**The NASA Docking System- Block 2:**
**Changes and Challenges for Lunar exploration**

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## Abstract

The NASA Docking System (NDS) Block 2 (B2) docking system is being developed to support NASA's lunar missions and has recently completed its major qualification tests. This paper will outline the changes required for lunar missions, the challenges encountered in executing the development and will provide lessons learned. The NDS Block 2 (NDSB2) systems are an evolution of the flight proven active NDS Block 1 (NDSB1) and passive International Docking Adapter (IDA) systems used on Starliner and the International Space Station. The NDSB2 represents upgrades, new capabilities, and new configurations for NASA next generation of space vehicles including the Orion crew capsule and the Habitation and Logistics Outpost (HALO) module for NASA's lunar Gateway program. NDSB2, shown in Figure 1, evolves the NDS Block 1 mechanisms, representing a next generation of capabilities. Docking systems are a core element of nearly all human space exploration endeavors and the NDS development is a bellwether for both commercial space and governmental programs.



**Figure 1. NDSB2, Active Docking System with Plume Cover**

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## Background

NASA Docking System Design History

The NDS Block 1 (NDSB1) and International Docking Adapter (IDA) systems were specifically developed for the commercial crew program providing transportation to the International Space Station (ISS) in Low Earth Orbit (LEO). The NDSB1 system has flown three times and has successfully docked to the ISS twice. There are two IDA units attached to the ISS, IDA-2 and IDA-3 (IDA-1 was lost on the CRS-7 launch). Since arriving on orbit, the IDAs have supported both the Dragon and Starliner vehicles for more than 35 dockings. The systems design and architecture of NDSB1 and the IDA have been used as a model, and a departure point for all other human rated docking systems. The NDSB2 systems have now completed their primary environmental testing including functional, pressure, vibration, thermal vacuum, leak and contingency (ordinance) separation. The system test campaign as well as the component qualification and verification activities provided numerous challenges and opportunities for future docking systems and other major space mechanisms to benefit from the experiences.

NASA Docking System Architecture

The NDS is designed in accordance with the International Docking Standard Interface Definition Document (IDSS-IDD), which defines the basic architecture to be implemented for docking operations [1]. In short, the NDS includes an Active half, typically on the chaser vehicle, and a Passive half, typically the target vehicle. The NDS includes some elements of androgyny but would not be considered fully androgynous. The NDS includes both a Soft Capture System (SCS) and Hard Capture System (HCS) [2,3]. NDS Block 2 includes a plume cover over the active docking system. This cover protects the docking system from the exhaust plume produced when the Orion launch abort system is jettisoned after a nominal launch. The NDS plume cover is subsequently jettisoned using spring plungers that are released by HCS hooks. Figure 2 shows an overview of the NDS Block 2 qualification tests.

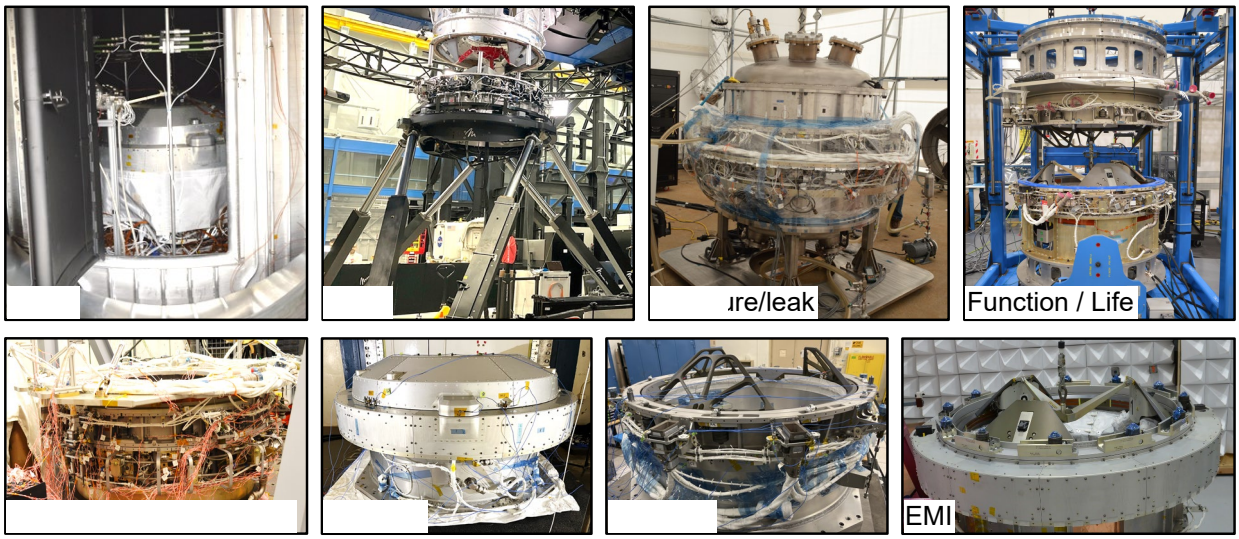


**Figure 2. Major Qualification Tests**

## Changes for NDS Block 2

NDSB2 was developed specifically to support NASA anticipated lunar missions and concept of operations (conops). The program followed a traditional systems engineering approach employing cycles of requirements and designs analysis but with an emphasis on reusing existing designs. The key elements of the lunar conops that impacted docking system design are shown in Table 1.

**Table 1. Lunar Mission Implications for Docking**

| Operation Change | NDS changes | Implications |
|---|---|---|
| New Vehicles | Expanded mass pairs | Expanded SCS mass certifications, (4T to 1900T apparent masses) |
| Launch Mass Restrictions | Reduced mass allocations | Mass Optimized Passive (104kg Passive System) |
| Co-Manifested Payloads | Docking during transit | Increased umbilical services, Radiation Hardening |
| Orbital Mechanics | NRHO, Slow and Fast Transits | Radiation Total Dose, New Thermal extremes, |
| Orion Attitude Constraints | Expanded Temp and Delta Temp | Colder Active, Hotter Passive, HCS Heaters, Sensor and Passive Hook changes, Increased active to Passive docking delta Temp |
| Lunar Gateway | Fuel Transfer, Mated Loads, Mated Life, Docking Cycles, High Power Transfer | New Fine Alignment Pins, New Utility packaging, Extended Service Life and docking cycle life |
| Orion Interfaces | Host Power, Host Commands | 120Vdc Power, Ethernet Command I/F |
| Beyond LEO environments | New requirements for Radiation, Thermal, Plasma, Charging and MMOD | New SCS guide lubrication, Increased avionics radiation Hardening, HCS heaters, New MMOD shields |
| New Launch Vehicles | Launch environment, Launch Abort System Jettison Plume | New Plume Cover, Changed Random Vibe and Quasi Static Loads |

Typical of all beyond-LEO missions, early NDSB2 trade and configuration studies focused on minimizing mass. This mass focus drove what is perhaps the single largest change for the Block 2 program, being a completely new passive docking system design. The new architecture moved away from the IDA androgynous hard capture system design toward a weight optimized passive only configuration.

