# THE LIFELINE: BEAGLE2 UMBILICAL CONNECTOR

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## ABSTRACT

This paper details the design and development process for the umbilical connector for the Beagle2 Mars Lander. The umbilical connector provides electrical power and vital telemetry from Mars Express to Beagle2. A mated pair of MIL-DTL-38999 Series IV connectors using standard 15-35 arrangement was extensively modified to meet the technical challenges of the mission, while accommodating the mechanical interface of the two spacecraft.

In the latter portion of this study, theoretical calculation of ejection mechanism was utilized to predict the umbilical connector separation force and time. The predicted values were then compared with the experimental data obtained and found to correlate very well. In addition, the empirical tests also demonstrated excellent reliability of the connector after short and long-term exposure to thermal vacuum condition. Overall, the test results proved that the design of this umbilical connector was very robust and met all technical requirements.

## INTRODUCTION

Currently racing towards its encounter with the red planet, Mars Express marks a new era in planetary exploration for the European Space Agency (ESA). A mission whose exploratory and scientific contributions are not only ambitious, but one that represents ESA's first attempt at its "flexible" low-cost approach at organizing and building a series of planetary exploration missions.

Along for the ride on this historic trip is a small Mars Lander dubbed "Beagle2." The result of a British consortium of universities, research support teams and aerospace industry, Beagle2 will analyze the Martian atmosphere and soil for evidence of life forms. The name Beagle2 was selected by the team to commemorate the sailing vessel 'Beagle' that carried Charles Darwin on his epic voyage. Beagle2 voyage will be no less challenging than its name sake, as the spacecraft will be required to perform a series of "high-risk" operations prior to reaching the surface of the red planet. The lifeline or umbilical that will be use for communicating with and monitoring each of these events during the launch and cruise phases of the mission, will be the Beagle2 Umbilical Connector.

The Umbilical Connector was designed to mount on the Spin Up and Ejection Mechanism (SUEM) and provide electrical power and signals. The SUEM itself provides structural support between Beagle2 and Mars Express during launch and throughout its journey to Mars. On arriving at the pre-determined ejection point, pyrotechnic protractors mounted within the SUEM release mechanism are fired. This action has two functions, one to release the umbilical connector and the second to release the Beagle2 Lander. The Lander ejection is achieved under the action of a release spring that forces the Mars Lander to spin helically and eject.

## TECHNICAL REQUIREMENTS

Without any means of propulsion, Beagle2 must "hitch" a ride on Mars Express orbiter to make its voyage to the red planet. Thus, the Beagle2 team was tasked with the challenge of forming a symbiotic relationship between the two spacecraft. This relationship would include (i) a mechanical means for joining the two spacecraft, (ii) an umbilical connection that would provide power and signal to Beagle2 during its journey; and (iii) a method for separating the Beagle2 lander from the Mars Express.

Much has been written about the Spin Up and Eject Mechanism (SUEM), designed and built by Insys of Ampthill, that will attach Beagle2 to Mars Express during launch and cruise phases, and release Beagle2 on its final journey to the Martian surface. The lesser known umbilical connection between the two spacecrafts serves an important role of transmitting power and signals between the two spacecrafts. In addition, before Beagle2 can be spun up and ejected, this connection between the two spacecraft must first be severed to prevent binding or tip off of the Lander.

During preliminary design of this "piggy-back" ride to Mars, the Beagle2 team originally envisioned the use of a miniature D-Sub connector as its umbilical connection between Beagle2 and Mars Express. A low voltage system requiring less than 40 pins for the conveyance of power and signal between the two spacecraft, the D-Sub seemed to offer the benefits of size, weight and cost. Furthermore, the minimal force required to separate the connector pair would be ideal during spin-up and ejection. However, as the mission requirements began to evolve, the team quickly recognized the inadequacies of a D-Sub connector. The shortcomings included shock, vibration and linear travel (positioning) during launch. In addition, the critical issues of cold welding, ingress of organic or inorganic particulate matter, and plasma bombardment during entry and final descent forced the team to search for an alternative interconnect that will address all these concerns.

In their initial search for an off-the-shelf solution, the Beagle2 team identified G&H Technology (G&H) as a potential supplier for its extensive experience in the design and manufacture of various space and launch interconnects. Inquires were made on several standard model connectors that incorporated low-force separations, thermal and electrical deadfacing, and electrically initiated separations. However, the chosen product was either too large, lacked one of the required features, or was simply cost prohibitive. After an exhaustive search, the team concluded that an off-the-shelf solution was impractical and a custom interconnect would be required in order to meet all of the mission requirements. However, this would prove to be a challenge as neither time nor funding for development of such a connector was a part of the team's initial plan. Furthermore, the connector would now have to be constructed to fit within the structures of the two spacecraft and the SUEM, whose designs were already well established.

PRODUCT BASELINE

Before focusing efforts on the development of a special interconnect that would meet all electrical and environmental requirements of Beagle2, the team would require a "product definition." The general requirements for the interconnect was defined as follows:

*"A single umbilical connector shall provide 37 (thirty-seven) electrical connections with a pin size of 22AWG. The wire terminations to the contacts in each half of the connector shall be made by soldering or crimping, crimping is the preferred method. In the mated configuration the connector shells shall provide an effective EMC screen.*

*The connector shall incorporate sealing to prevent the ingress of particles greater than 0.3microns in size to the inside of Beagle2."*

With this definition, a circular interconnect approach based on the MIL-DTL-38999 series of connectors was selected. The 15-35 insert arrangement per MIL-STD-1560 with 37 22-AWG, crimp-style contacts (see Figure 1) was identified to best meet the design criteria.

