

Figure 1: JWST before shipment to Launch-site

1. INTRODUCTION

The James Webb Space Telescope (JWST) was successfully launched on December 25th, 2021, on an Ariane V launch vehicle. JWST is NASA's flagship observatory and is the largest telescope ever launched, with an aperture of 6.5 meters distributed over 18 mirror segments. It is designed to see the farthest reaches of the universe in infrared, unveiling galactic structures, soon after they emerged from the Big Bang, as first light appeared from the aftermath [1]. It is an international collaboration among NASA and European and Canadian Space Agencies. Webb development was managed by NASA Goddard Space Flight Center with Northrop Grumman as the prime contractor. Space Telescope Science Institute in Baltimore MD operates the telescope with inputs from scientists across the world.

Central to the success of JWST were its complex Deployment Mechanisms. A key area where these mechanisms were applied was the Sunshield Assembly (SSA), the size of a tennis court of approximately 15 by 20 meters, which was folded into the Ariane V nose cone, and considered to be an exercise in origami. The size and launch requirements were realized with many unique designs to create a compact unit for launch.

The mechanical designs necessary to create the deployable configuration in many cases could not accommodate redundancy, resulting in many SPFs. In aerospace design of systems as complex and costly as JWST, various levels of redundancy are normally used to offset the potential for failure of components or subsystems as allowed by weight and cost tradeoffs. The mirror assembly, for example, has multiple ways of operating the system to achieve objectives and therefore has a level of built-in redundancy in the event a motor were to fail [4]. However, this was not possible for the sunshield assembly. SPFs are identified through failure modes and effects analysis (FMEA) using standard FMEA ground-rules. According to the SPF failure mode likelihoods, risk mitigation steps for design, inspection and testing were captured in the Critical Items Control Plan (Plan).

This paper explains the risk assessments, their evolution, and implemented checks and balances through an Integrated Systems (IS) enhanced Critical Items Control Procedure (eCICP) Verification and Validation (V&V) process put in place to make the deployments successful. The focus of the discussion will center around the mission critical sunshield. The work has always been in concert with Northrop Grumman, extending from initial FMEA to detailed design analysis, probabilistic risk assessment, mitigations of common causes, tests, and manufacturing controls. The following sections present what was successful and what was learned in the evolution of managing the risk of the deployment from the mission critical design review (CDR) to Launch and deployment.

2. *THE SUNSHIELD AND DEPLOYMENT DEVICES (YOUTUBE Video]: https://www.youtube.com/watch?v=AdZ4M8SkYBk*

The sunshield structure is described in detail by Arenberg et. al. [2]. Overall, it consists of the five 14.4 m x 21.1 m polyimide film membranes and the mechanical structures supporting the membranes:

- Unitized Pallet Structures (UPS)
- Spreader Bars
- Telescoping booms (Mid-Boom Assemblies (MBA)
- UPS Bipod Launch Locks

In its stowed configuration, the sunshield was held in place by membrane release devices or MRDs. The MRDs consist of a pin or stem inserted through the layers of the membrane, as shown in Figure 2.

The stem was held in place by a non-explosive actuator (NEA) using a split nut restraint. The nut was released upon delivery of current to the NEA, opening a fuse wire, and allowing a restraining wire spring to free the nut. Once the split nut was released, the MRD primary spring pushed the stem from the membrane, releasing it for deployment. The sunshield required 107 of these devices.

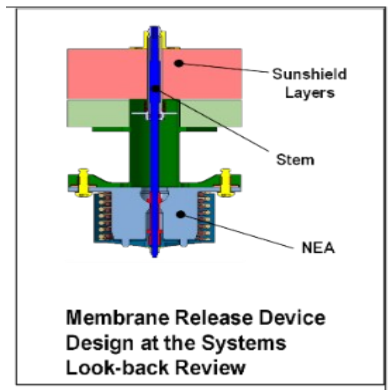

Figure 2. Schematic of MRD with NEA at its core. 107 of these devices were required. All needed to function in the deployment.

