Mars Science Laboratory
Heat Rejection System (HRS) Tubing Retractor

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Abstract—In support of the Cruise Stage form Entry Vehicle separation event for Mars Science Laboratory (MSL), two 3/8” aluminum tubes that are part of the Heat Rejection System (HRS) must be cut and retracted. Due to size and stiffness of the tubes to be retracted and the mass and volume constraints on MSL, the typical preloaded spring retraction mechanism was deemed not to be the ideal mechanism. Instead a pyrotechnic thruster was designed to perform the job. This thruster was baselined from the design details of an existing 5/8” cable cutter, but highly modified to meet the needs of the retraction device. Due to the added kinetic energy of an increased stroke, as compared to the cutter, a new attenuator to absorb the residual energy at the end of stroke had to be designed to keep the thruster housing from yielding. Volume constraints limited the size of the attenuator so the typical honeycomb crushable was not an option. Instead a collapsing thin walled tube design was analyzed, tested and implemented. Part of the analysis and testing was the process of correlating the difference between static and dynamic flow stresses of the attenuator material as well as the collapse modes of the cylinder walls. Upon completion of the preliminary attenuator design, proof of concept testing was done to validate the design of the retraction system such that the thruster has adequate capability to retract the HRS lines away from the Entry Vehicle. In that process the attenuator was also validated to absorb the majority of the thruster’s energy as not to yield any other components of the device.

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1 INTRODUCTION

It is embedded in the nature of exploratory spacecraft to constantly challenge the capabilities of the known and available technologies; when that does not suffice, new technology is created, most often evolving from other known technologies. The MSL spacecraft is no exception as it attempts to place more advanced and larger equipment on the surface of Mars. The Rover and spacecraft are far more massive and voluminous than their predecessors, and therefore every subsystem is challenged in finding ways to reduce mass and control volume while providing the same or better function as its ancestors. One subsystem highly sensitive to these changes is the separations subsystem. Its purpose is to ensure the safe separation of each Cruise, Entry, Descent, and Landing (CEDL) phase throughout the delivery of the MSL Rover to the Martian surface. With each increase of mass, the stronger nearly every separations mechanism must be – and closely following every increase of mass is an increase in volume, limiting the space in which the mechanisms operate. In the midst of the mass and volume of the MSL spacecraft, between the Cruse Stage and the Entry Vehicle, is a pyrotechnic actuator designed to perform its function immediately before the Cruise Stage is separated. The rationales behind its design are no different than those of the other mechanisms; however, prior to its conception no proven mechanism existed that had the capability to perform its function within the constraints imposed upon it.
2. THE PROBLEM

To appreciate the challenge involved in simply moving two 3/8” aluminum tubes four inches, an overview of the Cruise Stage – Entry Vehicle separation event is required:

As the MSL spacecraft approaches Mars, the Cruise Stage nears the end of its function and therefore must be jettisoned to prevent interference with critical atmospheric entry maneuvers. The “life support” for the Cruise Stage (power supply, functional commands, thermal control, etc.) is administered from within the Rover itself; such is the case with all MSL subsystems. Therefore the hardware providing this life support – electrical harness, Freon thermal lines, and Teflon purge lines - must be severed from the Entry Vehicle and cleared from the separation envelope representing the possible range of motion of the Entry Vehicle relative to the Cruise Stage.

The natural and most convenient way to configure the lines and cables is to route them in the direction of the Entry Vehicle’s separation motion, namely parallel to the z-axis. This is the configuration of all other separation interfaces on MSL, as well as the CS-EV interface on MSL’s predecessors. However, due to constraints driven by the mass and volume, this type of configuration was deemed severely problematic.

The lines were therefore routed through the side of the Launch Vehicle Adapter (LVA) of the Cruise Stage to a feed-through in the Parachute Cone of the Entry Vehicle. As Figure 2 illustrates, the geometric configuration of the LVA is a conical body encasing an inverted conical body, the Parachute Cone. Holes in each of these bodies provide access for the various lines to be fed through; the structures internal to the subsystems support the lines during launch and cruise operations.

