Development of the Multi-Purpose Transportation System for the Space Launch System (SLS) Core Stage (CS) Flight Article

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Abstract

NASA's Multi-Purpose Transportation System (MPTS) is designed to transport the Space Launch System (SLS) vehicle segments by waterway and roadway. It is tasked with transporting the vehicle from where it is manufactured to its intermediate test location and final launch destination. Its design incorporates mechanisms that release degrees of freedom to prevent excessive loading during transit and ensure a successful delivery of the vehicle to its intended destination. In addition to the Core Stage (CS) flight article, the system will also move three Structural Test Articles (STAs), the Dynamic Demonstration Unit (DDU), and a simulated CS Pathfinder (weight, center of gravity, outer mold line dimensions, and overall length) over road terrain at four NASA centers and on the Pegasus barge. The MPTS independently supports the article at both ends while operating as a combined unit through automated monitoring of its released degree of freedom and corrective responses. This allows the system to constrain its payload in a statically determinate manner while traversing highly variable terrain. Multi-body simulation of the transportation route is useful to predict free-body motion within its range of mobility. The MPTS has completed its design and analysis developmental cycles. This paper describes the design challenges encountered in developing this system of large-scale structure, which incorporates complex mechanisms. The unique techniques and methodologies developed for analytical assessment of the hardware are also discussed.

Introduction

In large launch vehicle programs, the design challenges presented during launch are apparent. However, many efforts leading up to launch are not so obvious. Included in those many efforts is the development of Ground Support Equipment (GSE), i.e., equipment that interfaces directly to the flight hardware after it leaves the production line. The MPTS supports the delivery of the NASA's latest launch vehicle, SLS. This hardware interfaces directly with the flight vehicle after it has been built, and is therefore classified as GSE.

Historically, different GSE designs have transported flight hardware. Developers customized the designs to meet the particular needs of each program. Every launch vehicle has depended on this equipment to transport it between various locations without inadvertently damaging it. NASA's past launch programs, including Apollo and Shuttle as shown in Figures 1 and 2, used customized equipment to transport flight hardware between NASA facilities.

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Figure 1. The Saturn V second stage moves over roads at KSC, using GSE hardware (Reference 1).

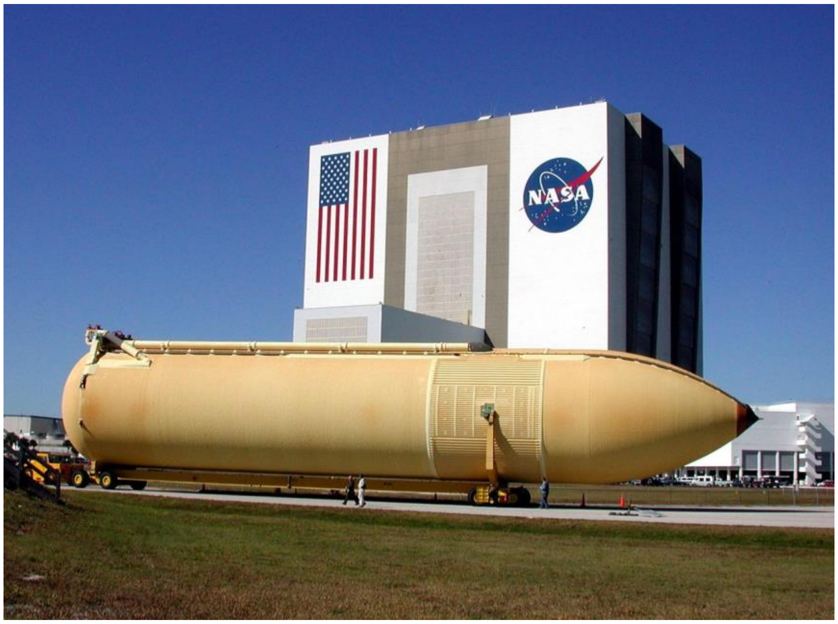

Figure 2. The Shuttle ET moves over the road at KSC (Reference 2).

However, the MPTS designed for SLS is different; its design is to accommodate multiple size articles. Figure 3 shows the initial concept of the MPTS where the intent is to support multiple hardware along with the possibility to be used in future programs.