## Design Challenges

Overall Active System Packaging

Packaging including cable routing, Micro-Meteoroid Debris Shielding (MMOD), electrical umbilical changes, larger avionics and new HCS heaters were the primary challenge for the new NDSB2 active docking system. The avionics were expanded to provide 120Vdc to 28Vdc conversion. The power conversion lengthened each docking system controller by 68mm with no change in the available tunnel vestibule volume. Routing and packaging cables and feedthroughs took multiple iterations.

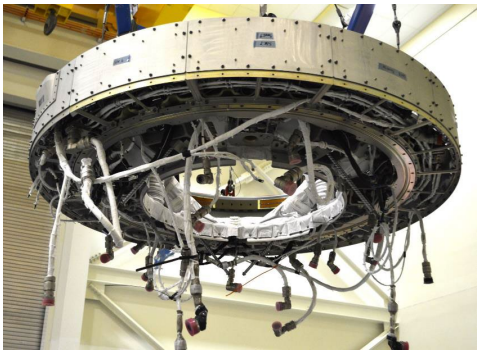

**Figure 3. NDS Block 2 Active Being lifted (without avionics)**

Mass Optimizations and New Functions Drove the Block 2 designs

The plan by the NASA Lunar Gateway Program to use docking systems as the primary method of assembling the pressurized elements of the Lunar Gateway space station created a very strong impetus to develop mass optimized docking systems. The Gateway topology has and will continue to evolve over time, but currently there are eight docking systems planned. The docking system mass would be a significant constraint if the IDA/NDSB1 mass was applied across the Gateway architecture. IDA was not mass optimized, being constrained mostly by launch volume and driven by the schedule for the commercial crew program and containing multiple contingency mechanisms including active hooks. The fully integrated mass of IDA is 526kg. The mass of the passive docking system portion of IDA based on the passive hard mate assembly is approximately 165kg. The comparable weight for the basic NDSB2 passive system is 104 kg for a net reduction of mass to Near-Rectilinear Halo Orbit (NRHO) of 488kg. This mass reduction of the passive was achieved by:

a. Contingency hardware removal - separators, active hooks and the interface sealed sensor.
b. Structural optimization – Reduced tunnel height and iterative stress analysis
c. Hook assembly deletion - The HCS hooks are integrated directly into the primary structure

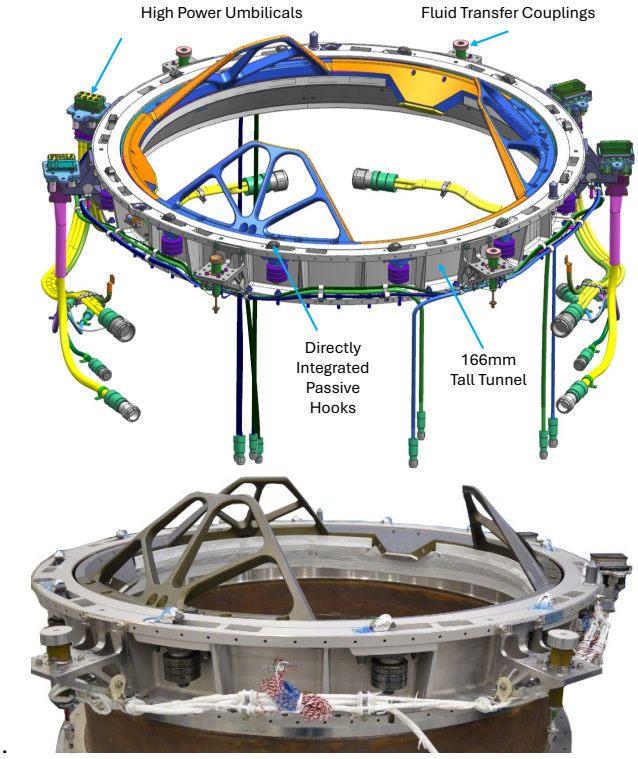


**Figure 4. NDSB2 Passive Docking System, CAD Model and Qualification Unit**

Starting with NDSB1 and the IDA as a point of design departure, early NDSB2 studies considered hybrid architectures for mass optimization (e.g. gateway based passive soft capture systems with active hard capture systems) but reverted to the traditional active, passive and androgynous functional allocations. The strategy for the mass reduction was to strictly allocate functions to the active and passive half and to minimize redundancy and contingency functions. Accordingly, the Active Docking System (NDSB2-A) was allocated the powered active mechanisms and associated avionics, while the Passive Docking System (NDSB2-P) largely contains static receptors for the NDSB2-A mechanisms. Additionally, the Hook Contingency Separation system was entirely allocated to the NDSB2-A. In other words, the NDSB2-P contains no pyrotechnic provisions. These architectural decisions resulted in an entirely new NDSB2 passive design (as compared to the IDA). Additional changes resulted from the NRHO environments, including a new lubrication scheme (Dry Film Lubrication (DFL) in place of Teflon Anodize for radiation tolerance), and adjustments to the hook design to support a larger difference in temperature between the

active and passive systems during docking. Finally, the passive units were allocated a complex and varying configuration of eight different umbilicals. The Gateway plans for uncrewed assembly and logistics flights increased the quantity and types of umbilicals required. These changes drove the need for multiple configurations of the NDSB2-P and a complex qualification program.

## Problems and Lessons Learned

Passive Tunnel Structural Redesign

Two major problems were experienced with the new NDSB2-P passive primary structure (tunnel) design. The first problem was structural interference with the dynamic motion of the active hook. This interference is shown in Figure 5 between the active docking system hook and the passive docking system structure. The interference was small and conditional for a nominal docking but represented a hard functional interference in the event of a contingency hook release.

