

## FLAT H FRANGIBLE JOINT EVOLUTION

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### INTRODUCTION

Space vehicle staging and separation events require pyrotechnic devices. They are single-use mechanisms that cannot be tested, nor can failure-tolerant performance be demonstrated in actual flight articles prior to flight use. This necessitates the implementation of a robust design and test approach coupled with a fully redundant, failure-tolerant explosive mechanism to ensure that the system functions even in the event of a single failure.

Historically, NASA has followed the single failure-tolerant (SFT) design philosophy for all human-rated spacecraft, including the Space Shuttle Program. Following the end of this program, aerospace companies proposed building the next generation human-rated vehicles with off-the-shelf, non-redundant, zero-failure-tolerant (ZFT) separation systems.

Currently, spacecraft and launch vehicle providers for both the Orion and Commercial Crew Programs (CCPs) plan to deviate from the heritage safety approach and NASA's SFT human rating requirements. Both programs' partners have base-lined ZFT frangible joints for vehicle staging and fairing separation. These joints are commercially available from pyrotechnic vendors. Non-human-rated missions have flown them numerous times. The joints are relatively easy to integrate structurally within the spacecraft. In addition, the separation event is debris free, and the resultant pyro shock is lower than that of other design solutions.

It is, however, a serious deficiency to lack failure tolerance. When used for critical applications on human-rated vehicles, a single failure could potentially lead to loss of crew (LOC) or loss of mission (LOM).

The Engineering and Safety & Mission Assurance directorates within the NASA Johnson Space Center took action to address this safety issue by initiating a project to develop a fully redundant, SFT frangible joint design, known as the Flat H. Critical to the ability to

retrofit on launch vehicles being developed, the SFT mechanisms must fit within the same three-dimensional envelope as current designs as well as meet structural loads requirements. There is increased mass associated with the redundant design, and the goal is to minimize the weight impact as much as possible. These requirements presented significant challenges, both technically and financially; these challenges will be explored in this paper.

Perhaps greater than the technical issues confronted during this design process, were the financial considerations. These were a significant part of the story of this design and development plan. Insufficient financial and labor resources were formidable barriers to completing this project.

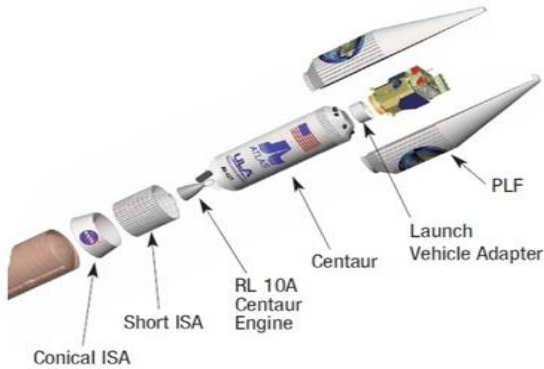
Nevertheless, JSC personnel successfully conducted several test series at JSC with very useful results. The many lessons learned drove design improvements, performance efficiency, and increased functional reliability.

This paper examines the significant technical and financial challenges that these requirements posed to the project team. It discusses the evolution of the SFT frangible joint design, including optimization, testing, and successful partnering of the Johnson Space Center (JSC) engineering and JSC safety organizations, to enhance the flight safety margin for America's next generation of human-rated space vehicles.

### FRANGIBLE JOINT DESCRIPTION

The primary function of a frangible joint is to separate launch vehicle stages or payload fairings. It offers a debris-free separation with significantly lower shock than a Linear Shaped Charge (LSC) separation system, and it weighs less than discrete release devices, such as separation nuts and explosive bolts. Figure 1 depicts where frangible joints are often used on a launch vehicle. Current unmanned spacecraft flight designs

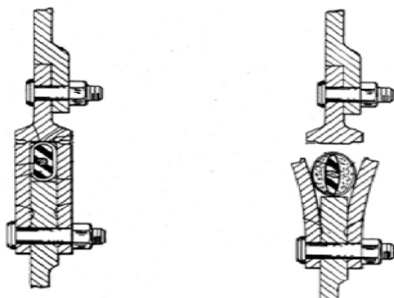
implement ignition redundancy by detonating the ends of the separation segments with zero-failure tolerance in the single cord between the detonators. Past attempts to achieve pyrotechnic failure tolerance focused on maintaining the existing exterior joint geometry and only altered the design interior by placing two explosive cords in the same relative location where there previously had been only one. This option was minimally successful. In contrast, the design described in this document is fully redundant and has two independent explosive trains.