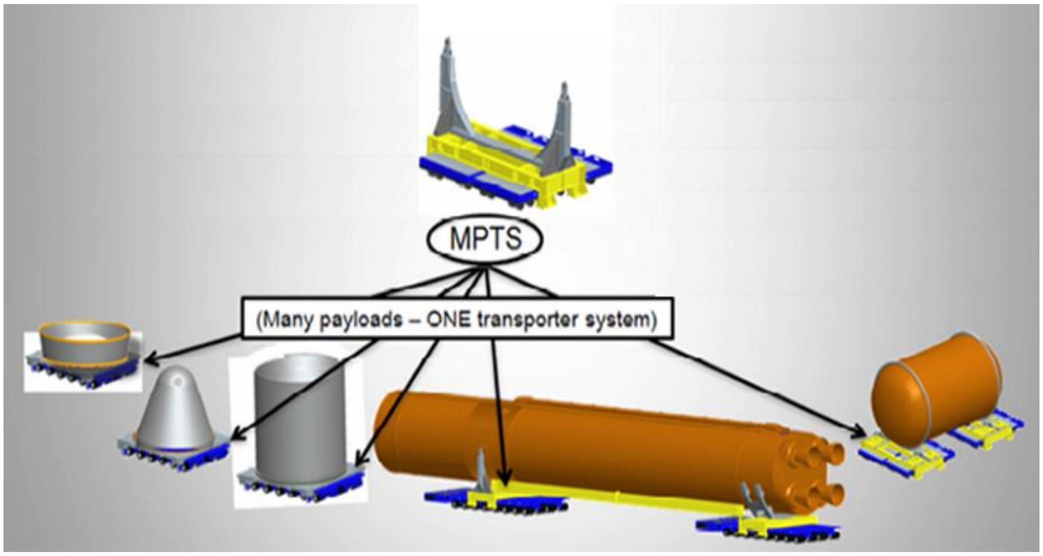

Figure 3. The CS flight hardware is among the payloads that the MPTS will transport (Reference 3).

Current planned uses for the MPTS include the shipment of the SLS CS – NASA's largest and heaviest rocket – as well as Pathfinder – a simplified simulation of the CS that is similar in mass and length – DDU, and three different STAs – each with their own distinctive mass and length. The various payloads will also need to be transported to different locations, as shown in Figure 4. The MPTS will take the three different STAs from Michoud Assembly Facility (MAF) in New Orleans, LA to Marshall Space Flight Center (MSFC) in Huntsville, AL while the CS and Pathfinder will be shipped to Kennedy Space Center (KSC) on Merritt Island, Florida via Stennis Space Center (SSC) in Hancock County, MS.

Figure 4. GSE is used for transportation at and to multiple centers, including KSC, MAF, MSFC, and SSC (Reference 4).

The MPTS design has encountered some unique challenges. Primarily, with its use to support various size payloads, a modular design was needed. Previous hardware, along with initial concepts, used a strongback, a structure connecting the front and back to form a single rigid unit. While including a strongback can simplify design, it quickly became impractical for the MPTS design. Some reasons to eliminate a strongback includes weight and maneuverability. Due to constraints of existing infrastructure such as roads and floor loading, the design weight of the MPTS had to stay below certain limits, and the size necessary to produce a rigid strongback structure to redirect loads away from the flight article were determined to exceed these limits. Following Hurricane Katrina, a levee was added along the transport route to address flooding. Surmounting this levee with something as long as the CS would have been difficult to accomplish with a strongback structure, and the operation to accommodate the different lengths would be taxing.

The elimination of the strongback left the front and back end of the article free to operate independently. To prevent an excessive load from occurring at payload interfaces, released degrees of freedom (DOF) are included at strategic locations. This also serves to improve the predictability of loads at the interfaces. Figure 5 shows released DOF at a high level.

