National Aeronautics and Space Administration

NASA Case Study *MSFC-CS1006-1*
By Brian O’Connor and Jennifer Stevens *Rev. 01/27/16*

Tethered Space Satellite-1 (TSS-1): Technical Roundabouts

In the early 1990’s US and Italian scientists collaborated to study the electrodynamics of dragging a satellite on a tether through the electrically charged portion of Earth's atmosphere called the ionosphere. An electrical current induced in the long wire could be used for power and thrust generation for a satellite. Other tether uses include momentum exchange, artificial gravity, deployment of sensors or antennas, and gravity-gradient stabilization for satellites. Before the Tethered Space Satellite (TSS-1), no long tether had ever been flown, so many questions existed on how it would actually behave.

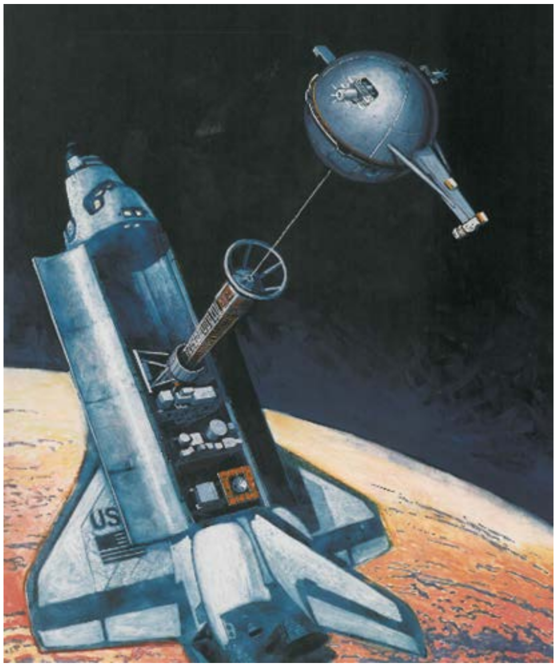

***Figure 1** Artist rendition of the Tethered Space Satellite (NASA)*

The TSS consisted of a satellite with science experiments attached to a 12.5 mile long, very thin (0.10 inch diameter) copper wire assembly wound around a spool in the deployer reel mechanism. With the Space Shuttle at an altitude of 160 nautical miles above earth, the satellite was to be deployed by raising it from the Shuttle bay on a boom facing away from Earth. Once cleared of the bay, the deployer mechanism was to slowly feed out the 12-plus miles of tether. Scientific data would be collected throughout the operation, after which the satellite would be reeled back in.

Pre-flight testing system level tests involved setting up a tether receiver to catch the 12.5 mile tether onto another reel as it was being unwound by the deployer reel mechanism. Testing only

---

Disclaimer: Copyright ©2016 United States Government as represented by the Administrator of the National Aeronautics and Space Administration. No copyright is claimed in the United States under Title 17, U.S. Code. All Other Rights Reserved. The views expressed in this document do not reflect official policy or position of NASA or the United States Government. It was developed for the purpose of discussion and training as directed by the Marshall Space Flight Center’s Chief Knowledge Officer. This material is extracted from publicly available sources and personal interviews with key mission personnel. It is not a comprehensive account of the mission and should not be quoted as a primary source. Feedback may be sent to Brian O’Connor, brian.f.oconnor@nasa.gov or Jennifer Stevens, jennifer.s.stevens@nasa.gov.

the reel mechanism is straightforward. This test becomes more complicated when the TSS is mounted on the flight pallet at Kennedy Space Center (KSC). The system level tests must be passed before the pallet can be installed into the Space Shuttle cargo bay.

A few months before flight, the TSS payload had been integrated onto the Spacelab pallet and system level tests, including unreeling and reeling the tether, had been successfully completed. Some of this testing equipment was then shipped back to the contractor Martin Marietta. Systems-level load analyses, which cannot be run until all information about each payload is finalized, was run in parallel with the physical integration of the hardware into the Shuttle payload bay. The coupled loads analysis, as it is called, incorporates any updates to the model due to system level tests, and any changes that were found during integration.

The coupled loads analysis revealed that a single bolt attaching the deployer reel mechanism to the support structure had a "negative margin" – which is an indication that it might fail during operation. Hardware certification rules do not allow for hardware to fly with negative margins, so this issue had to be resolved before the flight. Since there is conservatism in engineering analysis, there is an option to "waive" the margin requirement, and fly the experiment as is. On the other hand, a structural failure of one payload could have serious or catastrophic consequences to other payloads and possibly the mission. Minor design changes or fixes might be feasible within the payload bay prior to launch. Any major design changes that required the spooling test to validate the hardware, or for the pallet to be removed, would cause TSS not to be ready for the Shuttle launch.

