NASA Investigative Summary: Taurus XL T8 and T9 Mission Failures

Introduction

On February 24, 2009, a Taurus XL rocket (*Taurus T8*) carrying NASA's Orbiting Carbon Observatory (OCO) satellite failed to reach orbit. The Taurus T8 mission failed because the payload fairing did not separate during ascent, causing the rocket to not shed weight. As a result of the extra weight, the Taurus rocket failed to reach orbital velocity, resulting in a total loss of the mission. On March 4, 2011, another Taurus rocket (*Taurus T9*) carrying NASA's Glory scientific satellite failed to reach orbit. The Taurus T9 mission also concluded in a failure of the payload fairing to separate. The Taurus T8 and T9 missions both reentered earth's atmosphere resulting in break-up and/or burn-up of the rocket and satellite, and any surviving pieces would have been dispersed in the Pacific Ocean near Antarctica. The combined cost of both mission failures was in excess of $700,000,000. This document's purpose is to provide a top-level outline of NASA's updated findings pertaining to the cause of both mishaps.

The Taurus T8 and T9 rockets both used 63 inch diameter payload fairings to cover and protect the spacecraft during ground operations and launch. The payload fairing halves are structurally joined together and attached to the rocket using frangible joints. A frangible joint is a structural separation system that is initiated using ordnance. Initiation of the ordnance causes the ligament of the frangible joint extrusion to fracture, allowing the two payload fairing halves to be separated and subsequently jettisoned from the Taurus rocket. The frangible joints for T8 and T9 were made and assembled together, at the same time. The T8 and T9 frangible joint extrusions were manufactured by Sapa Profiles, Inc. (SPI) in its Technical Dynamics Aluminum (TDA) plant, in Portland Oregon.

The NASA T8 and T9 Mishap Investigation Boards (MIB) and Orbital Sciences Corporation (Orbital) T8 and T9 Accident Investigations Boards (AIB) were unable to determine the root cause of the failures. However, the T9 AIB and MIB both concluded that the T8 and T9 missions failed for the same reason: failure of a single frangible joint rail to completely separate at the forward end on each rocket. Subsequently, on August 18, 2012, NASA's Launch Services Program (LSP) began a technical investigation to find the root cause of the mishaps. As part of its investigation, LSP performed material properties testing on remnants (AKA: "trimmings") from the T8 and T9 extrusion processing and found the results did not match the certifications provided by SPI. Additionally, during this time period, NASA's Office of Inspector General (OIG) alerted NASA LSP of indications that test results for relevant extrusions may have been altered. NASA LSP published internal findings in January 2015 and has been working with the Department of Justice (DOJ) as part of its criminal and civil case effort.

LSP Technical Finding

Consequently, NASA LSP has determined the T8 and T9 failures resulted from a combination of three factors:

- -Charge Holder Thermal Contraction
- -Extrusion Ligament Thickness
- -Extrusion Material Properties

LSP determined the first two factors possibly contributed to the failure by potentially eroding margin; but, one factor, improper "Extrusion Material Properties" of the forward fairing side rail, was determined to be the cause.

Factor #1 Charge Holder Thermal Contraction
The function of the charge holder is to transfer explosive energy within the frangible joint. The LSP investigation examined charge holder contraction due to atmospheric temperature on the Taurus T8 and T9 launch days. LSP found that T8/T9 charge holders experienced a 0.38 inch thermal contraction along the side rail length. Although this contraction would not by itself have caused the T8/T9 failures, the ability of the frangible joint to fracture was reduced (*i.e.*, loss of fracture margin).

Factor #2 Extrusion Ligament Thickness
The ligament is the portion of the extrusion that fractures when the ordnance in the frangible joint is initiated allowing the two halves of the payload fairing to separate. The frangible joint extrusion drawing specifies that the ligament thickness shall have a certain minimum thickness and a certain maximum thickness. NASA performed ligament thickness measurements; the results show the ligament grew by 0.003 to 0.004 inches between 1992 and 2007 but was still within the drawing specification. The NASA measurements also identified that the die SPI/TDA used to make the extrusions wore asymmetrically over time (0.002-0.003 in.) from one side of the extrusion to the other side. The ligament growth was caused by wear of the extrusion die. Measurements of ligaments manufactured by SPI/TDA between 2002 and 2007 show the extrusions met the drawing dimensional requirements and did not exceed the maximum thickness requirement. The extrusions used on the T8/T9 missions could not have been made any later than 2007. Therefore, the ligaments on both T8 and T9 were within dimensional requirements but were on the "high side" of the specification. Although this ligament thickness would not by itself cause the T8/T9 failures, the ability of the frangible joint to fracture was reduced (*i.e.*, loss of fracture margin).