With the configuration and geometry of the separation interface being driven by mass and volume constraints, the detailed concept and hardware required for the separation event is driven by the mechanical system requirements. The following lists the level four and five requirements for the lines passed between the Cruise Stage and Entry Vehicle:

**Level 4 Requirements:**

- **Bundle Management** — the separations system must be designed to cut the harness or HRS bundles to prevent material from being forced to the edges of the cutter blades.
- **Dual Fire Command** — the pyrotechnic devices must accept 2 separate fire commands.
- **Cable Retractor** — the separations hardware must extract the severed utility bundle from the cable cutters to eliminate drag forces between the two separating.
Level 5 Requirements:
- Minimum retraction of 3", target 4"
- Flight design with 100% functional margin
- Controlled retraction envelope
- No rebound of retracted hardware
- No yielding of structure (testability)

The first two level-four requirements, bundle management and dual fire command, are satisfied by a JPL heritage mechanism known as the "Mega Cutter" (shown in Figure 2) and is housed on the Entry Vehicle side of the system. The third level-four requirement gives the top-level description of the action the retraction mechanism must perform. The self-imposed level-five requirements further describe what must be accomplished based on spacecraft geometry, separation dynamics, standard design practices, and hardware testing needs.

The hardware inhabiting the two pass-thru areas are separated by function for reasons that will quickly become obvious. One location is designated for the electrical harness bundle and a 3/8" Teflon purge line. If bundled properly, the harness and purge line will require approximately 25 lbs to retract fully at the minimum cold temperature, which can be accomplished via a passive spring mechanism. The second pass-thru contains the Heat Rejection System (HRS) lines, which are two 3/8" aluminum tubes filled with Freon for the spacecraft's thermal regulation. This posed the greatest unknown to the CS-EV separation event.

The HRS employs two thermal lines—one hot and one cold—to regulate the heat generated by the Rover's power plant as well as diminishing the effects of the harsh space environment. Heated Freon in the tubes is pumped from the hot Rover to the coldest part of the Spacecraft, the Cruise Stage, where ten radiator panels are secured along the outer perimeter. The cold Freon is then pumped back to the Rover to complete the cycle. Prior to the separation event, when the lines are severed, the Freon is vented into space. The baseline material for the HRS lines is stainless steel, but in certain critical sections, the tubes can be converted to aluminum via inertia welded bi-metal fittings.

The dilemma presents itself when one begins to formulate ways for retracting the HRS lines 4" from the Entry Vehicle; these lines, and all other hardware, are rigidly secured in place to be able to withstand loads induced during launch. The only way to accomplish this is to apply enough force at a specific point on each line to yield the material; the force must also have a stroke great enough to apply the force over a length of 4". The first step with this approach is to exercise the option of using the aluminum tubes and determine the force required to yield them.

HRS test lines were formed in various shapes to determine which proved most efficient to yield given the geometric constraints and what that force value was. Each were placed in a test apparatus shown in Figure 3 representing the restraining points on the Cruise Stage and tested via an Instron machine, which measures force vs. deflection. The graph in Figure 4 plots data taken from the Instron machine of the chosen flight configuration. The tubes yield at approximately 55 lbs force with a high degree of repeatability. If a spring—unquestionably the preferred method—were to be implemented to provide the retracting force, its initial loaded force must be approximately 60 lbs.

As seen in the level five requirements, the retraction mechanism must provide a force two times greater (100% margin) than what is required. This is due to separations mechanisms being single-point failures for mission success. Additionally, good engineering practice has the proof of concept mechanism designed with 150% margin as it is early in the design stage. Thus, the design-to-retraction...
force increases to 150 lbs. (Figure 5 shows a spring for reference with 0% margin.) Also imposed by the level-five requirements is the target retraction distance of 4". Implementing a spring with 4" of stroke parallel to the retraction motion is impossible given the geometric configuration of the cruise stage. As illustrated in Figure 5, the ideal mechanism to satisfy this requirement is a bell-crank that provides the lever arm to deliver a full stroke.

![Figure 5 - Spring and Bell-Crank Configuration on Cruise Stage With 0% Margin](image)

In satisfying the level-five requirements, the optimal spring is made from titanium, weighs an estimated 2.5 Kg (5.51 lbs), and measures 7.25" in length. This spring, while plausible, completely breaks the mass budget for the mechanism and causes several possible clearance issues within the Cruise Stage structure.