3. *DESIGN ANALYSIS LEADING to I and T*

3.1 FAILURE MODES AND EFFECTS ANALYSIS [FMEA]

Failure modes and effects analysis (FMEA) was among the reliability analyses performed during the development of JWST. Initial design FMEAs were conducted across the spacecraft elements including the sunshield assembly reducing binding and snagging. This FMEA was revisited and refined during 2019-time frame to assure its completeness in assessing the impact of Common Cause Failure (CCF) and its impact to Critical Items Control Plans (CICPs) after discussions with Northrop Grumman respective Design Engineers and GSFC Subject Matter Experts (SMEs).

3.2 NEA RELIABILITY ASSESSMENT

The probability of firing or fusing of the wire was calculated using a stochastic physics of failure model [5]. Monte Carlo (MC) simulation and load-strength interference were used to drive the model. The MC calculated the distribution of the strength of the fuse wire with applied current given expected variations in current and wire diameter.

Using this procedure, the likelihood of the device firing was estimated to be 0.9996 at 3 A applied for 35 milliseconds [3]. This probability of success (Ps) was significantly lower than that provided in the NEA supplier's reliability submittal.

4. TECHNICAL CHALLENGE EMERGING IN INTEGRATION & TESTING AND ASSEMBLY OPERATIONS

Webb's complex construction was plagued by redesigns, schedule slips, and cost overruns. During 2018 an independent review board (IRB) found that a handful of human errors had caused more delays and cost increases. (a) The telescope's propulsion valves were damaged when engineers used an inappropriate solvent to clean them. (b) Dozens of screws that fastened the telescope's massive sunshield came loose during vibration tests. And (c) faulty wiring during tests sent excess voltage into the observatory's transducers [7].

"These testing incidents led NASA to breach its $8 billion development funding cap. The report said human errors cost the program $600 million and caused 18 months of delay [7, 9]

NASA released its planned corrective action in response to the IRB on 26 Jun 2018 [8].

5. AN INTEGRATED SYSTEMS APPROACH

Change: In Feb 2019, during final stages of I&T at Northrop Grumman, at the request of GSFC Mission System Engineering, Reliability spearheaded the effort to develop and implement an innovative Integrated Systems Enhanced Critical Items Control Plan (eCICP) Verification and Validation (V&V) approach based on the success of NASA on the Agency's Human Space Flight Program including the lessons learned over the years.

The eCICP V&V process significantly contributed to 100% successful deployment of all mechanisms after launch, which were precursors to the JWST mission. A loss of any of these 344 SPF items would likely have resulted in a catastrophic loss of this $10B Space Telescope

5.1 GAME CHANGER

In early 2019, the GSFC Reliability engineering lead with extensive experience from NASA's Human Space Flight Program was challenged by Mission Systems Engineering to help the JWST.

The CICP process was enhanced using an innovative and effective enhanced CICP Verification and Validation (V&V) developed jointly by GSFC and NG team under the leadership of GSFC Reliability and championship of GSFC Mission Systems Engineer in partnership with NG's Management and NG design team. This leveraged the specific lessons learned to meet the needs of JWST in the final stages of I&T at NG and at the launch-site from:

(a) *Cultural Change similar to NASA's Challenger accident 1986*: Implemented needed V&V to mitigate operational risks through specific process details/steps developed jointly by JWST GSFC-NG engineering team [10,11].

(b) Risk and Reliability – Process variance minimization and its V&V using Integrated System approach. Common Cause Failure (CCF) impact to Risk and Reliability of integrated system similar to *NASA Shuttle Independent Assessment Team (SIAT) Report – Mar 2000* & Columbia Accident report [12, 13, 10].

(c) Implementing Common Cause Failure (CCF) Modes and Causes and applicable V&V to mitigate JWST mission risks in eCICP *similar to what was mandated on NASA's Human Space Flight Program (year 2004) & [12, 13]*

These evolving details included proactively documenting required checks and balance at each step from part level to higher level assemblies and to aggregate subsystem from design, manufacturing, I&T to deployment (see Fig. 5 and 6) with well-defined strict quality rigor (Figure 4) depending on the complexity of I&T and confined/limited accessibility. This enabled risk mitigation at each indenture level of assembly to the complete observatory I&T in 4 swim lanes linking flight hardware to software and its interactions with human elements including Launch-site (Fig 3). This included updates to FMEA and eCICP with CCF Modes/Causes and reassessment of Reliability predictions and other sensitivity studies to stay focused on value-driven details late in the project.