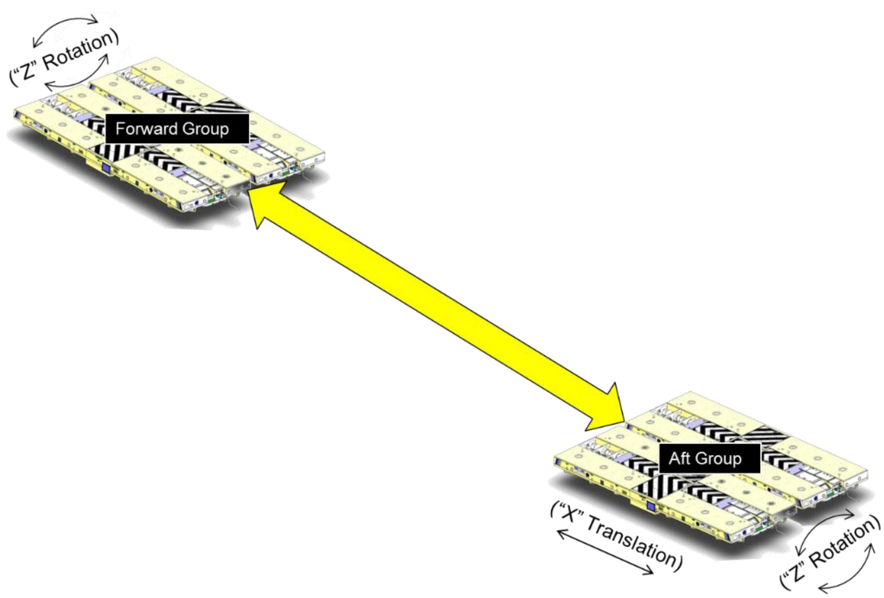

Figure 5. The MPTS includes released DOF, to prevent excessive loads at payload interfaces.

In place of the strongback, a laser alignment guide on the transporter maintains the separation distance. A monitoring system tracks relative motion of multiple released degrees of freedom. The combination of the released degrees of freedom and monitoring system provides the means for the article to traverse compound road contours, as illustrated in Figure 6. A remote-controlled drive system will shut down if set travel limits are violated.

Figure 6. The MPTS articulating over the contour of the road.

Design and Analysis Challenges

Designing the heaviest and largest rocket to date is not an easy task. Designing a transportation unit for that rocket comes with its own challenges. With the increased size, the need for larger and stronger hardware also increased. This shifts the selections of hardware, such as bearings for released degrees of freedom or bolts in fastened joints, from commonly produced parts, to specially-sized items that are difficult to procure.

Figure 7 shows an example of some catalog-available vendor hardware. The catalog lists a range of sizes for a particular part. The larger load-rated items are in less demand, and therefore require longer lead time. The increased size makes handling difficult, and special consideration is needed for even simple touch tasks. The size also makes logistics a challenge; passing through doors that were adequately sized for smaller articles designed in the past becomes a tight-fit operation. A balance between managing loads and maintaining an optimum size was ultimately achieved.

HR-1000CT UN Threads

Frame Size No.	HR-1000CT Stock No.	Working Load Limit (lbs.)*	Torque (ft-lb)	Dimensions (in.)								Mass Each (lb)
				Bolt Size A ‡	Eff. Thread Projection Length B	C	D	Radius E	Diameter F	G	H	
2	6608103	1900	28	1/2 - 13 x 2.25	0.70	6.32	1.96	1.25	0.75	4.20	2.50	3
2	6608112	1900	28	1/2 - 13 x 2.75	1.20	6.32	1.96	1.25	0.75	4.20	2.50	3
2	6608121	3000	60	5/8 - 11 x 2.25	0.70	6.32	1.96	1.25	0.75	4.20	2.50	3
3	6608130	4800	100	3/4 - 10 x 3.00	0.85	8.59	2.96	1.63	1.00	6.25	3.25	11
3	6608139	6200	160	7/8 - 9 x 3.00	0.85	8.59	2.96	1.63	1.00	6.25	3.25	11
3	6608148	8300	230	1 - 8 x 3.50	1.35	8.59	2.96	1.63	1.00	6.25	3.25	11
4	6608149	12500	470	1-1/4 - 7 x 5.00	2.10	11.31	3.71	2.00	1.44	8.13	4.00	24
4	6607669	20000	800	1-1/2 - 6 x 5.50	2.60	11.31	3.71	2.00	1.44	8.13	4.00	27
4	6607727	20000	800	1-1/2 - 8 x 5.50	2.60	11.31	3.71	2.00	1.44	8.13	4.00	27
5	6607670	28000	1100	2 - 4.5 x 7.50	3.20	15.15	4.00	2.69	1.75	11.64	5.00	69
6	6607671	45000	2100	2 1/2 - 4 x 9.50	3.73	19.93	5.75	3.00	2.75	14.47	5.62	157

Figure 7. The Crosby Group catalog of Cold-Tuff Heavy Lift Swivel Hoist rings (Reference 5).