### 3. THE SOLUTION

After an initial look at the basic requirements for the HRS line retractor – high force, high margin, small volume, low mass – one could quickly conclude that the spring-driven system is not adequate. Conversely, a pyrotechnic system does fulfill these requirements; however, the design, test, and qualification programs for a new pyrotechnic devise have proven highly expensive - so high that JPL has not attempted to develop a new pyrotechnic devise since the 1960s.

In a culture where redundancy is standard and single-point failures are only allowed when absolutely necessary, there is a strong tendency to stay with what is proven and trusted. And there exist several trusted pyrotechnic devices that have flown on mission after mission without failure. This hardware comes in various sizes and is used for a number of applications, and one, in particular, coincides quite well with the needs of the developing HRS retraction system.

The 5/8" cable cutter is one of JPL’s well trusted pyrotechnic devices with a strong history in flight missions. With a housing diameter of approximately 1.25" inches, the Cutter maintains a small enough of profile it fit easily in the designated area for the HRS retraction system. The 5/8" cable cutter is powered by the NASA Standard Initiator (NSI), which is screwed into one end of the cylindrical housing – the other end being a piston/blade and anvil. When the NSI ignites, the rapid gas expansion within the chamber pushes the piston with a sharp wedge on the far side through whatever material is to be cut and ultimately imbeds it into a steel anvil to absorb the residual energy.

Available data taken from a booster bomb test indicates the NSI provides an initial force of 800 lbs. The powder in the NSI is designed to burn very quickly to create rapid gas expansion; the force exhibited will be a near-impulse; as the gas cools rapidly the thrust diminishes exponentially. While this is not an ideal booster to deliver a continued thrust over four inches, the initial impulse of 800 lbs far exceeds the design-to force of 150 lbs, and create enough energy for the piston to provide the required stroke. Additionally, the prospect of modifying a proven and flown devise to solve the problem eliminates several roadblocks impeding the development of a pyrotechnic solution.

Modification of the 5/8" cable cutter is required for it to be suitable to retract the aluminum tubes. The most important strategy to modifying the cutter is to do so without compromising its integrity as a proven flight devise. This is accomplished by dividing the assembly by function:

- **Booster** – the NSI and it's interface with the housing, the chamber where the combustion takes place, and the piston & o-ring assembly
- **Cutter** – the blade that is integrated with the piston, the anvil that absorbs the blade’s impact, and the cap threaded into the housing to hold the anvil in place.

The principal concept is to change the booster end of the assembly as little as possible to maintain the integrity of the pyrotechnic design while modifying the “cutter” end to perform the function required. In essence, the blade is converted to an actuator with a threaded end that an assembly is attached to that grips the two HRS tubes. The housing is elongated by approximately three inches, as is the actuator, to deliver a full four inches of stroke to the system. This design concept will allow the HRS lines be retracted the full distance by a device with a mass of approximately 0.5 kg.

### 4. THE HARDWARE

**Booster**

A single change to the “booster” segment of the assembly was made for clearance in the flight configuration by moving the NSI from the end of the housing ninety degrees
to the side. The chamber volume and piston geometry remain unchanged.

**Thruster**

Significant changes are required to make the opposite end functional. What was a blade is now an integrated piston and four inch thruster, the housing has grown to accommodate the thruster. The anvil has been replaced by an attenuator to absorb the energy of the piston (to be discussed further). The threaded cap has been altered with a hole for the thruster to clear. The end of the thruster is threaded where a collar screws onto to provide a clamping point for the tube grip to attach. This tube grip is designed specifically for this application, but is the only part of the assembly that cannot be applied for another use. This assembly is designed to be easily adapted for other purposes.

![Figure 6 - Thruster Concept Cross-Section](image)

**Attenuator**

Data and analysis of the NSI booster indicate that not only with the piston yield the lines as required, but will also deliver enough energy at the end of stroke to severely damage the thruster housing and cap. With a stroke of four inches, the impact energy of the piston on the cap was calculated to exceed 2,500 lbf-in. With the main interest of testability and reuse of test articles, some type of attenuator was required.