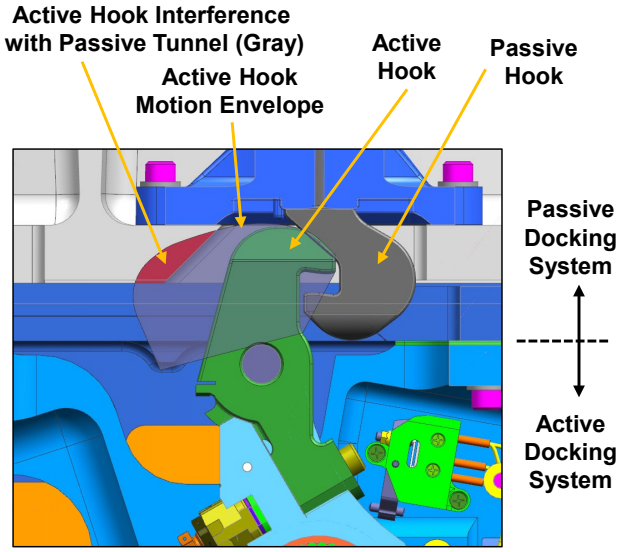


**Figure 5. Active Hook to Passive Tunnel Interference**

The second issue resulted from analysis of the passive hook for contingency release shock. The passive hook normally being loaded in tension resulted in the initial fastener sizing being based on low inertial loads. As the design matured Statistical Energy Analysis (SEA) was conducted on the passive design. The SEA determined that the fasteners which retained the hooks were at high risk of fracture due to the shock loads experienced during an active system contingency release. A redesign was required to mitigate this problem.

The lessons learned include:

1) The active hook motion envelope in IDSS IDD does not include contingency hook release motion. Despite being an internationally developed and approved standard the IDSS IDD the hook motion envelope wasn't adequately defined with the deficiency being masked by design precedents.
2) Requirements validation should have been performed between SRR and PDR
3) Independent of systems engineering requirements, designing two mechanisms to operate together requires early motion and dynamic envelope assessments.
4) The passive shock loads are large and should have been identified as a potential design driver as part of initial component sizing.

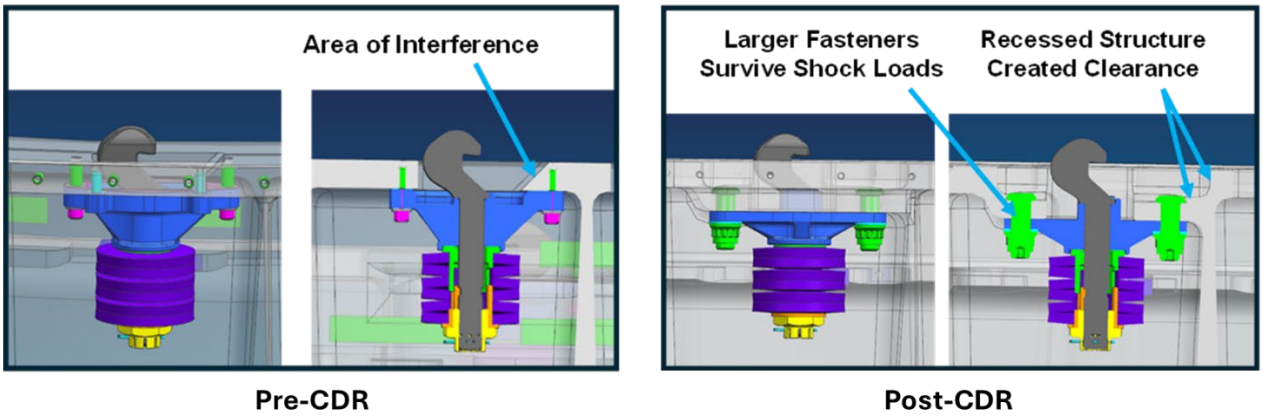


**Figure 6. CDR design and Post CDR redesign**

Hook Motor Qualification Failure

NDS uses an Electro-Mechanical Actuator (EMA) to drive the primary structural hooks open and closed. The Hook EMA includes redundant motors coupled with a differential and a gear reduction to drive a "gang" of six hooks simultaneously. The hook loads are large requiring large Hook EMA motors. The motors are one of the heaviest individual components in NDSB2 with a mass per motor at greater than 0.5kg. The NDSB2 program reused the NDSB1 Hook EMA with very minor improvement to the motor grounding, bonding and shielding scheme.

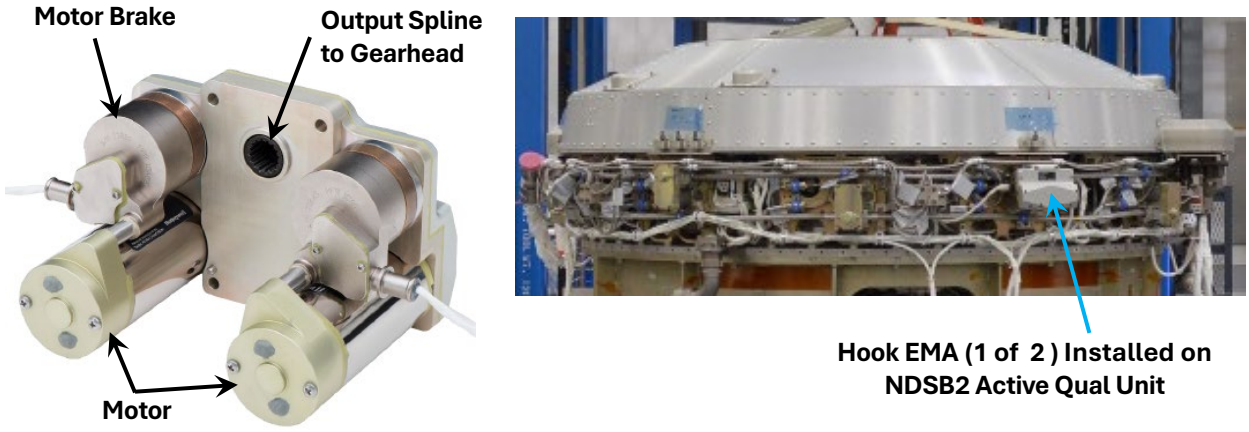


**Figure 7. Hook EMA Component (left) and Installed (right)**

The Hook EMA development during the NDSB1 program was straightforward, so the failure of the Hook EMA during NDSB2 qualification testing was unexpected. The Hook EMA Qualification unit failed functional testing following random vibration testing. Troubleshooting and investigation isolated the problem to the motors. One motor had failed completely (no rotation) while one motor continued to operate but with noisy current characteristics. A combination of electrical tests, non-destructive inspections (CT scans) and systematic disassembly isolated the failure to broken motor lead wires near the solder connection to the commutation bars. One of the motors had fractures in three of seven wires while the second motor had one fractured wire.