Factor #3 Extrusion Material Properties
Through testing that was done in 2014 (known as the N41-1 Test), it was shown that an extrusion not meeting the Orbital material property specifications was a sufficient condition to be the sole cause of an incomplete fracture of an A-series fairing rail frangible joint. The test article that did not fracture was from an extrusion supplied by SPI and certified by SPI as meeting the Orbital material property specification; but, independent testing proved the material properties did not meet the requirements.

The NASA LSP Technical Investigation's Logic Trail

Both missions failed because the payload fairing did not separate during ascent
The T9 MIB determined that for both the T8 and T9 missions the frangible joint on one of the forward side fairing rails did not fracture at the top end of the fairing. As a result of the extra weight since the fairing did not open, the Taurus rocket failed to reach orbital velocity, resulting in a total loss of the OCO and Glory missions.

LSP determined that SPI supplied the extrusions for the fairing rails that flew on the Taurus XL T8 "OCO" and T9 "Glory" missions
The Taurus XL 63 inch diameter fairing uses what Orbital calls an "A-series" extrusion. Per Orbital drawing, each A-series extrusion must be made from 6061-T6 aluminum and meet the following minimum material properties standards in accordance with AMS QQA 200/8:

- Yield strength (yield): 35 kpsi or greater

- Ultimate Tensile Strength (UTS): 38 kpsi or greater
- Elongation: Greater than 8% measured using a 2 inch gage length

All A-series extrusions from the inception of the Orbital frangible joint in 1992 through February 2013 were produced by SPI/TDA. According to Orbital documents, SPI/TDA was the sole-source A-series extrusion supplier through February 2013; there was no alternate supplier. Therefore, without question, the frangible joint extrusions that flew on T8 and T9 were produced by SPI/TDA.

The NASA OIG determined SPI systematically altered extrusion test results

NASA OIG discovered that SPI, the extrusion supplier to Orbital (the manufacturer of the Taurus XL launch vehicle and now known as Northrop Grumman Innovation Systems (NGIS), had altered extrusion material property test results from failing to passing, and had falsely provided material property certifications stating the extruded material met Orbital specification requirements.

Records of SPI's handwritten material properties test results obtained by NASA OIG and later shown in court documents revealed SPI made alterations to more than 2,000 test results between about1996 and 2006, which affected more than 200 customers. Some examples specific to the frangible joint extrusion are:

-Altered Test Results – On seven occasions between 1996 and 2002, SPI/TDA altered test results for frangible joint extrusions delivered to either Orbital or its subcontractors. SPI's internal test records show handwritten alterations changing failed test results to passing.

-Discrepant Material – SPI/TDA delivered frangible joint extrusions to Orbital under two purchase orders (Feb & March 2007) and certified that the material met standards when in fact it did not. Although SPI's internal records show a passing test result from each order, independent testing by NASA later proved extrusions from both lots failed to meet material properties standards.

-Suspect Material – Between 2002 and 2003, there are four Orbital frangible joint extrusion orders where evidence suggests discrepant material was likely delivered, even though SPI's records do not show alterations. For example, on July 22, 2002, SPI/TDA extruded 25 pieces of frangible joint extrusion for Ensign Bickford Aerospace Defense (EBAD), an Orbital subcontractor. SPI's records show two test samples from the lot were tested at the same time; the first test sample failed and the second one passed. SPI/TDA used the passing result from the second sample to certify the order and ship the material.

In addition to altering test results at its TDA plant, SPI also engaged in altering test results in its central Portland test lab. In September 2015, SPI disclosed to the DOJ that from at least 2006 to August 2015, test lab employees were routinely involved in altering material properties test results. According to court documents, SPI later determined its employees altered over 4,100 test results affecting over 250 customers from about 2002 through about 2015. SPI's test lab manager pled guilty to fraudulently altering failing test results to make them pass, and to training and directing lab employees to alter test results. Court documents also state the manager created a set of written procedures for lab technicians to consult for instruction on how to alter test results.