Following the egress from the facilities building, the next challenge is to travel on the road. Consider, for a moment, the one-time transport operation of the shuttle Endeavour through the streets of Los Angeles from the airport to the science center. Careful planning was performed in evaluating its travel route. Obstacles were assessed and removed as needed along the travel path; adjustments were needed to avoid impacts. Figure 8 shows a snapshot from a video of the shuttle as it travels from the airport to the science center.

Figure 8. Snapshot footage of shuttle Endeavor during its transport through Los Angeles (Reference 6).

A similar evaluation was performed in the design of the MPTS. Because this transport operation is meant to be repeated for different articles, consideration of the terrain and any obstructions along its path must be made. Factors include road grade, turns, signposts, overgrown flora, culverts, and bridges. Careful consideration of the travel path was taken to ensure the MPTS, while transporting its cargo, is capable of traversing the terrain without additional effort to modify the terrain or travel path.

This consideration led MPTS development to the challenge of evaluating the released degree of freedom our transportation system provides. Numerous computer model simulations and dynamic analyses were performed to ensure the range of motion provided by the system is adequate to support the path it needs to travel. The simulations involved creating a 3D model of Saturn Boulevard at the Michoud Assembly Facility in New Orleans, LA. The model was generated from data collected in a road survey, which includes the grade created by the levee that was added after Hurricane Katrina. Traversing this levee would require the unit to ascend and descend a steep grade, while making a turn and negotiating a bank in the road. This all occurs while each end is individually managing the sectional contours of the road beneath it. The evaluation was conducted using MSC Adams to ensure there is sufficient range to prevent the movements from bottoming out and to avoid unintentional loading of the article being transported. This simulation includes a flexible finite element model of our GSE hardware and the various payloads it supports, which is connected by joint mechanisms. The flexible body also includes contact definition between mating surfaces and accounts for dimensional tolerances that could develop in production. The maximum design range of motion also required consideration. Excessive motion would result in a larger-than-necessary structure that would create ingress/egress problems of wheel loading, and weight concerns on the road, and over bridges and culverts. The maximum range of motion also necessitates evaluation from a loading standpoint in order to ensure the shifting load does not overload a section of the hardware or article. With the MPTS designed to support multiple sized articles, the evaluation was conducted on each unit to ensure all the articles would be safely transported by a single MPTS design.

Most importantly, the objective is to ensure the design does not impart loads that could potentially damage the flight hardware during transport. The challenge stems from requiring the MPTS to be designed to the standard factors of safety for ground equipment, but a lower factor of safety is used in the design of the launch vehicle as a means of lowering the weight. Added to the complexity is how the loads are applied to the vehicle. The design of flight hardware typically considers the launch loads as the driving load case. However, the vehicle is typically transported horizontally. The loads induced by the MPTS are imparted in a different orientation during the transportation loads as compared to the launch environment.

The vehicle design seeks to minimize the need for local reinforcements. Early discussion with the flight vehicle engineer allowed us to determine the interface definition between the article and the MPTS. This is to ensure suitable locations are provided on the flight hardware capable of supporting the transport load without the need to add weight for localized reinforcements. The collaborative effort includes the identification of interface locations along with the number and size of the contact area. Attachment brackets are designed to connect to these interfaces. This minimizes the weight on the flight article, but also adds the challenge of designing brackets that are light enough to handle, or are situated in a manner allowing the use of support equipment. On-site installation also makes alignment and tolerance control difficult, particularly when attempting to align multiple parts as shown in Figure 9. With various articles requiring transport, the MPTS is designed to accommodate the different tolerances associated with aligning the multiple attachment locations.