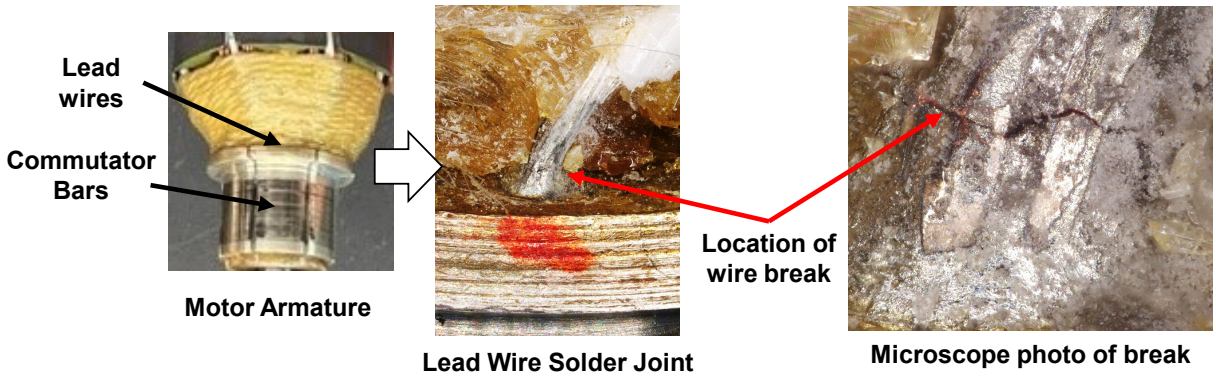


**Figure 8. Overview of broken lead wires**

Investigation activities continued with the next focus being to address whether the wire failures were the result of failed solder, overheating, or mechanical overload and/or some combination of these. A detailed metallurgical evaluation (Scanning Electron Microscope SEM & Energy dispersive X-ray EDX) was conducted on the broken wires. These evaluations concluded the following:

1) The fracture was roughly planar and perpendicular to the wire strand direction through both the solder infused stranded copper wire consistent with a net section tensile failure
2) There was no evidence of global overheating, solder migration or re-melt beyond the fracture surfaces
3) The solder remained intact in the flange and below the break
4) The breaks occurred where stresses are expected to concentrate, specifically where the section reduced and the wire material direction changed
5) The fracture surfaces suggested a fatigue failure, but the evaluation was complicated by re-melting
6) The exact initiation site could not be established due to smearing and re-solidified materials
7) All the materials identified were consistent with the design (copper, solder, and wire insulation)

The overall conclusion was that the mechanical break occurred first (during vibration tests) followed by local re-melting attributable to arching and/or intermittent contact during attempted operation of the motors.

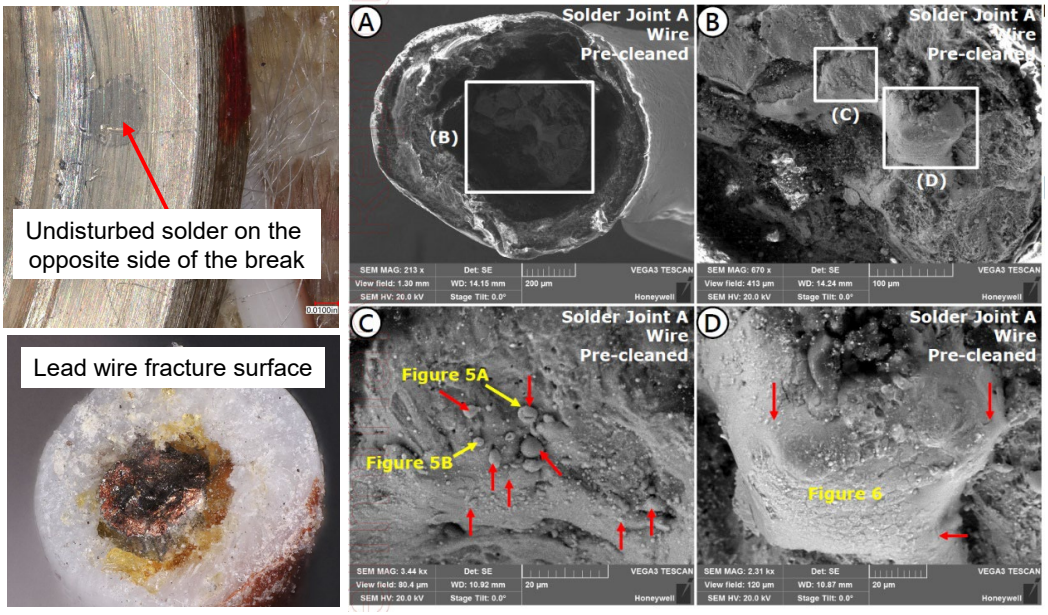


**Figure 9. Metallurgical Evaluations of the broken lead wires**

The failure investigation then shifted to focus on the root cause and to understand why these motors had failed the NDSB2 environment after successfully being qualified for NDSB1. The difference between the

random vibration spectrums for NDSB1 and NDSB2 were not large. Since the Hook EMA had substantial NDSB1 test history, there was minimal instrumentation on the qualification test article. A single control and response accelerometer were employed with the response accelerometer not located near the motors. Consequently, a series of engineering tests subjected engineering units to shaker table sine sweeps and low-level random vibration tests with accelerometers that were installed at multiple points on the motors, brakes and housing. This testing identified multiple high frequency resonances in the frequency range of 700-1100hz. The testing also showed substantial cross axis acceleration due to the structural cantilevers for the motors and brakes. A particularly large resonance was seen in the motors at a frequency of 950hz. These frequencies were in a range that had specifically been increased for the Block 2 program. This increase in levels was not driven by the flight Maximum Predicted Environments (MPE) but rather by a change to the Minimum Workmanship Level (MWL) standard as the program moved from the ISS legacy test standard SSP-41172 to the newer space vehicle test standard SMC-S-016.