You Make the Call

- What are some options available to you to deal with the issue that has arisen?
- What would you investigate in order to better inform yourself? Whom would you talk to?
- How would you define a major change that requires a retest? That is, what constitutes a "major change" that triggers the need for a new spooling test?
- If you were the Flight Director of the Shuttle program (and you're responsible for the astronauts' lives) would you sign the waiver allowing the mission to proceed with a negative margin?

What is Negative Margin?

A Spacelab pallet provided the mounting between TSS and the Shuttle bay, serving as a platform for the multi-purpose equipment support structure which held the experiment hardware. The satellite was designed by the Italian Space Agency to house five Italian and five US experiments. Marshall Space Flight Center (MSFC) and Martin Marietta teamed to produce the tether, deployer, and supporting equipment. MSFC was responsible for project management and system integration. Martin Marietta led the design of the tether deployer. Part of MSFC's lead integrator duties involved completing verification closures and system level analyses, including the coupled loads dynamics analysis.

Safety factors to be used and requirements about acceptable margin are specified by a Program as requirements. The factor of safety was set by the Shuttle program in this case, and handed down to a project as a requirement for payloads.

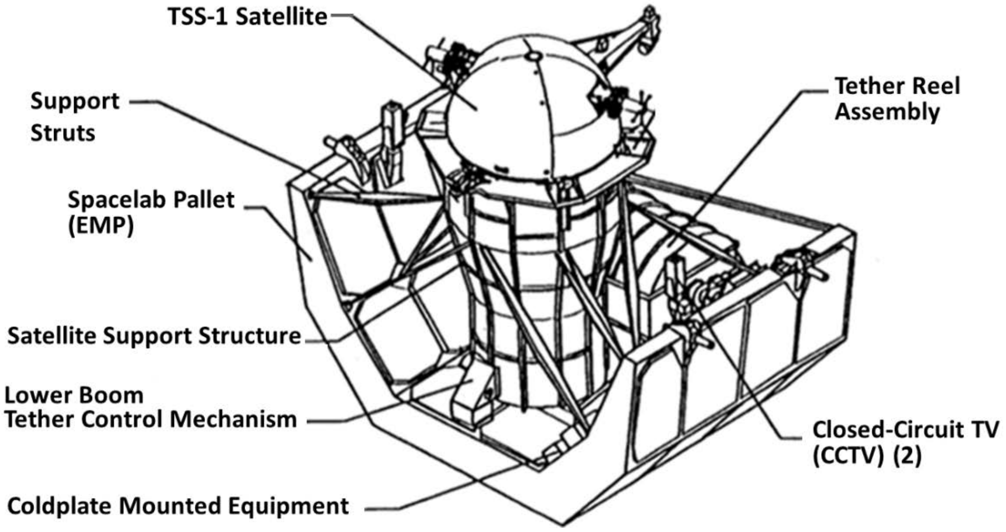

Figure 2 Interfacing components of the Tethered Space Satellite (NASA)

The final coupled loads analysis for the Verification Loads Analysis Cycle was completed by Rockwell Downey, a subcontractor hired by the Shuttle program to perform the analysis. The results, using the verification loads analysis, showed that a bolt, attaching the deployer reel mechanism to the support structure, now had a negative margin.[1]

Coupled Loads Analysis

The goal of performing coupled loads analysis (CLA) is to perform a dynamic analysis of a complete vehicle such as the Space Shuttle, from which a payload-specific stress analyst will derive the input forces and then calculate the resultant stress distribution in their payload. CLA requires each payload provider to build a mathematical model of its system, and then send the

---

[1] See Appendix A for an explanation of margin

model to a model integrator. The integrator combines the different payload models together, then performs a dynamic analysis of specific flight environment cases. The results of the dynamic analysis are then given back to the payload-specific analysts to perform a stress analysis. It is called a "coupled" analysis because each payload affects the others. A scenario might be where payload A was very diligent and built a good model, but payload B did not and had errors in its model. The errors from payload B may end up affecting payload A, and payload A could potentially calculate incorrect stresses through no fault of its own.