**Figure 1:** Spacecraft Separation Systems Using Frangible Joints

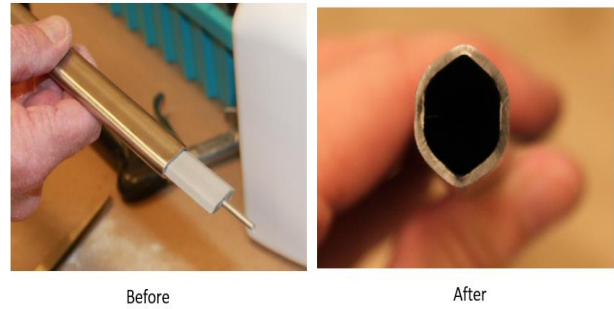
The frangible joint design has an explosive cord centered inside a steel tube with an elastomeric charge holder. This is the expansion tube assembly (XTA). The XTA serves the dual purpose of transferring the explosive cord energy to the joint while also containing the pyrotechnic combustion by-products. Detonation of the explosive cord, also known as a mild detonating fuse (MDF), sends a shock wave through the structure and expands the confinement tube. Both the shock and expansion force contribute to the separation.

In Figure 2, the cross-sectional shape of the tube has two flat sides and the cord centered between the flats. Detonating the cord returns the tube to a round shape and fractures the structure in its expansion path.



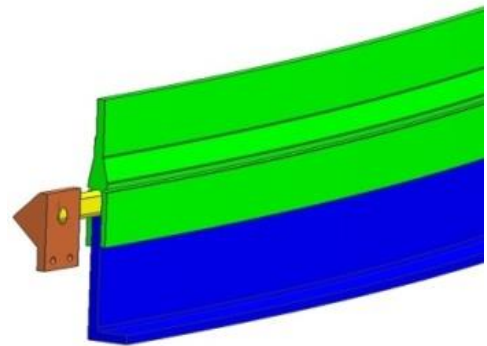
**Figure 2:** Cross Section of a Single XTA Frangible Joint

Figure 3 illustrates the before and after of a typical XTA.

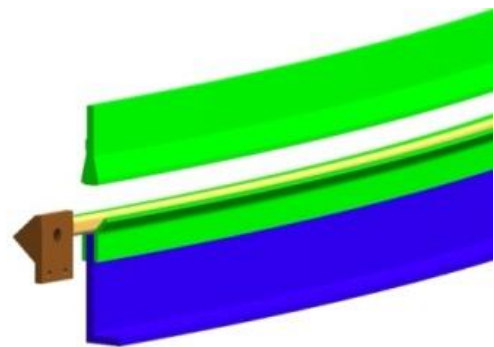


**Figure 3:** Typical Expanding Tube Assembly

Figure 4 depicts the XTA fracturing the separation plane when activated.



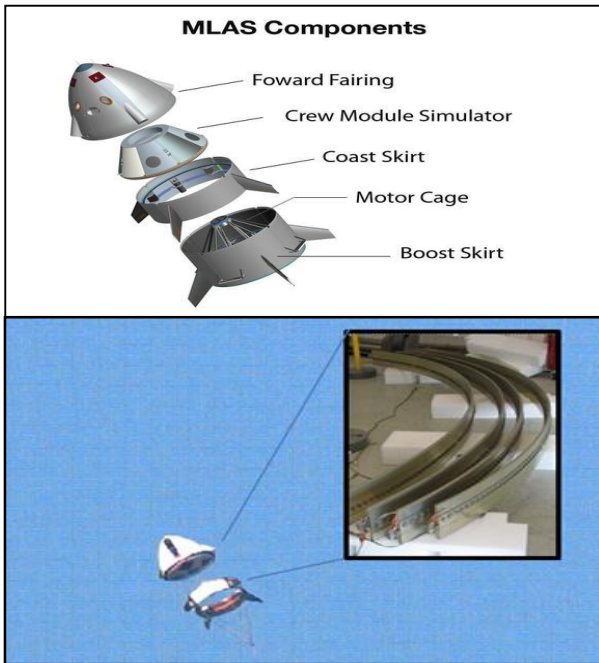
**Figure 4a:** Pre-Separation Frangible Joint



**Figure 4b:** Post-Separation Frangible Joint

## FRANGIBLE JOINT APPLICATION

Figure 5 illustrates a typical fairing separation system.



**Figure 5:** Max Launch Abort System (MLAS) Frangible Application.

These separation designs are ZFT, and the Orion Program and the CCP have designated them for use in highly critical operations where failure to function, or premature function, leads to LOC/LOM outcomes.