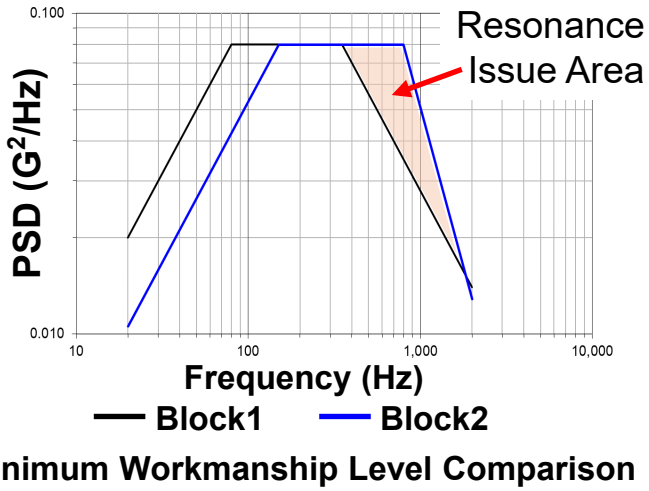


**Figure 10. High Frequency Random Vibration Level Increases for Block 2**

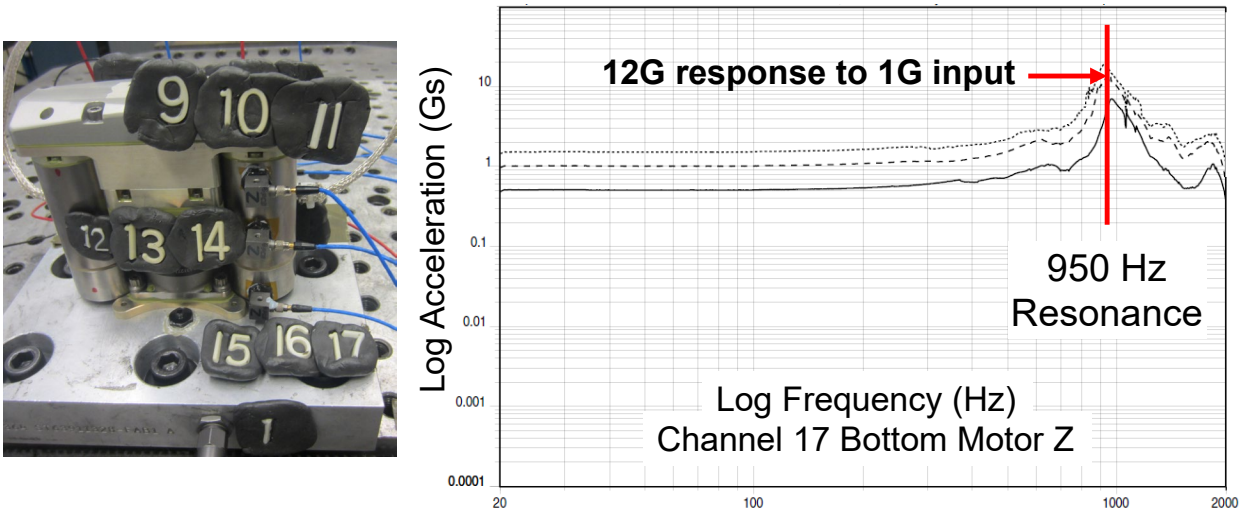


**Figure 11. Sine sweeps configuration and sample results**

The corrective action implemented was to adjust the qualification and acceptance test vibration levels by reducing (notched) at the specific resonant frequencies. These notches maintain margins above MPE. Discussions with random vibration subject matter experts suggested the change in the MWL test

requirements was associated with a desire to screen lightweight surface mount electronics at higher frequencies during acceptance testing.

The lessons learned associated with this failure investigation including the following:

1) Establishing a root cause in a complex flight component can require a wide variety of high-tech resources. This problem employed: X-rays, CT scans, development vibration testing, optical microscopes and scanning electron microscopes.
2) The MWL defined in SMC-S-016 may need to be tailored when testing heavier mechanical components versus avionics and electronic components.
3) Re-qualifying a component to a more severe environment should start with basic sine sweeps frequency scans to understand the components' response to the new environment
4) Qualification testing should include response accelerometers on all major subcomponents and include monitoring and or response limiting.

Mated Loads and Fine Alignment Changes

The early phases of the Block 2 program saw uncertainty regarding whether the mated load capability established by the IDSS IDD would be sufficient for the Orion and Gateway program and Human Landing System programs. Unlike the ISS which primarily used Common Berthing Mechanisms (CBMs) to connect pressurized elements, the Gateway modules are being assembled using IDSS compatible docking systems. The smaller lighter dockings systems provide a mass advantage, but their smaller diameter also limits the moment loads that they can react.

In reviewing the mated loads for NDSB2 concerns were identified with the torsion allowable established by the IDSS IDD standards. Research determined that the legacy Shuttle (APAS) docking systems were qualified to a higher standard. Gateway integrated loads analysis codified the original shuttle docking system torsion requirement as the requirement for the NDSB2 program. IDSS IDD revision G was released in January 2026 with a higher torsion mated load case for future in-space habitats.

**Table 2. IDSS IDD (rev F) mated loads compared with new NDSB2 Loads**

| Mated Loads | Pressure | Compression | Tension | Shear | Bending | Torsion |
|---|---|---|---|---|---|---|
| **IDSS Max Loads (Rev F)** | **1,100 hPa** | **17,700 N** | **17,700 N** | **16,700 N** | **65,300 N-m** | **15,000 N-m** |
| **NDSB2 Max Loads** | **1,100 hPa** | **17,700 N** | **17,700 N** | **16,700 N** | **68,700 N-m** | **65,215 N-m** |

Unfortunately, during the early requirements analysis phases analysis of this new load showed the NDS Block 1 design was less capable than the new requirement established. This was due in part to differences in the structural designs as well as the current analysis standards. The NDS Block 1 guide pin was not good for the higher Block 2 torsion load. Several options were evaluated. The obvious option was to reduce the load back to the NDSB1 levels. A second option included relying on the friction between the hard capture system flanges to react some or all of the torsion load vs the guide pin. The final option was to redesign the guide pin and tunnel interface to meet the higher torsion requirement.