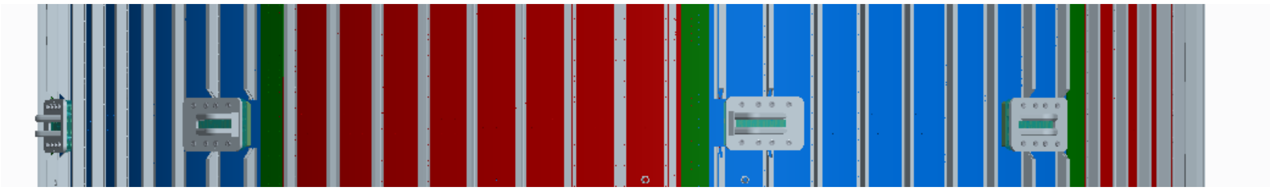

Figure 9. Illustrative depiction of multiple interface locations.

Lessons Learned

<u>Additive Manufacturing</u>
Additive manufacturing processes, commonly referred to as 3D printing, were used to generate tangible models of the MPTS. This offered a unique and straightforward approach to replicate plastic models of individual components of the SLS transportation system. A picture of a model generated in the preliminary phase of MPTS development is shown in Figure 10.

Figure 10. Preliminary conceptual additive manufacturing model.

Creating models generated through additive manufacturing was an expedient way to understand and demonstrate the interdependency of MPTS mechanisms. Released degrees of freedom at various locations of the MPTS affect both local and global movement of the combined payload and transportation system. The relative motion of the system was able to be simulated real time with a scaled down version of ground support equipment. The model shown in Figure 11 demonstrates MPTS relative motion.

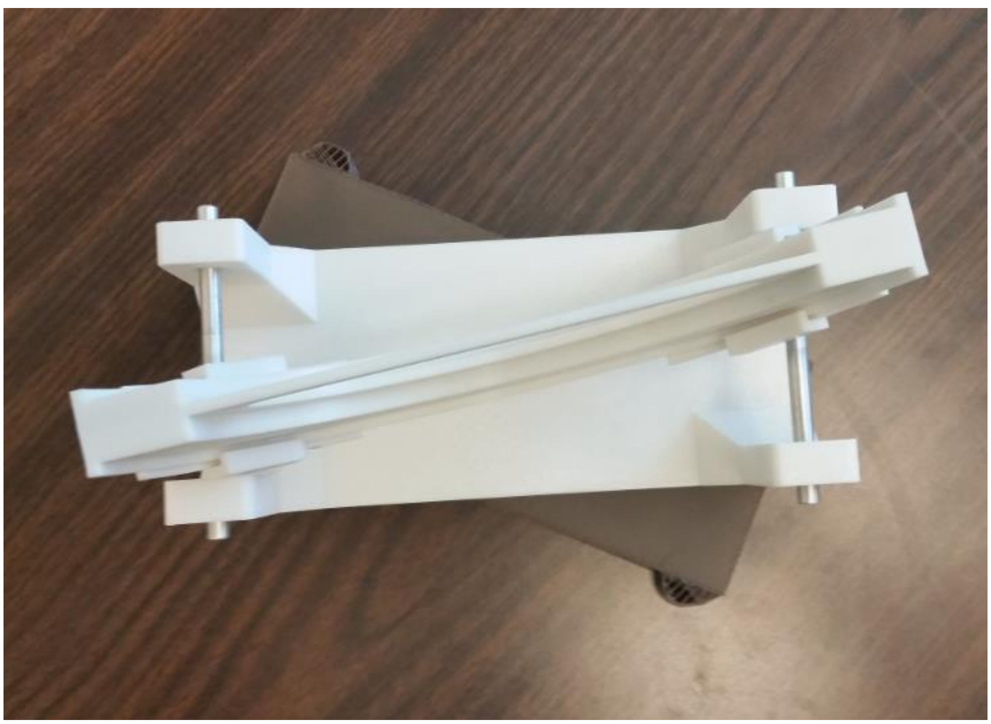

Figure 11. MPTS Additive Manufacturing Model (Top View)

In addition to predicting system response, during the early development cycle, additive manufacturing models served as advantageous visual aids to assist with communication of concepts. Handheld models provide a foundation for quickly grasping concepts with increased levels of engagement during collaborative sessions.