In general, once individual models are delivered to the integrator, coupled loads analysis takes three months to complete. Usually, three system level analysis are done: Preliminary Design Review (PDR), Critical Design Review (CDR), and a final verification analysis. The final verification analysis is done after each payload has successfully completed dynamic testing, which is just before shipment for integration with the vehicle. Therefore, final verifications is very late in the game to catch a hardware capability issue. Sometimes results from the dynamic test show errors in the model, and causes model updates that must be incorporated into the verification analysis. Because it takes three months to do the coupled loads analysis, by the time the loads are given to the payload stress analyst, it is very close to flight.

One of the major drivers of the dynamic analysis is the landing load for touch down. It was originally based on loads that were measured from aircraft fighters doing high speed landings on aircraft carriers. At the time of the TSS project a number of Shuttle flights had been completed, but that high of a load had never been measured. However, it was still seen as a possibility. Upon questioning the owner of the landing load value, the decision was that there was no way they would allow a decrease in the load value.

In TSS, a number of updates were done to payload-specific models after the dynamic testing was completed. This included the discovery of an error in the multi-purpose equipment support structure model, which showed that one of the joints was over constrained. When this constraint was released, it allowed the structure to "breathe" or move a little, and transfer more load into the deployer reel mechanism.

There are two major driving load cases for the dynamic analysis. First, is a 10-second portion of Shuttle lift-off. Second, is a two second portion of landing when the landing gears hit the ground. The updated stress analysis, using the final verification loads, showed that potential loads at Shuttle touch down during landing caused the negative margin in the bolt.

Stop and Think:

- How does the timing of the analysis cycles complicate hardware delivery and integration?
- What can you do early on in a project cycle to prevent unexpected updates to an analysis model from causing a major issue near launch?
- What would you say to the analyst if they came to you with this problem?

Proposed Fastener Change

An option to eliminate the negative margin would be to replace the bolt with the negative margin with a similar bolt but made of high strength metal. However, high strength fasteners are typically a long lead item, and the normal procurement process was too slow to obtain in time to make the launch date. A search across NASA did not yield an acceptable replacement bolt.

An alternative, proposed by the design team, was to replace the current fastener with a shear wedge. A shear wedge looks like a C-shaped clamp. It provides a different load path between two plates. Analysis using a shear wedge showed a positive margin for the joint, and it could be implemented in the schedule timeframe.

The hole that the fastener was inserted into was a through hole, and therefore the hole accepted the new fastener. Verifying this with the designers, who double checked their drawings, it was reported back that the change was minor, and everything looked ok.

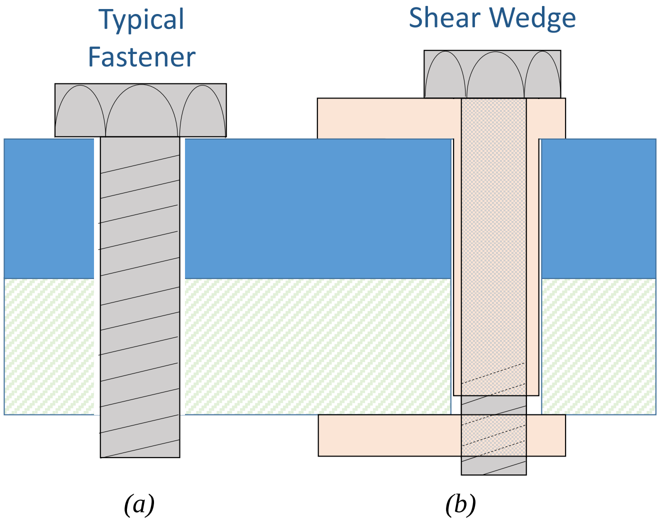

Figure 3 Fastener configurations for TSS-1 (a) nominal fastener in joint assembly, (b) modified joint assembly

You Make the Call:

- Which option (fly on margin, procure a new high strength bolt, use a shear wedge, or other) would you choose?
- If you make a change, do you think you need to do a spooling test?
- Is there anything further you think should be assessed before deciding?

The Rest of the Story

The first TSS electrodynamics mission was launched aboard the Space Shuttle Atlantis (STS-46) on July 31, 1992, as a joint mission between the United States and Italy. Operations were nominal. With the Shuttle in orbit at an altitude of 300 km (160 nautical miles), TSS-1 deployment began. The boom with the satellite was extended, raising the satellite and tether "upward" (toward space). The tether began deploying at a rate of 5.9 inches (15 cm) per minute. At 78 meters the tether stuck. The snag was resolved and the tethered continued until it reached a length of 256 meters, where it stuck again. The satellite reached a maximum distance of about 260 m (854 feet) out of the planned 20,500 meters (12.5 miles). Eventually the tether was reeled back in, and the satellite stowed. It was not until after inspection of the hardware after landing that the problem was found to be a protruding bolt that jammed the deployment mechanism and prevented deployment to the full extension. The bolt in question was the late-stage modification to the reel system.