After determining that the Block 1 structural design was insufficient analysis efforts focused on using the friction created by the hook loads to react torsion. On paper using standard handbook Coefficients of Friction (CoF) this approach appeared that it would succeed. Lacking CoF data for the specific high strength aluminum alloys and surface finishes used in the docking systems, pin and disk testing was conducted at NASA tribology labs using representative samples. Unfortunately, that testing revealed the reliable CoF was much lower than would be expected from published mechanical engineering handbook data. Having run out of potential mitigations, the program embarked on a structural redesign of the guide pin. Block 2 guide pins and tunnels were modified to include a larger bearing area to react loads in the aluminum tunnel structure

The tolerances of the guide pin design at the pin socket pair have always been problematic with the potential for interference due to thermal distortions and jamming in off nominal circumstances. Furthermore, the tolerances are not tight enough to share load across both pins in the pin/socket pair. Given that only one of the two pins at the pin socket pair would react loads and the potential for interference was significant, the NDSB2 Active design was modified to substantially reduce the pin diameter (AKA skinny pin). The skinny pin length on the NDSB2 Active mechanism remained unchanged to ensure target vehicle undock complete sensors are activated during docking and undocking operations.

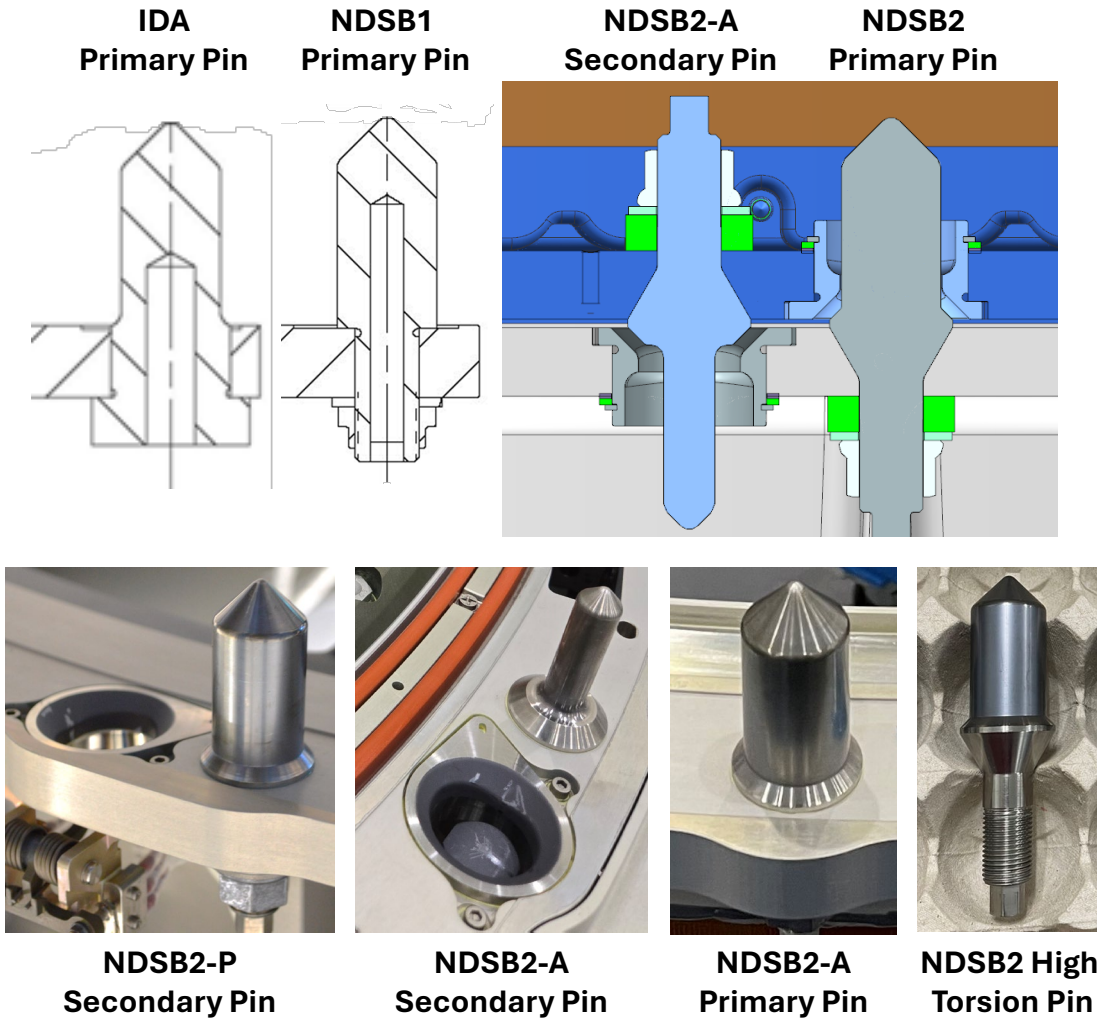


**Figure 12. Docking System Fine Alignment Guide Pin Designs**

The lessons learned regarding the increase in torsional mated loads include:

1) The risk associated with establishing a requirement based on a legacy capability when the design and analysis standards were different was larger than expected and resulted in an unplanned redesign.
2) Standard handbook data on CoF cannot be relied on for critical applications.

Docking System Primary Structures

The design and tolerances associated with the primary structures of an IDSS IDD compliant docking system should be understood to be near the limits of manufacturing capabilities. The Hard Capture System (HCS) upper flange and nearly every dimension of the Soft Capture System (SCS) ring and guides are controlled by the interoperability standard (IDSS IDD). Over the course of the NDS program more than 6 suppliers

have been contracted to produce these structures. Only two of these suppliers have demonstrated an ability to produce these structures without significant defects. One supplier was terminated for failure to produce acceptable hardware. Two suppliers provided hardware that was eventually used for flight but with each flight item having many (50 to 100+) minor defects that needed material review board approvals. The manufacturing processes including sealing surfaces, general surface finishes/flatnesses, coatings (anodize and chem films), surface lubrications (dry film, Teflon anodize) and inserts/fasteners are very complex. The best techniques of successful companies are often proprietary, but the following general lessons learned are provided:

1) It is recommended to select multiple suppliers until the first article has been proven.
2) Even the best suppliers will likely have some minor defects (scratches, nicks etc). Engineering support resources that are cognizant of the important functional implications will be essential.
3) It is expected that some parts will not be acceptable for flight and will need to either be downgraded to non-flight or scrapped. Raw material purchases should include an allowance for manufacturing attrition. (eg spare forgings)
4) Defects on an active system can potentially be accepted by evaluating their impact on the performance of the active system when docking to a compliant passive system. Defects on a passive system can be more difficult to disposition, especially if they involve the interfacing surfaces as no single definition of an active can be assumed.
5) The structures while appearing to be standard aerospace machined parts should be considered long lead requiring substantial time for manufacturing trials and development parts.
6) The dimensioning and tolerancing approach in the IDSS IDD standard is decidedly last century and not representative of state-of-the-art ISO standards. Examples include multiple critical dimensions that are made to theoretical surface intersections lacking any direct measurements. The authors see substantial room for improving the docking standard, directly implementing GD&T standards and model-based definition but the cost and legacy traceability are difficult obstacles.