Dynamics Simulations

Multi-body simulation of the transportation route has proven to be a useful tool to ensure the mechanisms will remain within the specified travel ranges, and to identify the locations on each route that are likely to be most challenging. General analysis tools for multi-body dynamics were already available, but a process for turning road survey data into boundary conditions needed to be developed from scratch. The MPTS inherently relies upon contact and various types of nonlinearities that cannot be linearized away. Adding control systems for dozens of wheel modules, with many contact definitions between a road surface and the tires, would make a miles-long roadway simulation strain solvability and still require a lot of guesswork. As an alternative, the as-built survey data was used to create splines for the center, and each side of the road. The splines incorporate features such as cross-fall, crown, and grade. A simplified mechanism of links and joints spans between the splines in order to be pulled along the path without binding. The resultant pitch, yaw, roll, and elevation for each location is imposed on a dynamic model of the MPTS mechanisms. Thereafter, the model is able to illustrate points on the surveyed road, the system will have the least available range-of-motion margin, and operators can respond to this information appropriately.

Since the MPTS mechanism model is built using both dynamically-reduced finite element models and realistic joints, it is also possible to capture the effects of structural flexibility, friction, and gapping. Through simulation, it was discovered that tolerances on a number of mechanisms needed to be kept extremely tight for the system to operate properly. A degree of freedom that is designed to be released at a particular location requires it to be released there, and nowhere else. Simulating the effects of tolerances revealed a loose fit of certain interfaces would result in redundant joints and indeterminate states for the system. This simulation resulted in a changed design, resulting in tight or adjustable interfaces at critical locations.

Friction Testing

In the first complete, end-to-end test of the integrated system, it was discovered that the friction at a critical joint was higher than anticipated. Moreover, this friction was high enough to impede proper operation. Initially, there was no plan in place to quantify or monitor this friction, but the Test Load Facility, designed to statically load the structure, proved flexible enough to perform this task. This led to the development of a means to test friction levels for critical functions (mechanism joints) which are essential to how the system operates. This testing should also be included for periodic maintenance during the design life of the system.

Another lesson associated with the friction test was the need to fully understand a vendor product, even something considered intuitively simple like a friction liner. A specific liner was selected in the design, based on the specification provided by the vendor. This liner was expected to have a coefficient of friction range that was crucial in one of our released degrees of freedom, and be capable of supporting the maximum calculated load during our transport operation.

During testing, it was discovered the friction load was higher than expected, and the friction coefficient of the liner was not as anticipated. Further research indicated the liner material is a specially designed product where the friction coefficient decreases with increasing load as shown in Figure 12, which is counter-intuitive with classic textbook problems.

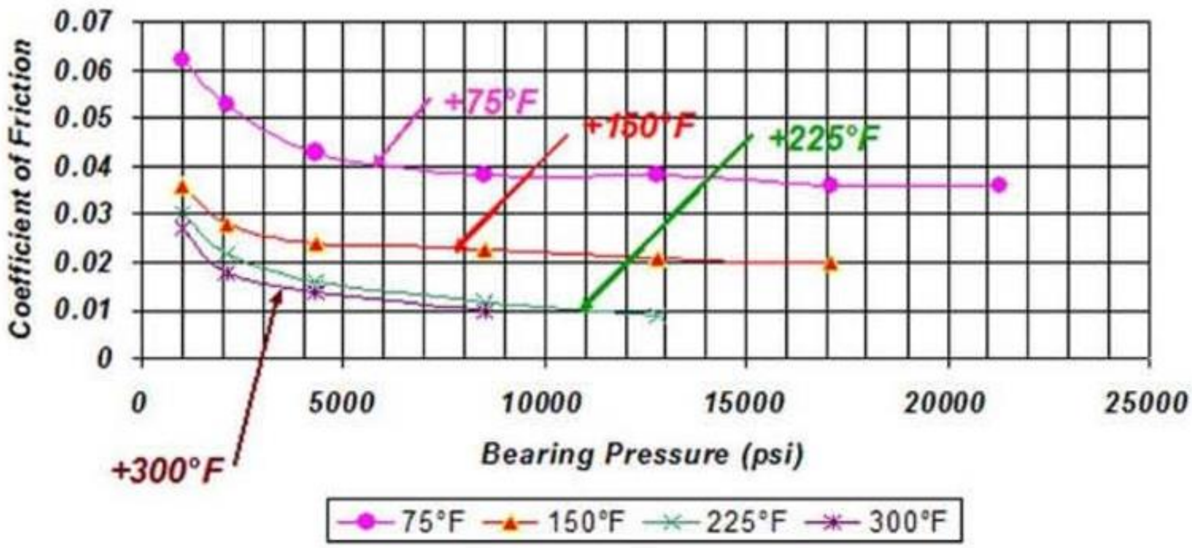

Figure 12. Vendor-reported coefficient of friction in relation to bearing pressure loads (Reference 7).