This system pursued a strategic and holistic Integrated Systems Engineering approach to mitigate risks through an enhanced Critical Items Control Plan (eCICP) process addressing risk mitigation steps from individual parts/SPF items to the aggregate system I&T. Later in 2020, three more sub-aggregate CICPs at major subsystem levels and two Integrated System Launch-site CICPs were added to capture the needed V&V for documented check and balances addressing system interactions, critical clearances, integration, logistics and interdependencies, of hardware, software, and human elements to minimize the risks to the best humanly possible (Fig 3.).

Critical process steps of mechanisms were organized into 3 categories of quality rigor (Fig 4). Categories 2 and 3 were very stringent process steps carried out by NG's engineering with oversight of GSFC SME, while Category 3 was carried out by GSFC SME, then NG Engineering and quality. High fidelity graphics were created for Sunshield assembly to ensure 100% correct installation of 107 MRDs/NEAs. High fidelity photographs were taken as pre-planned contingency in case some observations do come up at Launch-site inspection after its transportation to the launch-site.

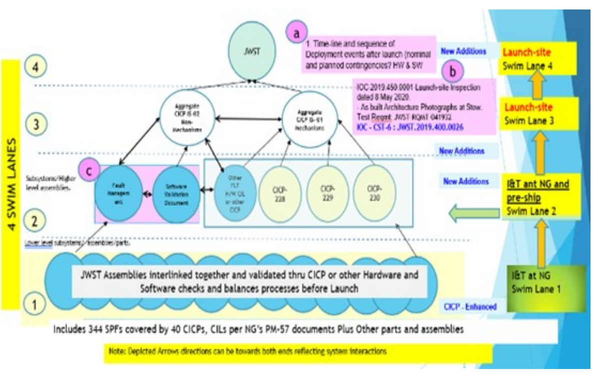

Figure 3: JWST Integrated Systems Enhanced CICP – Swimlane approach [18]

Cat 01 - NASA Data Review (Standard Process)
o Review data/final report and verification objects
o No requirement for real-time witness or sign-off, but NASA may choose to witness
Cat 02 - NASA Witness and off-line signoff in CAPE (at end of modules signoff for all steps)
o Witness event (i.e. deployment etc.)
o Real-time event witness, but signoff in CAPE can be later (i.e. after photo/video review if needed)
§ I&T authority to proceed without completion of NASA CAPE signoff
Cat 03 - NASA Inspection/Witness and signoff in CAPE
o Participate in hardware inspection
§ Perform inspection or
§ Review photos or video of inspection
o Real-time witness and sign-off required (unless specifically waived by NASA)
§ A I&T hold for operations that close out the inspection area. NASA signoff before releasing hold

Figure 4: Enhanced Quality Rigor

NEA Redesign: During late 2019, one NEA failed during I&T at NG. GSFC Reliability actively participated in the failure investigation of the NEA failure at NG and its redesign by the NEA vendor during early 2020 under strict insight/guidance by NG and GSFC. This helped the NEA vendor improve the Design FMEA and Process FMEA, reassess its reliability predictions and implement enhanced process variance control, enhanced inspection process to minimize human errors. This new design was qualified under enhanced process controls, enhanced in-line inspections and testing providing additional confidence to the technical community at NASA and NG.