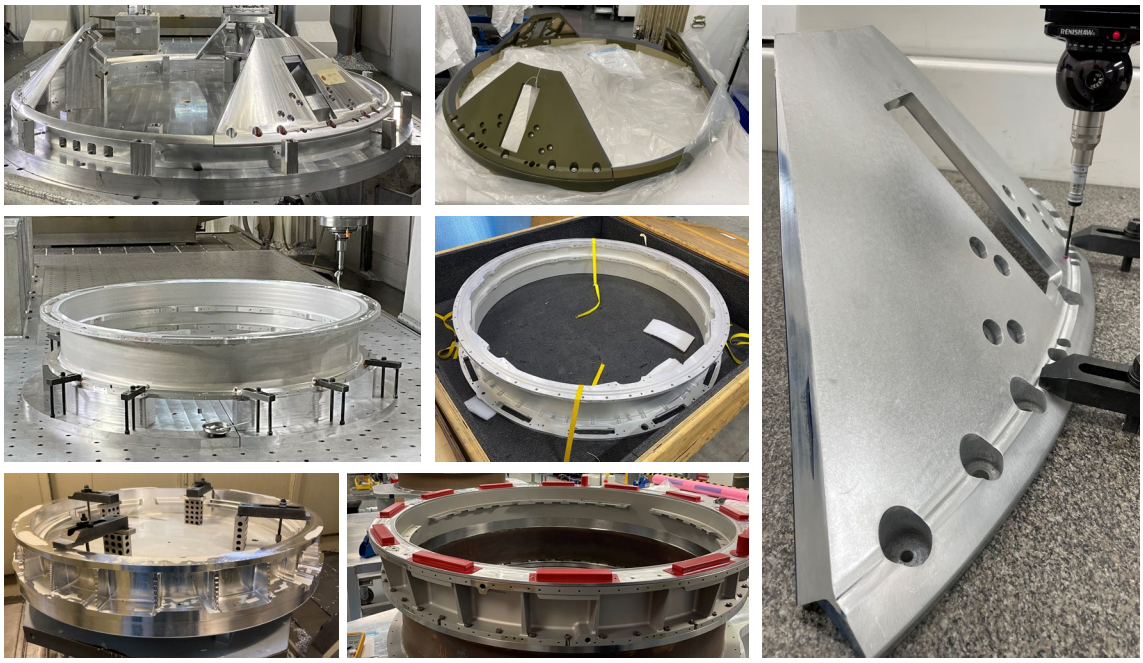

**Figure 13. Manufacturing of HCS and SCS Primary Structures**

Thermal Vacuum Test Fixture Pulley Sticking

The NDS System required Thermal Vacuum (TVAC) testing to validate thermal models, to verify system performance under Hot and Cold operational and non-operational extremes, to verify performance under the maximum difference in temperature between the two docking systems, and to accumulate an appropriate number of docking cycles under TVAC conditions for life cycle testing. During these tests, docking, undocking, and plume cover deployment are all performed, exercising all mechanisms and

functions in the NDSB2 systems. The testing is performed in NASA's MSFC's Sunspot chamber using the NDSB2 TVAC Fixture. This fixture supports the Active NDS on a turntable to provide radial offsets. A static counterweight is used to offload the mass of the NDSB2-A Soft Capture System ring. The Passive NDS is suspended from the top of the fixture, balanced by counterweights, and can be lowered or raised as part of docking simulations. The Plume Cover is installed in place of the Passive NDS for its tests. The counterweights and motors which accomplish these tasks are connected by a complex network of cables and pulleys which distribute their forces to the appropriate locations. The design of the NDSB2 TVAC fixture is an evolution of the NDSB1 fixture, enlarged to accommodate the larger size of the NDSB2 units.