Figure 4 Close up of TSS-1 from Space Shuttle Atlantis bay

Although TSS-1 did not deploy properly, and the voltage and current reached using the short tether length were too low for most of the experiments to run, there was still some science data retrieved. Low-voltage measurements were made, and variations of tether-induced forces and currents were measured. New information was also gathered on the "return-tether" current.

Most significantly, TSS-1 demonstrated the feasibility of deploying the satellite to long distances, settled several short deployment dynamics issues, and reduced safety concerns. TSS-1 conclusively showed that the basic concept of long gravity-gradient-stabilized tethers is sound.

The TSS mission was reflown in Feb. 22, 1996 on STS-75 on the Space Shuttle Columbia as TSS-1R. TSS-1R successfully deployed to 19.6 km (12.3 miles) before the tether suddenly broke and the satellite sprung to a higher orbit. Despite being disconnected from the Shuttle, flight control at Johnson Space Center (JSC) and Marshall Space Flight Center (MSFC) were able to restart some experiments, which were able to continue for three days, until the satellite batteries died. While TSS-1R also failed to complete its mission, both TSS-1 and TSS-1R provided invaluable data on long tethers in space.

APPENDIX A: A Long Explanation about Margin

Note: Engineers use stress (lbs/ square inch) as the unit of comparison for this analysis, but many people will relate to it better by considering it a force or load (lbs). Since people understand weight, we will use the term load and stress somewhat interchangeably here, but engineers will find this galling.

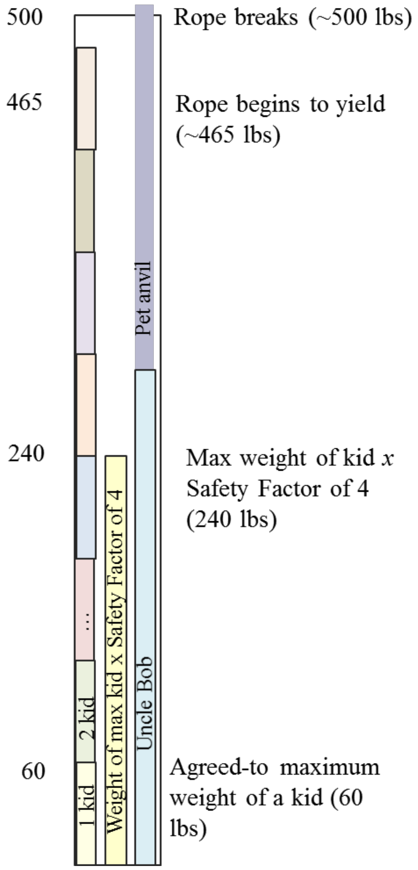

Figure 5 Illustration of relationships of weights and limits

In engineering analysis, margin is an indication of how close to the safe limit of operation hardware is expected to be. In calculating how much load a component can take before it breaks, engineers know the limits of when standard materials like metals and composites will start to yield and when they will actually break. The engineer knows the yield strength (where a material will start to give way) and the ultimate strength (where the material will break). For example, an engineer might decide to build a rope swing with a tire on it. The engineer might have tested the rope and the tire together, and found that the rope would break at, say 500 lbs, but it started yielding at 465 lbs.

There is some uncertainty about the exact amount of load a component will actually take, so engineers use a "safety factor", some agreed-to multiple of the load, to ensure the part stays within the range where the material is known to be okay.

Also, an assumption we may make is that the maximum kid weight should be 60 lbs. We just guessed because we didn't have the time to weigh a statistically significant number of kids and find a predicted A-basis value for the maximum expected weight. This is an assumption.

Therefore, if a person wants to allow 1 kid to swing on a tire swing, and the agreed to safety factor is 4, the engineer will design the swing so that it will be able to hold at least 4 60 lb kids, even though the swing is "rated" to hold 1 kid. As long as the calculated (predicted) load on swing rope (60 lbs) multiplied by the *safety factor* (4) is less than the yield strength (465 lbs) or ultimate strength (500 lbs), whichever is agreed to by contract, then the swing would be considered safe for one kid.

For this calculation scenario we will use the ultimate breaking strength of 500 lbs to be our agreed-to limit.

If we were optimizing the design of this swing because we don't want to pay for better rope than we have to, then we would be able to choose a rope that had a limiting "stress" load of 240 lbs and the swing would still be rated for one kid. The everyday person we could reason that it would be okay to put 4 kids on it and it would probably be okay, but we are more sensitive to the consequences of being wrong, so we give ourselves some room for error, our safety factor.