The following graphic (Fig 5] provides a glimpse of eCICP at the NEA component level and second eCICP graphic [Fig 6] provides a glimpse of Integrated System eCICP capturing checks and balances due to interactions, integrations and hardware/software interdependencies and relationship with higher level assemblies

JWST Single Point Failure (SPF) Mitigation Verification Report
(NEA and MRD integration is at NGAS while some NEAs are integrated on the spacecraft at the launch site)

a. SPF Item and quantity for each size NEA Launch Release Mechanism		b. Status Date (month/day/year) 5-12-2021
c. Critical Item Control Plan (CICP) Number CICP-056	d. Failure Mode Number Reference EBAD FMEA in CICP verification folder	e. SPF Mode / Cause Failure to release Premature release

Failure causes
- Binding/deformation of bolt
- Contamination
- Mechanical shock/vibration
- Overloading, material
- Handling
- Workmanship

f.1. Have all mitigations been completed? ☒ Yes ☐ No
f.2. If Yes to f.1, are all mitigations' documentation provided? ☒ Yes ☐ No ☐ TBD
Explanation (required for No/TBD):

g. Mitigations

#	Mitigations Identified on the CICP (Design, Review, Inspection, Test, Failure History, Operational Use, Handling)	Verifications	Documentation (Document, Section number, Step)	Status	Approval (reviewers name/initials and date for each step)
1	Design – The link wires are tension loaded to 50% of failure based on unit testing	Fuse wire measurements and analysis: EIDP and VSOL for approvals	¼ LW: artifacts folder https://collab1.myngc.com/eRoom/JWST14/MissionAssurance/0_176447 EIDP link https://collab1.myngc.com/eRoom/JWST15/ConfigDataMgmt/0_1987e7	EIDP delivered artifacts need review	

Figure 5: NEA eCICP at Part level

JWST Integrated Systems Critical Items Control Plan Verification Report

a. SPF Item Aggregate Mechanisms - Sunshield Assembly, OTE and SC Bus Drawing 327600 - Observatory Top Level Assembly drawing		b. Status Date (month/day/year) 10/5/2021
c. Critical Item Control Plan (CICP) Number CICP-IS-01 Scope: This includes all critical inspections and testing involved at the Launch-site before lift-off through this and its interdependent CICP IS-02 Applicable Document: Launch-site Engineering Inspection IOC JWST 2019.450.0001 Rev A 22 July 2021 a) Appendix A: Unplanned Operations Inspection Checklist – # of inspection by NG RDE 1- 262 b) Appendix B: Post-ship inspection checklist – # 262-527 c) Appendix C: Inspection Checklist for Final SSC Configuration # 1 – 179 d) Appendix D: Inspection Checklist for Observatory lift from HCROF to PAS2624VS in Building SSC – # 1-14 e) Appendix E: Inspection Checklist for Final SSB Configuration # 1-10 f) Appendix F: Inspection checklist for final hardware inspections (BAF pre ISIM dry-purge) # 1-107 Ariane Satallite / Launcher – Combined Operations planning document - AS.3 NT A256 190 JWST Rev XX	d. Failure Mode Number **Interdependencies** - CICP-228, CICP-229 and CICP-230 plus the associated communication subsystems commands & - Interdependent Launch-site Additional Failure Modes & verification electrical and Software data in CICP IS-02.	e. SPF Mode Failure Mode and Failure Causes Failure Mode: Failure to Deploy any one of the Mechanisms involving SC Bus, Sunshield and OTE Failure Causes: **Workmanship (Missed inspection and/or process steps, Membrane Snags/damage)** – Planned Mitigations: Inspections per **embedded Excel file** in this CICP by NG RDE and witnessed by GSFC SME and QA and check-sheets by both teams uploaded to CAPE and then e-room as verification record for each Appendix of IOC 2019.450.0001 **Contamination/FOD** - Mitigation documentation: JWST-PLAN-019345 - JWST Launch Site Contamination Control Plan (NASA Doc) JWST.2020.300.0150 - JWST Observatory Contamination Control Implementation Plan for Northrop Grumman Operations at the Launch Site **Mishandling : Planned mitigation:** Launch-site protocol per IOC 2019.450.001 and Ariane A5.3 NT A256 190 JWST Any missed pre-planned contingencies- **Planned mitigations:** Due diligence by NG RDE and GSFC SMEs and QA. Critical Clearance of select Flight hardware (MMA-58). **Planned mitigations:** JWST.2019.300.0023