LSP determined that discrepant extrusions made by SPI flew in the base rings and side rails on both the T8 and T9 missions

On several occasions, SPI delivered substandard extrusions (*i.e.*, material that did not meet the requirements outlined in Orbital drawings), which were used by Orbital in certified flight hardware for NASA, and other government customers. Two key examples are included below:

> ***Three Purchase Orders Linked to T8 and T9 Base Rings – Pro-Type Remnants***
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> Pro-Type Industries Inc. (Pro-Type) was the machine shop that cut, drilled and rolled the T8 and T9 frangible joint extrusions purchased from SPI/TDA. Pro-Type retained frangible joint extrusion remnants from the work they performed. Four of the remnants (36.5" each) matched the lengths of what would have been left over after making two Taurus base rings. The chemical composition of the base ring remnants are a match for only three purchase orders, which were extruded by SPI/TDA in Feb 2000, May 2002, and July 2002. Records show Pro-Type processed extrusions for the Taurus T6 mission prior to Feb 2000; so they are not remnants from the T6 frangible joints. The Taurus T7 mission flew a 92" fairing and used a different type of extrusion than T8 and T9; therefore the remnants are not from T7. These four base ring remnants could only have come from Pro-Type's machining of extrusions for the T8 and T9 missions. SPI records show handwritten alterations of test results for two of the three purchase orders that these remnants could have come from (Feb 2000 and May 2002). NASA performed material properties testing on all four remnants, which resulted in three failing to meet minimum yield strength and two failing to meet both yield and UTS requirements. Therefore, discrepant extrusions made by SPI/TDA flew in the base rings and aft side rails on both the T8 and T9 missions.
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> ***T8 & T9 Forward Side Rails***
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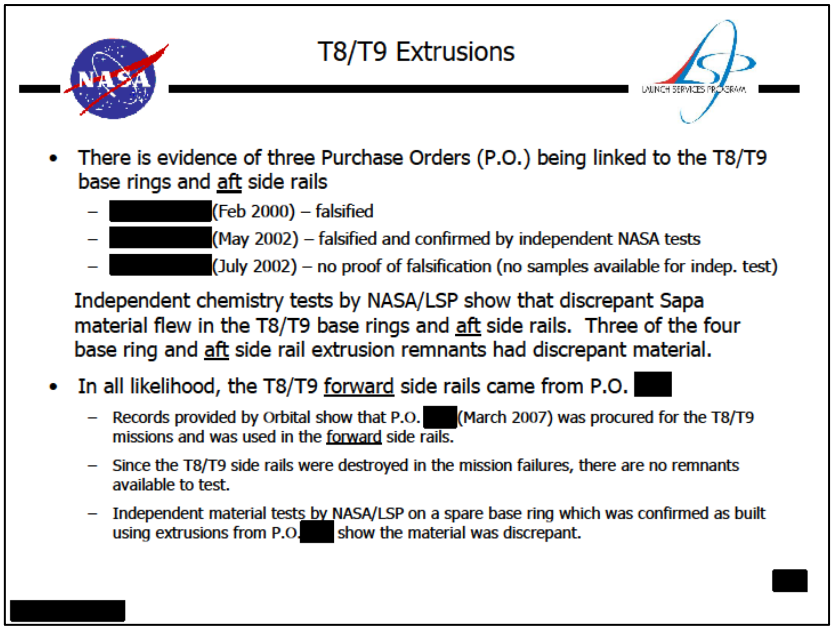
> Due to the length of a Taurus forward side rail frangible joint extrusion, no remnants were left over after machining. Since the T8 and T9 forward side rails were destroyed in the mission failures, there are no samples available to directly test. However, that was not the end of the story. On March 28, 2007, SPI shipped 10 frangible joint extrusions to Orbital via purchase order. Orbital bought these extrusions specifically to build the frangible joints for the T8 and T9 missions. Extrusions from this order were also used to build a spare fairing base ring, which was made just after the T8 and T9 fairing base rings and side rails. SPI's records show the extrusions passed material properties testing and SPI certified the extrusions met Orbital's drawing requirements. However, during this investigation NASA LSP performed material properties testing on the "leftover" T8/T9 spare base ring made from some of these extrusions, and both halves of the ring failed to meet standards. Orbital's records indicated that the forward side rails, the place where the fairing frangible joint for both the T8 and T9 missions failed to fracture, came from the discrepant material that was part of the March 2007 Orbital purchase order.