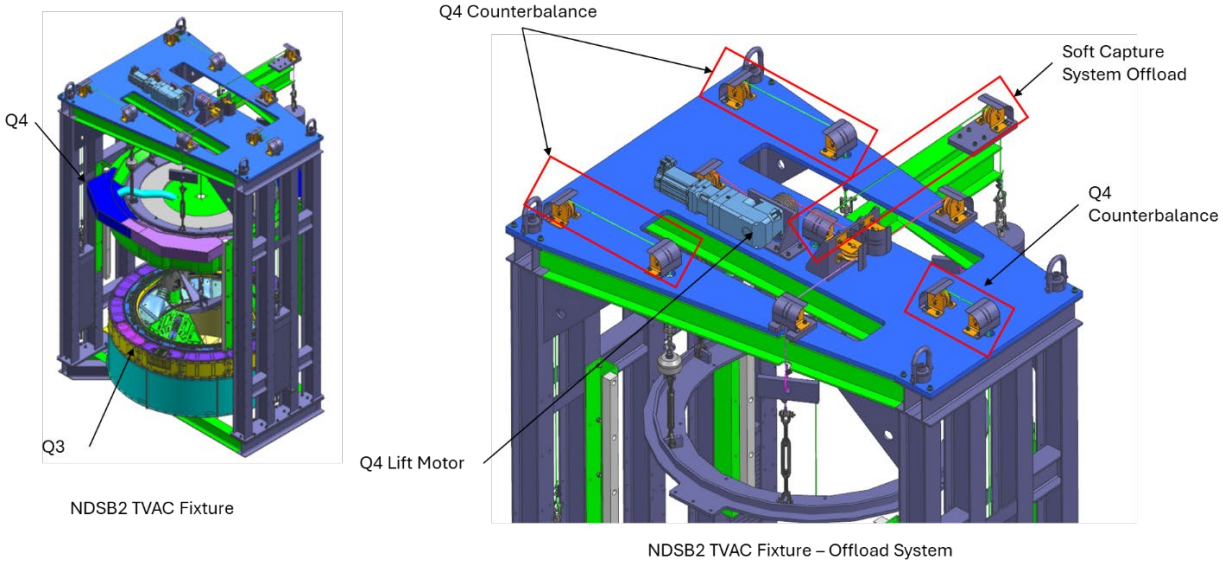


**Figure 14. NDSB2 Baseline TVAC Fixture**

During the initial cold TVAC cycle for the NDS, while lowering the Passive NDS for docking, there was insufficient force to cause the Soft Capture System Linear Actuators to Lunge, leading to failure to dock. Further investigation showed the cause of the failure was increased friction in the test fixture pulleys supporting the Passive NDS. The pulleys were analyzed for causes of this friction, and it was determined that the grease in the pulleys was solidifying at cold leading to increased friction. The cause of the grease solidification was two-fold. First, insufficient cleaning of the factory grease was performed during assembly. The pulleys are commercial off the shelf (COTS) items, with an unknown grease, but which had been shown previously to be incompatible with the NDS test temperatures on NDSB1. A similar failure occurred during NDSB1 TVAC testing, which was resolved by cleaning out the factory grease and regreasing with Braycote. Disassembly of the NDSB1 pulleys showed a mixture of greases. Bearing on the pulley were press fit, meaning a total disassembly was not feasible. This meant some of the grease likely remained in the pulley, even after cleaning. Secondly, the pulleys were incorrectly assembled, with spacer washers not included between the pulley and supporting bracket. This led to unintended contact between the pulley and bracket.

The incorrect assembly was corrected, but by itself did not resolve the failure. The NDS team determined that a full cleaning was not possible without fully disassembling the bearings, which could have been destructive. Testing of cleaned pulleys showed they continued to be susceptible to freezing. Therefore, the decision was made to add additional heaters to the pulleys, add thermal protection adjacent to them, and to change how the TVAC Chamber was operated to maintain test fixture pulleys at more benign temperatures. After implementation of these changes the system successfully operated through the entire test.

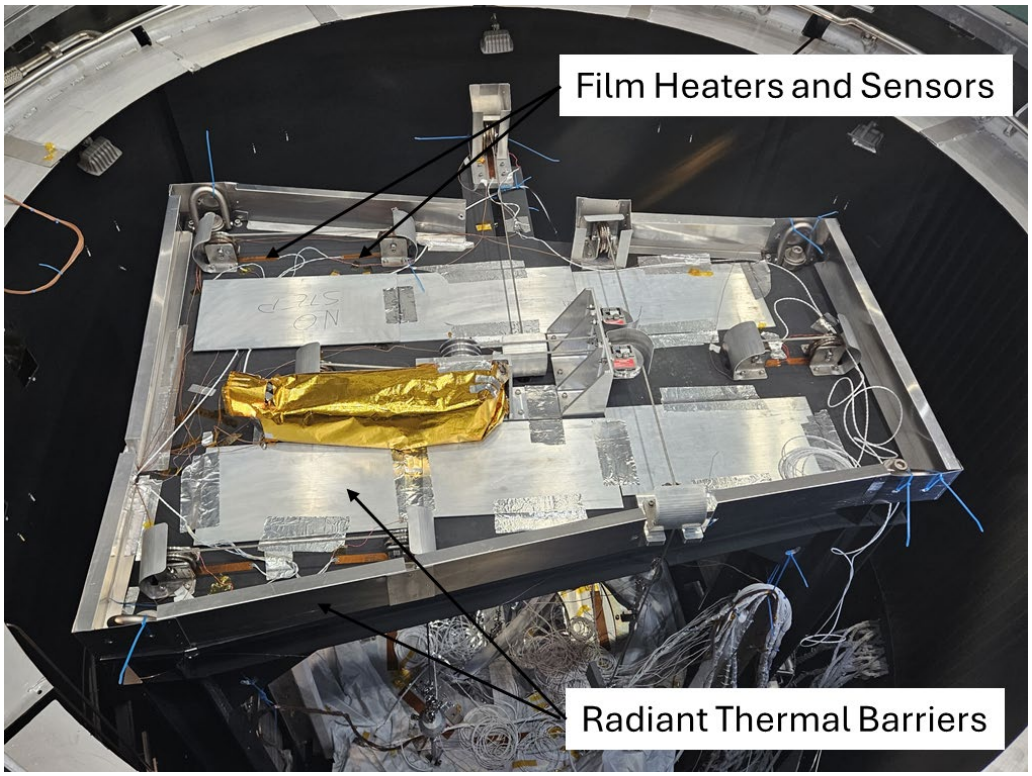


**Figure 15. Updates to NDSB2 TVAC Fixture**

Lessons learned from these issues include the following:

1. Whenever possible, perform a validation test on complex fixtures in a relevant environment prior to the test. In the case of the NDSB2 program, this was deemed impractical due to the cost and schedule needed to run the test. However, the fixture was available well ahead of the test and could have been checked out. This likely would have saved around a month of troubleshooting time.
2. The use of COTS parts, which is nominally efficient in many cases, requires additional scrutiny for unintended consequences. While it was known that the pulleys included grease that was incompatible with the NDS temperatures, it was not understood that standard cleaning operations were insufficient to fully remove it. A deeper understanding of the part would have led to design changes which could have mitigated this issue.
3. The reuse of previously used designs should come with appropriate scrutiny. Test fixture pulley successful usage on NDSB1 led to incorrect assumptions about its acceptability for the NDSB2 application. =. This is not to say that reuse is inappropriate; rather that, when using COTS parts, designers should take full ownership to ensure the design of COTS parts is acceptable for each new application.

## Conclusions

- The extensibility of the NDS Active Soft Capture System previously projected [2] has been qualified providing the Orion vehicle new capabilities for beyond low earth orbit exploration.
- Qualifying proven systems for new missions, new conops and new standards can provide unexpected challenges especially during formal testing.
- The new NDS Passive provides mass and resource advantages for the NASA Lunar Gateway HALO module.
- Developing complex space mechanisms provides challenges for every phase of development, design reuse, modification, new design, manufacturing, test and qualification.
- NDS development continues to advance docking standards with the max torsion load and guide pin changes being incorporated into IDSS IDD rev G.

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