To date, no NASA human-rated program has selected the use of ZFT frangible joints. The Shuttle Program for emergency crew egress selected and flew XTA sub-assemblies installed in the side hatch and overhead window jettison assemblies to break a series of bolts. They were not required to sever a continuous joint segment, as currently proposed for the Orion and CCP vehicles. These SSP designs were aligned with the NASA heritage SFT design philosophy, using redundant XTAs to maximize the best chance for system function, which is in stark contrast to the ZFT XTA proposed for use in the next generation of spacecraft.

## PYROTECHNIC COMPONENT FAILURES

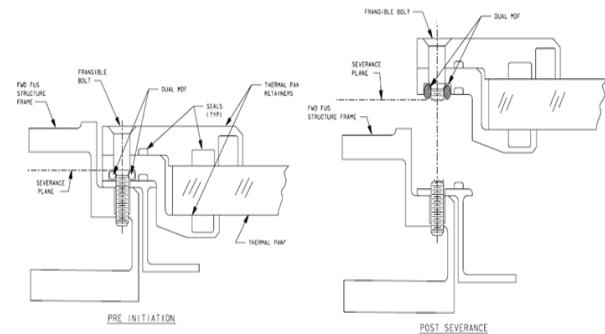
NASA has documented several cases, specifically relevant to frangible joints, in which ZFT pyrotechnic devices have failed. The root causes of some component failures have been resolved; however, other incidents remain unresolved, even after extensive investigations. Due to following best practices and employing functionally redundant pyrotechnic trains in human spacecraft, it is possible that more flight failures

occurred than were discovered and documented. Several ZFT failure cases are discussed below as illustrative examples.

### Case Study 1: Shuttle Overhead Window Jettison Qualification Test

The Space Shuttle Orbiter overhead window assembly contained explosives to allow ground egress in case the crew was not able to exit normally through the side hatch upon landing. The inner window contained dual expansion tube assemblies, while the outer window had dual MDF lines (see Figure 6).

After a successful jettison of the outer window during a qualification test, inspection revealed that one of the MDF lines had not fired as planned. The root cause of the MDF failure remains unknown. The implementation of redundancy enabled complete functionality of the system.



**Figure 6:** Shuttle Overhead Window Jettison System

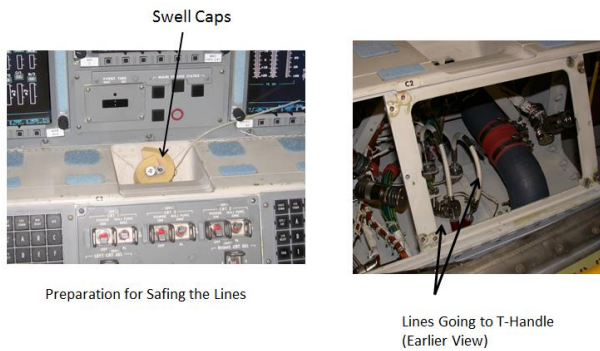
### Case Study 2: Shuttle Flexible Confined Detonating Cord (FCDC) Failure

During safing operations following the retirement of the Shuttle Orbiters, the Program management made the decision to fire these lines in place due to the extensive efforts required for complete removal. As a result, technicians removed all pyrotechnic devices from the vehicles, with the exception of the window egress system FCDC lines and the exterior T-handle initiator. They also installed swell cap function indicators on the end of each line.

Upon firing, one of the caps did not swell as expected, indicating that the line did not fully function. Further investigation revealed a fault between an elbow fitting and the swell cap located at the center console (see Figure 7).

Although the root cause of the failure was not determined, the leading theory is that repeated and excessive bending of the lines during cockpit refurbishment degraded the FCDC.

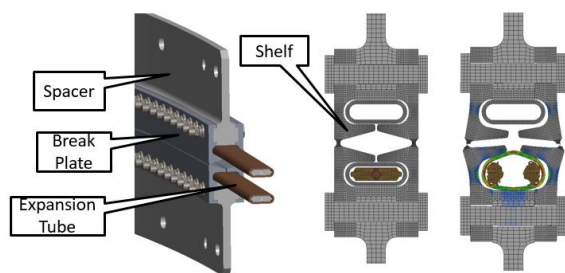
System functionality was achieved specifically due to SFT redundant design implementation.



**Figure 7:** Shuttle FCDC Lines Being Configured for Safing

## FLAT-H CONCEPTUAL DESIGN AND OPERATION

Figure 8 illustrates how the Flat-H design is configured. Both break plates have shelves extending out close to the center of the flat surfaces of the XTAs. When one or both XTAs function, the expansion rotates the corresponding break plate shelves. The rotation of the shelves severs the ligaments in both break plates, separating the Flat H joint. A combination of tension and torque at the break plate ligaments causes the fracture.