LSP determined SPI's Extrusion Process was incapable of supplying extrusions that could meet the required material property specifications

According to court documents, SPI has acknowledged altering test results on extrusions sold to hundreds of its customers on thousands of occasions over a 19 year period.

In a more recent example, in February 2012, NASA purchased a flight certified frangible joint base ring from another government agency as backup hardware for NASA's NuStar mission. The extrusion used in the NuStar base ring was manufactured by SPI/TDA on January 5, 2009. In April 2017, NASA destructively tested the NuStar base ring to measure its extrusion dimensions. The ligament measurements on one side were within specification; however, the other side consistently exceeded the maximum allowed limit. The out-of-tolerance ligament thickness observed in the NuStar ring indicated a lack of both dimensional control and quality inspection processes by SPI/TDA. The out-of-tolerance oversized ligament in the NuStar ring would cause an additional unplanned loss of fracture margin. SPI/TDA produced the NuStar extrusion, which was outside the dimensions allowed by the Orbital drawing, but delivered the extrusion with a *Certificate of Mechanical Properties* claiming it met the drawing requirements.

These facts demonstrate that SPI's production process was not capable of consistently extruding material that met specifications.

LSP Determined Substandard Extrusion Material Properties is enough to be the sole cause of a frangible joint not to fracture on command

In 2014, frangible joint test article N41-1 was functioned in a controlled laboratory environment and the test article did not completely fracture at one end of the extrusion. The N41-1 test article was assembled using procedures that were consistent with the way the T8 and T9 flight frangible joints were made. During the function test, the N41-1 test article was mounted on a flight-like stationary fixture. The N41-1 article was functioned inside an air conditioned laboratory so there was no contraction of the charge holder from thermal effects. The N41-1 ligament thickness was measured and found to be within the Orbital drawing requirements. The extrusion in the N41-1 test article was manufactured by SPI on May 13, 2002. Independent material testing showed the extrusion in test article N41-1 was discrepant and failed to meet the material properties requirements of the Orbital drawing. The N41-1 test article components (*e.g*., ordnance core load, charge holder, and expanding tube) met the frangible joint requirements. The only discrepant component in the N41-1 test article was the material properties of the SPI manufactured extrusion. The N41-1 test demonstrated that discrepant material properties can *by itself* cause a frangible joint to not fully fracture.

LSP Determined that "Charge Holder Slumping" is not a credible cause for the T8 and T9 launch failures

Orbital's T9 AIB postulated that the mission failures might have been caused by the rubber charge holder inside the vertical frangible joint side rail contracting (*i.e.,* "slumping") due to the acceleration of the rocket. (NASA notes that Orbital was unaware at the time of the T9 AIB that SPI had altered test results for the extrusions it had supplied.) To date, only two tests have been performed to determine if slumping could have occurred on the T8/T9 flights. In 2011, Orbital performed centrifuge tests as part of its AIB investigation at the NTS Laboratory in Santa Clarita, CA. The Orbital tests used a centrifuge to produce accelerations on various fairing side rails to characterize if slumping could occur in flight. NASA considers the Santa Clarita centrifuge test to be invalid for the following reasons:

- Vibration environment was not flight-like (*i.e.,* a concrete shaker was used to simulate the vibration, however, the vibration produced was not the correct frequency/magnitude).
- Thermal conditions were not controlled (*i.e*., centrifuge was outdoors and subjected to temperature variabilities, which were not adequately monitored).
- The Santa Clarita centrifuge had a short arm resulting in a large acceleration gradient, which did not resemble acceleration experienced during a launch.
- Test configuration was not flight-like. No extrusion was used; only an expanding tube.