The intent of the attenuator was to be a thin-walled steel cylinder that attaches to the inside of the cap and the end of the housing barrel. The cylinder would fit concentrically around the thruster push rod to allow it to stroke freely until the piston made contact with it. The attenuator would then buckle uniformly to absorb energy from the system at a constant rate. The maximum force induced on the thruster housing is the buckling force of the attenuator which must be reacted by the cap and barrel. To properly size the attenuator, the structural limit of the cap and housing was analyzed to be approximately 4,500 lbf after factoring in standard safety multipliers. This became the maximum force required to buckle the attenuator.

The attenuator design was initially based from theories and equations from "Structural Impact" by Norman Jones [1], which mainly reveals conclusions on buckling columns based on specific test data. The primary lesson taken from this text is that all variables – material, diameter, thickness, dynamic vs. static stress, end conditions, etc. – contribute differently, and somewhat unpredictably, in separate combinations. Therefore, the least complicated way to design a buckling column for a specific purpose it to run tests off of initial information available, analyze the data, and re-design based on new conclusions. This iterative process ultimately involved using an apparatus with the same internal geometry at the thruster barrel, cap, and piston. This created a “contained” buckling condition where the column could not flow freely inward or outward without contacting a surface. Figure 7 shows buckled attenuators of varying wall thickness from both contained and uncontained tests.

![Figure 7 - Attenuator Test Iterations](image)

The “uncontained” test series was performed to validate the assumptions made from the “Structural Impact” test cases; buckling forces were three times higher than predicted, and therefore the flight-like contained test series took shape. The force vs. distance data taken from the latter test series is shown in Figure 8. The red dashed line represents the maximum allocable buckling force calculated through structural analysis. This number is half the value mentioned.
above because the value gathered from analysis was for static loading. The velocity of the piton clearly indicates a case of dynamic loading. In his book, Jones concludes that distresses could increase the bucking force by a factor of two; the validation of this conclusion was to occur during pyrotechnic testing of the device.

From linear interpolation of this data, a column with wall thickness of 0.016" requires a mean static force of 1345 lbf and dynamic force of 2690 lbf to buckle. In deciding the length (L) of the attenuator, Jones assumes:

\[ L = 1.3 \frac{\text{Energy}}{F_{\text{dyn}}} \]

In the case of a 0.016" thick column, the attenuator must be 1.2". Also observed in the test data is a slight spike in force during the initial buckle of the column, while this spike is relatives close to the peak levels of the buckle, it is unknown what the initial spike is in a dynamic scenario. Therefore, the decision was made to pre-buckle all attenuators to past the initial spike prior to the thruster test campaign.

5. The Test Program

To ensure the concept is viable and to characterize events that are not easily quantifiable, a series of pyrotechnic tests is required. The following test program was performed, each test to achieve specific objectives:

- **Mass Test**: The thruster pushes a 100 lb mass along a rail assumed to be frictionless

Objective: Characterize the energy provided by the thruster and calculate the initial force.

- **Structural Integrity Test**: 1) Fire the thruster with no mass attached and a 120% NSI booster. 2) Fire the thruster with the piston locked and unable to stroke and a 120% NSI booster.

Objective: Demonstrate the assembly housing and cap has the strength withstand a misfire under worst-case conditions.

- **Nominal Retraction Test**: 1) Test the devise in a flight-like configuration. 2) Fire the "Mega-cutter" to sever the HRS lines prior to retracting.

Objectives: 1) Demonstrate the thruster can retract the HRS lines as intended. 2) Characterize the motion of the HRS lines during retraction. 3) Demonstrate the shear pin is not prematurely severed as the "Megacutter" severs the HRS lines.

- **Margin Retraction Test**: Repeat the Nominal Retraction Test using HRS lines that have three times the stiffness if the nominal lines.

Objectives: Demonstrate the system provides adequate energy to have 100% margin in launch configuration.