More often than not, we have to use the materials we have instead of materials bought specifically for an application. In this case, we decide to use the rope Grandpa has hanging in his barn. Turns out it has a breaking strength of 500 lbs. More capability than we need but it works.

Since we know we have included a safety factor, which makes our calculation "conservative", we know that if we decided the consequence would likely not be too serious, we could go ahead and let 4 kids and their dog on the swing and it would probably be alright. But maybe not. Issues like how well the rope was made or if someone overstressed it but didn't break it before we used it could affect how much load it could take in reality. The closer we come to the limiting stress, the riskier it is that it might fail before we predicted it would.

Margin

Margin is a metric that indicates how close to the safe limits the design is. Margin is calculated from a stress prediction using the equation shown below. The limiting stress is defined by the capability of the material, and is usually the yield or ultimate stress value. A negative margin means that the predicted load multiplied by the safety factor exceeds the safe limit. A positive margin indicates that the predicted load multiplied by the safety factor is less than the safe limit, and the hardware should be safe.

$$Margin = \frac{Limiting\ Stress\ (yield\ or\ ultimate)}{Predicted\ Stress\ \cdot Factor\ of\ Safety} - 1$$

Example of a Margin Calculation

Say we design a swing. We do some tests and determine that we can put 500 lbs on the swing before the rope breaks. We might have designed it to hold 1 kid, who weighs at most 60 lbs and we are required to use a safety factor of 4.

In this case we can know that even though it should hold 1 kid who weighs less than 60 lbs, we're pretty sure it can hold 8 kids because 8 kids x 60 lbs = 480 lbs (predicted "stress"), which is less than the limiting stress of 500 lbs.

But, what we might not know is that the assumption we made about the maximum child's weight might be wrong. There is some uncertainty about it because we are just guessing and we haven't been kids in a while. There is also some uncertainty that the rope we have is possibly a little bit weaker than the rope we tested. It might have aged. Since there are factors outside of our control, and since we can't always get data to support our assumptions, we put a safety factor on our estimates to give us some room to be wrong and still be safe.

To be safe we will multiply our maximum kid weight by the safety factor of 4.

From that we know that 1 kid will be safe because 1 kid x 4 x 60 lbs = 240 is less than 500 lbs (our maximum limit). But, is the swing safe for 2 kids? With the math, 2x4x60 = 480, which is less than 500 lbs, so yes. You could say that the swing is rated for 2 kids.

You would not be able to rate it for more than 2 kids, but you could rate it for 2 kids and a puppy if the puppy is under 5 lbs. (5 lbs x 4 = 20) BUT, as you add more kids and puppies, you would run a risk of the rope breaking because you would be much closer to that limiting load of 500 lbs.

In terms of *margin*, then, if you had 1 kid, your margin would be

[500/(60x4)]-1 = [500/240] -1 = 2.08 – 1 = +1.08 This is a positive margin, so you are okay

If you had 2 kids, your margin would be

[500/(2x60x4)]-1 = [500/480] -1 = 1.04 – 1 = +0.04 This is a positive margin, so you are okay. But, it's a lot smaller than for 1 kid.

If you had 3 kids, your margin would be

[500/(3x60x4)]-1 = [500/720] -1 = 0.69 – 1 = – 0.31 This is a negative margin. Three kids are not allowed.

But it looks like only a little bit negative. A safety factor of 4 seems like it would be too high. But how much negative margin might be okay?

You can change the margin to a positive number if you reduce the safety factor to something less than 4. This means that you could waive the requirement for having a positive margin with a safety factor of 4. You would have less conservatism in your analysis. You can do the math so that you know how much safety factor you need before you reach a 0 margin.

You can also "sharpen your pencil" by taking out conservatism in the limiting stress, or you can confirm assumptions about the hardware response by testing more exact configurations of the hardware or engineering more precise models. This isn't always a help because as a more precise model may show that there is less capability than originally thought, or you have more locations of negative margin than you thought rather than providing evidence that you are actually okay.

But that is why you have a safety factor in the first place – because you don't always know about the things that you haven't modeled. And the models might also be misleading.

Finally, you might think that it's all well and good, except somebody told you there was a bad windstorm last night, with winds up to 70 mph in some locations. Your neighbors have limbs down. But you've tugged on the rope and it all looks okay. So, is it okay to swing? In this case you have a system problem that would limit the number of kids who could swing safely, which means that a different analysis is needed.