Figure 6: Launch-site Integrated System eCICP

The launch-site Integrated System CICPs IS-01 IS-02 plans were finalized in early Oct 2021 to guide specific GSFC and NG Subject Matter Experts (SME) to inspect the observatory after arrival at the launch-site and during I&T (about 600 inspection points). Each of the ~600 inspection points included the compliance to 3-tier stringent quality rigor process steps defined by NG and GSFC SMEs and sign off in NG's configuration management system. GSFC Reliability was in constant communication with NG-GSFC Launch-site team and integrated into the documentation signature process to ensure that no CICP process step is inadvertently missed. *NASA Launch-site Test Requirement document drove compliance to CICP IS-01 and IS-02 process steps before launch as a specific requirement.*

Key launch-site hardware-software interactions [14] were verified and validated through FCA (Functional Configuration Assessment) and PCA (Physical Configuration Assessment) plus the multiple aliveness testing including software check-sum verification at the launch-pad jointly approved by NASA SMEs, SQA and NG's SW and Electrical Engineering Leads per CICP IS-02.

6. REDESIGN OF NEAs (2019-2020)

GSFC and NG Reliability and Engineering played a key role in coordinating the efforts at the NEA vendor during redesign and requalification.

Establishing a robust benchmark (both quantitative and qualitative) for guiding these activities was achieved via innovative adaptation of PRA/PFMEA/DFMEA methods. The key features of this approach include the following: 1) enhanced collaboration and teamwork between designers/customer/partners/suppliers, 2) integrated reliability analysis platform, 3) establishing an integrated FMEA/CIL database, 4) Design FMEA, 5) Process (workmanship) FMEA/PRA, 6) making Reliability an integral part of design and I&T process.

7. NEA PFMEA & PRA GROUNDRULES AND ASSUMPTIONS 2019-2020:

1. The production process and key design features from DFMEA used to establish workmanship failure modes introduced during each assembly operation step
2. Standard systematic FMEA process (e.g. one failure mode at a time, mutual exclusivity, etc.)
3. Each inspection/testing point provides independent mitigation opportunity for corresponding failure mode
4. Probability of workmanship defect, Q_o and probability of inspection escape, Q_{insp} are independent between operation steps and inspection/test points respectively
5. Historical manufacturing data used for estimating defect and escape probabilities
6. Reliability of a given operation step and/or identification of operation defects (in K subsequent inspection points) introduced by that operation prior to I&T is computed by the following equation:

Equation (1) $$R_{o_i} = 1 - Q_{o_i} \times \prod_{J=1}^{K} Q_{insp_j}$$

7. Assuming there are N operation steps, reliability of overall device is computed by taking the product of N reliability terms:

Equation (2) $$R_{device} = \prod_{i=1}^{N} R_{o_i}$$

Note that the equation (1) and (2) are approximations of the steady state vector solution for a discrete stochastic process involving defect generation and identification/escape sequences. Exact solution differs since there are overlapping inspection/test points that serve as common detection nodes for multiple operations. In other words, a given inspection/test point can be mapped to more than one operation step. The accuracy of this approximation has also been validated by means of simulation and sensitivity analysis methods. A contour plot shown in figure 7 illustrates the sensitivity of device reliability in response to changes in the production defect vs. inspection escape rates

As described in the previous section, the deployment of solar array, sunshield and telescope required a total of 178 NEA release devices consisting of various types and sizes. Uncovering mechanical redesign/improvement opportunities during qualification testing triggered closer examination of numerical reliability assessment associated with these family of release devices.

This also revealed that the workmanship contribution on the final device reliability had to be closely evaluated. The original device reliability reported by the subcontractor was found to be incomplete and lacking since it utilized neither the field nor the test data. On the other hand, applying the PFMEA/PRA approach described herein produced a reliability range of approximately 0.9994-0.9996 depending on the size and features of each one of the 6 device types under conservative assumptions.