Although the Santa Clarita test indicated slumping was possible, Orbital was only able to reach this conclusion on non-flight like articles in non-flight environments while operating the centrifuge at acceleration levels greater than what Taurus experiences in flight. LSP review of the Santa Clarita centrifuge data found that no correlation can be made between acceleration, vibration input, and the amount that the charge holder slumped during centrifuge testing.

Because of concerns with the validity of the Santa Clarita tests, another government agency paid to have a second test performed at the Goddard Space Flight Center (GSFC) centrifuge. The side rail was tested at GSFC and the test showed no slumping. The GSFC test conditions are considered more flight-like:

- Vibration environments were more flight-like (*i.e.,* vibration frequency and magnitude consistent with applicable flight environments).
- Thermal conditions were controlled (*i.e.,* centrifuge is indoors and frangible joint's temperature was consistent with applicable pre-launch operating temperature).

- The longer arm of the GSFC centrifuge provided a smaller acceleration gradient and therefore resembled flight acceleration more closely than the Santa Clarita centrifuge.
- Test configuration was flight-like; expanding tube was inside a flight extrusion.

Based on the GSFC centrifuge tests, the other government agency and Orbital cleared slumping as an issue for that government agency's fleet. The test at GSFC with more flight-like environments showed no charge holder slumping even with a margin run conducted at accelerations 16% greater than flight. The GSFC test also applied random vibration (at Maximum Predicted Environments, worst case seen in flight) for a duration lasting 10 seconds longer than flight. Although the payload fairing geometry of various side rails are somewhat different, the side rails tested use the same A-series extrusions; therefore, conclusions can still be drawn from these tests. The more flight-like centrifuge tests show that charge holder slumping was not occurring. The data does not support Orbital's hypothesis that T8 and T9 were more susceptible to charge holder slumping than the previous four successful flights with a 63 inch diameter payload fairing.

The final significant piece of evidence pertaining to possible charge holder slumping on T8 and T9 is that Orbital's AIB and NASA's MIB concluded that a single frangible joint rail on one side of each rocket failed to fracture. However, during flight the effects of acceleration act on both side rails. Therefore, physics does not support the conclusion that acceleration would only cause slumping on one side and not both.

Livermore's Limited Role in the Investigation

NASA hired the Lawrence Livermore National Laboratory (Livermore) to provide advanced lab services to support NASA's broader technical investigation of the T8 and T9 failures. Livermore's role in supporting LSP's technical investigation was to perform modeling and conduct tests to anchor its models. The Livermore models were analytical math models that simulated frangible joint operation. In December 2014, Livermore provided conclusions to NASA that appear to contradict NASA's current findings. For instance, in 2014 Livermore concluded: *"The only single factor that had a large enough effect to prevent fracture at the initiating end is contraction of the charge holder inside that end of the extrusion."* Additionally, its report contains a table that lists *"charge holder contraction* [slumping]*"* as the only significant factor that could have contributed to the T8 and T9 failures. NASA's purpose for asking Livermore to model slumping was to determine what the effects would be *if*, hypothetically, slumping occurred. Based on NASA's request that Livermore model the effects of slumping, its report assumed slumping occurred on T8 and T9. Livermore's conclusions are based on a premise, that slumping from acceleration happened during T8 and T9 when in fact, there is no evidence to support it. Livermore performed no tests to determine whether or not slumping actually occurred on any Taurus mission. Its conclusions on "slumping" were unsolicited by NASA, and because its conclusions were not based on all of the data known at the time, and due to additional data that became known later in NASA's investigation, its conclusions can only be viewed as interim. As NASA's investigation continued to progress, additional data was discovered that changed some of the assumptions and input data used by Livermore. Therefore, NASA's final determination of the cause of the T8 and T9 failures supersedes Livermore's conclusion.

Conclusion

Orbital's AIB and NASA's MIB established that the T8 and T9 missions failed because a single frangible joint side rail at the forward end on one side of each rocket did not completely separate. NASA LSP's independent investigation further concluded that charge holder thermal contraction and extrusion ligament thickness may have each contributed to the failures by eroding the frangible joint's fracture margin, but the data shows the combined effect of both factors could not have caused the failures by themselves. The only other factor that could have significantly eroded the margin enough to cause the frangible joint failure was discrepant material properties of the T8 and T9 frangible joint extrusions supplied by SPI.