**Figure 8:** Flat H Redundant Frangible Joint with Two Expanding Tubes

Our new design has two XTAs unlike the earlier designs, and the XTAs are positioned horizontally, as opposed to the vertical positions as shown in Figure 2. This “flat” position makes a more compact assembly for structural support and stability. The Flat-H assembly is comprised of two XTAs that join the adjacent structures, along with two break plates, which sandwich

the XTAs and spacers with fasteners, thereby holding the assembly together. Thus, SFT status can be achieved.

## PROTOTYPE TESTING: FRANGIBLE JOINT LESSONS LEARNED

In early 2014, the Johnson Space Center (JSC) Pyrotechnics Group began the fabrication and preliminary evaluation of the Flat-H design. Requirements dictated that the design could be retrofitted on existing vehicle configurations and that it could accommodate the flight loads for the Orion Service Module fairing separation. The early Project Objectives were:

- Developing concepts into fabrication drawings;
- Performing approximately 15 firings at JSC;
- Developing hardware for further work to perform testing at White Sands Test Facility (WSTF) using high speed data acquisition equipment; and,
- Conducting stress analysis and load testing.

The schedule was success-oriented and provided a limited window of opportunity to leverage WSTF assets. Since the schedule for testing opportunities was prohibitive of a full typical design review cycle, rapid pace events occurred. No delays for dynamic analysis, no predictive models, and no time for failure analysis, if needed, were possible. Thus, the empirical design development approach was based exclusively on trial-and-error, professional experience, and intuition. Data collection and review supported the design refinement process.

The JSC tests resulted in successful separation using a single XTA, and demonstrated that the design could sustain compression and tensile structural loads. Unfortunately, when testing a similar configuration at WSTF the joint failed to separate. The team believes movement in the spacers and flexing of the bolts that hold the joint together caused the failures. With the unfavorable test results at WSTF, design momentum was temporarily lost.

A tremendous wealth of data from the WSTF testing required assessment, reduction and analysis to proceed. The analysis revealed exactly what happened to the Flat-H during the testing. Data analysis determined that there was relative motion between the joint components where there should have been none. Energy from the XTA firing was lost due to this motion, and this energy loss prevented the joint from breaking fully. Using the WSTF failure test data, JSC Pyrotechnic group completed reconstruction of the analysis models. The

analysis revealed that modifications to the design would correct the failure. Consequently, there was excellent correlation between the actual WSTF test data and the JSC analytic model data. The results of this initial test phase motivated further investment in the Flat H concept.

This further investment was accompanied by an augmentation of project goals, pursuing closure of the initial test matrix with the common goal of serving all three human spaceflight programs – Orion, Space Launch System (SLS), and Commercial Crew Programs. Note this is a significantly larger role than originally envisioned for this project.

The funding of the new model validation approach increased design credibility, test predictions, and an understanding of component interactions for risk mitigation. In addition, it enabled team members to create purposeful analytic models, employing test data and prior corporate test knowledge of frangible joint technology.

The potential on-ramp of three programs provides for the utilization of the technology, needing only an opportunity to pass performance tests at JSC Energy Systems Test Area (ESTA) and WSTF. It also enables us to take the calculated steps to prepare for the next set of configurations and tests, including assessing load cases with new geometry and curved assemblies.

## **2016 FLAT-H FORWARD**

The project leadership anticipates returning to the Human Exploration Operations Mission Directorate (HEOMD) armed with the necessary data that warrants the investment into the next project phase that develops a frangible joint specific for Orion vehicle needs. This will reduce the LOC risk for future flights namely Orion's EM-3 mission and beyond where there are crew onboard. Early in the development process, the project may have to add the rolling of three, 5-foot joint segments as an activity to demonstrate the feasibility of the manufacturing process that emulates the Orion vehicle's geometry. Additional funding will be required, and a four-month timeline extension to procure curved geometry sections for combined load tests and the statistical data base enhancement. The estimated start date will be fiscal year 2017.

The JSC Pyrotechnics Group mitigated the flaw in the design, proposed a new test results based design configuration that precluded relative motion in testing, and successfully fractured the joint along its length using lower core load MDF than initially predicted. These are very significant strides made on the partial funding and in a matter of a few months.

Further investment has increased confidence in the SFT technology readiness state for full-scale development. Also, it gives the project an opportunity to demonstrate low cost additional functional tests at ESTA, as well as structural load carrying capability. This two-pronged data-driven approach entails modeling and analysis coupled with non-destructive and destructive testing. The data rich test suite attains the ultimate goal of the creation of an analytic joint model that can be used to assess a multitude of configurations prior to entering the destructive test validation phase of any vehicle or geometry specific joint design.