The coefficient of friction documented by the vendor is based on this condition. An evaluation of our design indicated our bearing pressure on the liner was below what was needed to achieve the desired friction. Our worst case loading conditions, which includes higher level wind loads in combination with the worst case operating, was considered in the selection. However, under normal operating conditions, the bearing pressure is significantly less and resulted in a negative impact to our anticipated friction loads.

Advertised properties provided by vendors should be investigated early in the design development process. Meanwhile, hardware strength evaluations should be conducted using enveloping values with additional margin until the stated properties can be verified. With the understanding of the vendor's required condition, the MPTS was able to be modified, and the friction load was verified to be within acceptable range after the changes were made.

<u>Managing Interfaces and Parallel Development Efforts</u>

To streamline the overall process, MPTS and payload development schedules included overlap. That is, the GSE design began before the payload designs were finalized. This reduced risk for the overall program because it allowed each side of the interface to take the other into account. If the GSE were developed after the payload design was completed, the payload design runs the risk of not having an interface with adequate strength to be transported, necessitating costly redesign effort. While concurrent development is desirable, two key challenges arose: how to address mismatched Factors of Safety (FOS) requirements and how to manage design changes in the payload.

GSE is typically required to meet higher FOS than the payload, and this was the case for the MPTS and its payloads. Early in the design phase, questions arose regarding how to enable each side of the interface to meet its requirements. *GSE loads can and do drive flight hardware design*, albeit at a local level in most cases.

Mismatches were addressed in the following manner: for interfaces where the payload added an interface solely to provide an attachment for the GSE, the interface was designed to allow the GSE to meet its required factors of safety. These interfaces were determined by the payload in order to minimize the impact to the payload. For interfaces where the interface was also used for flight, a less desirable situation, the interface design still attempted to allow the GSE to meet its required factors of safety. However, in these situations, there was often less flexibility to accommodate the GSE, and waivers to the GSE requirements often came into discussion. In situations where reduced FOS were considered, proof load planning became a point of discussion because FOS below the proof load level would mean the GSE could yield during proof testing.

In all cases, the goal was to allow GSE to meet its FOS requirements, as this is ultimately a benefit to the overall program in that it reduces risk of damage to valuable hardware during transportation.

One challenge of two designs working concurrently is that changes to one side of the interface impacts the other interface. As payload designs evolved and the needs of the interfaces became better understood, the MPTS design frequently had to adapt. For some component designs of the MPTS, this required up to three significant redesigns and an unplanned development effort. As a result, design reviews and drawing releases were regularly adjusted. While program schedule fortunately allowed for these redesigns, planning them upfront would clarify expectations for affected teams.

Summary and Conclusion

Throughout the development of the MPTS, various methods and tools were used. This included developing 3-D printed models, performing multi-body simulations, and conducting tests. These methods aided in the production of a highly complicated system capable of adapting to the multiple articles it was tasked to support. 3-D printed models provided a means to understand and demonstrate complicated mechanisms inherent in the design. Performing multi-body simulations allowed a means of verifying the released degrees of freedom and the limited range of motion they provide. The use of models and simulated analysis offered a cost-effective means to identify critical locations, features, and tolerances. Testing has also proven to be essential to ensure the MPTS functions appropriately. This aided in assessing specific issues that would have otherwise been overlooked on paper, or with smaller scale modeling. Early communication is key to successfully delivering hardware in a timely manner. All the work performed in developing the MPTS was done in conjunction with the design of the flight hardware. This was accomplished by identifying the interface locations on the vehicle and understanding the MPTS requirements to safely deliver the spaceflight hardware to test locations and the launch platform.

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