### Mass Test

Three test runs were performed, all successful. Data was gathered via high-speed photography as all other instrumentation - string potentiometer and accelerometer - were damaged from the pyro-shock. From the data gathered, the following information was calculated:

- Time for full stroke < 1/100 s
- Velocity of mass at end of stroke > 7.5 ft/s
- Energy delivered from system > 1000 lbf-in
- Initial force from booster > 950 lbf

![Figure 8 - Static Crush Force (lbf) vs. Distance (in)](image-url)
The force calculation indicates that the thruster delivers of seventeen times the force required to yield the HRS lines and an attenuator is unquestionably needed. However, after examining the attenuator, no buckling was observed other than the intentional pre-buckling. This was either due to the 100 lb mass absorbing much of the energy, or the attenuator prediction being far off the mark.

Nominal Retraction Tests

Flight-like HRS lines were manufactured and places in the test fixture with their ends fed through the “Megacutter” orifice. The first test was a single fire of the cutter to sever the HRS lines. This is a high-energy pyrotechnic devise and in previous tests of the cutter, HRS lines have been known to eject from the test fixture, escaping their restraints and hit the ceiling. The main concern was the energy from the cutter will cause the HRS lines to move forward, prematurely shearing the shear pin in the cap. The test proved to be benign as the energy was absorbed by the bends and field joints in the HRS lines.

Structural Integrity Tests

In this case, an uneventful test is a successful one. The free-fire test provided little excitement with only a small amount of yielding at the base thread of the housing where the cap screws on – this was expected. Additionally, the attenuator had been crushed fully indicating the design for the actual application was somewhere between un-buckled and completely buckled with yielding of the structure. Again, the only numerical data was collected via high-speed photography:

- Time for full stroke > 1/500 s

Like the “free fire” test, the “lock shut” test was also uneventful. No data was to be gathered, no attenuator was required, and no damage to the assembly was observed.

Margin Retraction Tests

As discussed earlier, as self imposed requirement at JPL for such mechanism is a demonstration of a minimum margin of 100% in the flight configuration. At early design stages it is good engineering practice to design to at least 150% margin. Confident in the energy delivered by the NSI, three
200% tests were conducted; as the mass test indicated, there was over 1600% margin in the system.

The test perfumed as well as the nominal retraction with the attenuator buckling approximately 80%, an amount ideal for the flight retraction. The HRS line motion was uniform and high-speed photography captured the following data:

- Length of stroke: 3.5” to 4”
- Time for full stroke < 1/200 s

The full retraction time slowed less than 1/500 s after a 200% load increase.

**Attenuator**

Upon completion of the test campaign, the attenuator were removed from the test articles and compared to one another, as illustrated in Figure 12. The attenuator from the nominal HRS retraction appears to be a complete buckle indicating the final sizing calculations were quite close. Additionally, no yielding of the structure was observed, unlike the “free fire” test. However, there is no easy way to answer the question of the amount of margin left to protect the hardware. Margin can be physically observed in the “Margin HRS” sample from Figure 12 in that there is an unbuckled section remaining. The decision was therefore made to increase the length of the attenuator by 0.25” while keeping all other parameter the same. Further schedules acceptance testing will verify this final design.

![Figure 12 - Attenuator Comparison](image)

6. CONCLUSIONS

The test campaign to prove the concept was an outright success with no failures observed. This verifies the adaptability of the 5/8” cable cutter. The basic design of the modified piston of the thruster is nonspecific enough where it can be adapted for a number of future applications. As these applications require different levels of thrust and stroke, the basic hardware can remain unchanged as the attenuator can be designed to “tune” the mechanism for each application. Even in the infancy of its concept, the HRS retractor was being studied for other needs on the MSL spacecraft. Surely other missions will find a valuable use for it as well.

**REFERENCES**

[1] Norman Jones, Structural Impact, Cambridge University Press, 1989.

**BIOGRAPHY**

**Eric Roberts** received his BS in Aerospace Engineering from the University of Michigan in 2001 and earned an MBA from UCLA’s Anderson School of Management in 2005. His NASA experience began as a Raytheon contractor for support engineering on MSL. Eric has subsequently formed his own independent contracting company, Flight Hardware Engineering, Inc., and is currently contracting directly to JPL for the remainder of the Mars Science Laboratory program.

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