## **NEW FLAT-H DESIGN APPROACH**

Unlike the first approach trial-and-error, test-only methodology, this new project plan includes modeling and analysis coupled with validation testing. It will save schedule time and provide good data correlation. Exploiting LS-DYNA simulation should yield the highest fidelity output in both 2D and 3D configurations yet available.

The modeling and analysis tasks to be completed include:

1. Construct models to recreate the results from previous ESTA testing.
2. Reconstruct models to recreate the results from previous WSTF testing.
3. Build models to evaluate enhanced designs
4. Perform static loads analysis using appropriate models.

The rationale for requesting both 2D and 3D models is that 2D evaluation is limited in certain areas. One rationale specifically concerns the assembly bolt response to firing. The 2D model treats the through bolt as a solid, unmovable beam, whereas the 3D model more accurately shows the flexure of the fastener. That bending equates to energy loss, which is then unavailable to break the joint. Both model configurations will enhance our understanding of how the joint behaves. The initial WSTF test cycle provided evidence of the distinction between the modeling techniques. Prior to those tests, only 2D analyses were performed. These did not provide the predictive results of energy loss due to component slippage. However, that failure phenomenon was validated via analysis utilizing a 3D model.

The ultimate goal is to create a model that can provide predictive results for varying joint geometries and configurations. The optimization process may illustrate that the functional margin can be increased significantly. The analytical results should show where energy is lost or misdirected. Once discovered, it can be mitigated. The outcome will be a configuration that routinely breaks the joint using minimized explosive

cord loads. That would provide a functional margin and the potential to lower the pyro shock transferred to the vehicle.

In mid-2016, the JSC Pyrotechnics Group will conduct tests at ESTA and WSTF. These tests are described in detail below.

The ESTA firings will be conducted in pairs, where two tests will be performed on one test article. The test article will have the primary and secondary expanding tube assemblies (XTAs) installed in the joint, but only one XTA will be functioned at a time. The first firing will show positive separation of the joint. The unfired XTA will then be functioned. The second test configuration is to show that the XTA, when fired and when not using the resultant energy to fracture the joint, remains contained within the joint half. This is a critical design feature needed to prevent the highly detrimental release of excess Foreign Object Debris (FOD). Two separate joint subscale article will be tested.

The Project will conduct the structural load testing. This will require the evaluation of joint sections in both tension and compression. The results should show a positive margin in either case and should also align with the LS-DYNA model predictions.

Following the JSC test campaign, the intent is to return to WSTF, where the Pyrotechnic group will conduct two additional test firings. The newly designed test articles will be configured exactly as they were for the ESTA tests. However, only one XTA will be functioned to effect separation. Eliminating the second XTA functioning precludes the potential of damaging expensive hardware test assets, due to excessive energy release.

#### **FUTURE FLAT-H FRANGIBLE JOINT TESTS**

In fall 2016, a series of functional tests at the WSTF will be scheduled to understand the complex separation dynamics of the new joint design. The WSTF test data will provide substantial detail regarding the effects, which will support enhanced analysis modeling verification. Several tests will be identified to sufficiently establish the feasibility of a new design. This test plan will accompany a Memorandum of Understanding (MOU) between the NASA Engineering and Safety Center (NESC), the JSC Pyrotechnics Group, and JSC Safety to leverage single-use instrumentation assets, including digital image correlation, photon Doppler velocimetry (PDV), and other cameras as needed, at WSTF.

#### **CONCLUSION**

The pyrotechnic industry relies upon single-lot control, quality assurance, and rigorous testing to develop confidence in SFT device designs. However, even in ideal situations where these practices are fully implemented, process escapes still occur during production. For frangible joints, which rely on subscale, instead of flight-like test articles, assurance in reliability diminishes. While SFT is the standard for pyrotechnic devices used in human-rated vehicles, such devices must become commercially available, just like the ZFT devices utilized on non-crewed vehicles.

The causes of frangible joint pyrotechnic failures have proven elusive. Both of the failure cases presented in this paper lack full explanations. Given the majority of failures have no determined root cause, there may be more problems lurking than testing has exposed.

Substantial effort has been invested to completely understand the failure modes and design sensitivities of frangible joint devices. Even with a comprehensive understanding of frangible joint technologies, human errors, such as improper installation, poor handling methods, deficient procedures, inadequate manufacturing methods, and substandard materials and faulty workmanship, are inevitably a risk to crew safety, and must be controlled and effects mitigated. The SFT frangible joint achieves redundancy and increased reliability, and crew safety through pyrotechnically failure tolerant design utilizing a single fracture plane.