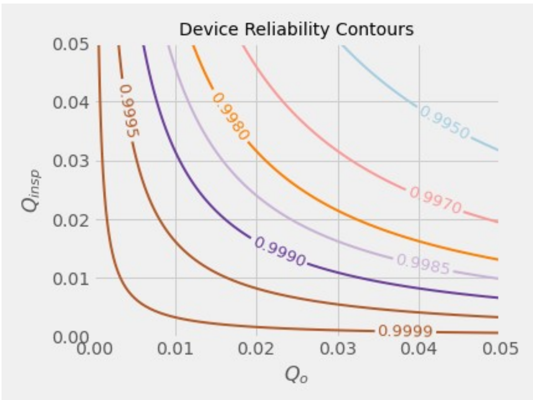

Figure 7. Sensitivity contour plots

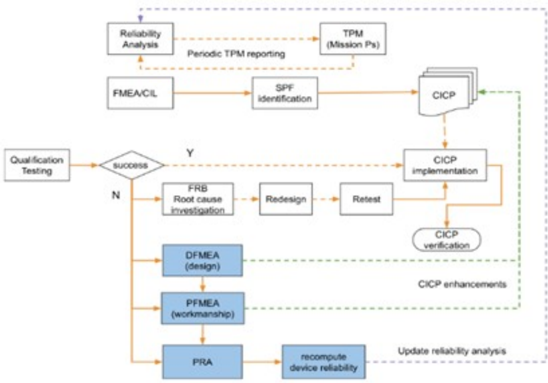

Figure 8: NEA Reliability Reassessment 2020-21
[Blue boxes represent initiatives to fix NEA processing]

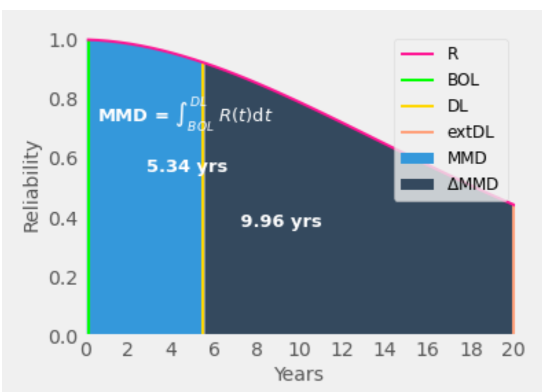

Figure 9. Spacecraft Mean Mission Duration plot

Finally, the figure 9 illustrates the significant mean mission duration improvement (5.34 vs. 15.3 years) for the Webb, largely attributable to the flawless execution of all deployment sequences.

CONCLUSION AND LESSONS LEARNED

JWST launched on Dec 25, 2021, with 100% success of Deployment Mechanisms ahead of schedule per the planned deployment sequence: https://www.youtube.com/watch?v=7nT7JGZMbtM&t=81s.

Dynamics behind eCICP:

1) Exemplary Teamwork and Effective Coordination: GSFC Reliability ***Leadership under Championship*** of Mission Systems Engineering: Exemplary collaborative team efforts of NG and GSFC 30-40 multidiscipline team members, using this IS Enhanced CICP approach led to 100% successful deployment of JWST by 12 Jan 2022 without a single hitch. All JWST deployment risks processed in accordance with the JWST Risk Management Plan were retired at that time.
2) For complex space systems, it is prudent to *develop and update FMEA and CICPs in collaboration with Design Engineering team* reflecting the latest architecture with specific checks planned upfront during I&T in CICP with assigned quality rigor with discrete details and linked to Risk Management [7].
3) While quantitative Reliability Analysis is valuable for conceptual trade studies, its applicability to risk decisions during later phases require a broader perspective. Operational Reliability is influenced by other factors such as CCFs, critical clearances, hardware-software interdependencies, system interactions and workmanship that are not fully accounted for. The PRA/PFMEA approach presented herein provides a "customization" in response to program specific reliability challenges.
4) **Opportunity**: Other major aerospace projects can benefit from this JWST eCICP process.
5) **Recommendation:** Future missions include eCICP, addressing I&T of the Observatory with the Rocket to minimize human errors risks (to avoid what JWST faced during Launch-site processing).

Link to latest on Webb: https://jwst.nasa.gov/

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