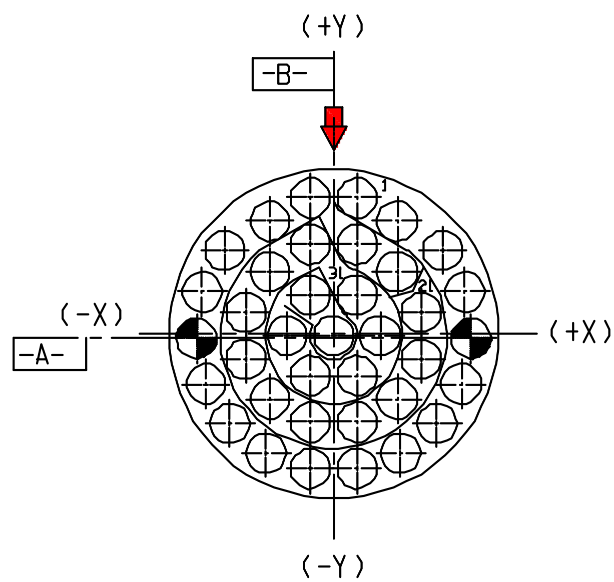


Figure 1. 15-35 Arrangement I/A/W MIL-STD-1560

Since the connector needed the ability to separate prior to full "spin-up and ejection" of Beagle2, a standard MIL-DTL-38999 connector pair could not be used since the basic design feature of a MIL-DTL-38999 connector requires positive mating and locking of the two connector halves. An additional separation mechanism had to be developed and added to the connector. As such, the

G&H Model 1179 "Low-Imparted Impulse Blind-Mate Connector", originally developed for the Taurus and Pegasus launch vehicles, was established as the baseline. This structurally mounted and retained connector pair provides the blind-mating of payloads to their bus or launch platform and a zero separation force during deployment (see Figure 2).

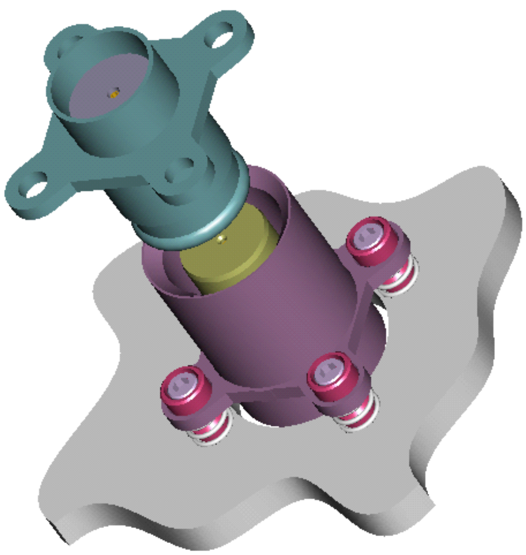

Figure 2. G&H Model 1179 Low-Imparted Impulse Connector

Besides the use of a standard MIL-DTL-38999 insert arrangement, the G&H Model 1179 connector also included the following key features:

- Anti-binding and roll-off interface
- Adjustable angular misalignment in all axis
- Lightweight aluminum alloy shell
- Withstand high shock and vibration levels
- 360° EMI protection
- Low-force contacts and spring-assisted separation for zero-force separation

This preliminary definition and heritage approach formed the basis of the initial solution for the Beagle2 Umbilical Connector.

## DESIGN CHALLENGES

As the team began to refine the connector design requirements, it became apparent that the preliminary specification did not anticipate several difficult challenges.

During the search for an off-the-shelf solution, the Beagle2 team continued forward with its design of an aero structure for Beagle2 and its SUEM interface with the Mars Express. Upon reviewing the G&H Model 1179 solution, it became apparent to the team that integrating any connector into the available space between the two spacecraft would be a serious challenge. The existence of hard-mounting points for both the connector plug and receptacle was far and few. This was caused by the presence of instruments tightly packed and mounted on the inner shells of both Mars Express and Beagle2. Furthermore, it was obvious that mating and demating the connector would be impaired by the fact that the SUEM introduces a helical rotation of the Beagle2 Lander during installation and ejection. Since a typical circular interconnect requires an axial path for mating and demating, the rotation created by the SUEM would clearly inhibit the normal operation of the connectors.

The non-axial release of Beagle2 created by the SUEM requires that the two connector halves be completely separated prior to spin-up and ejection. As such, an electrically initiated separation device that could be activated prior to spin-up and ejection was suggested. Although the incorporation of such a device would solve the rotation predicament, it simultaneously posed two additional problems: envelope and power. The growth in both volume and mass of the connector is of paramount concern for obvious reason. In addition, there was insufficient power source available to initiate such as device. This left the team with the only option of a mechanical means of separating the connector halves prior to the spin-up and ejection of Beagle2.

## FINALIZATION OF DESIGN

With a better understanding of the integration process and SUEM structure, the design of the connector and its mounting location could now be finalized. As such, a preliminary concept for a mechanically initiated connector was developed and presented during a design review. It employed a spring-loaded plug housing that was mated and held in place by a yoke. Actuation occurred when the yoke was physical removed and the plug housing retracted itself from the mating receptacle (see Figure 3). At first glance, a spring-loaded plug assembly seemed to offer a simple means of separating the two connector halves. However, it was noted that the yoke provided little restraint and may be a single-point failure due to shock and vibration. In addition, the yoke had to be tied to one of the pyrotechnic protractors for release.

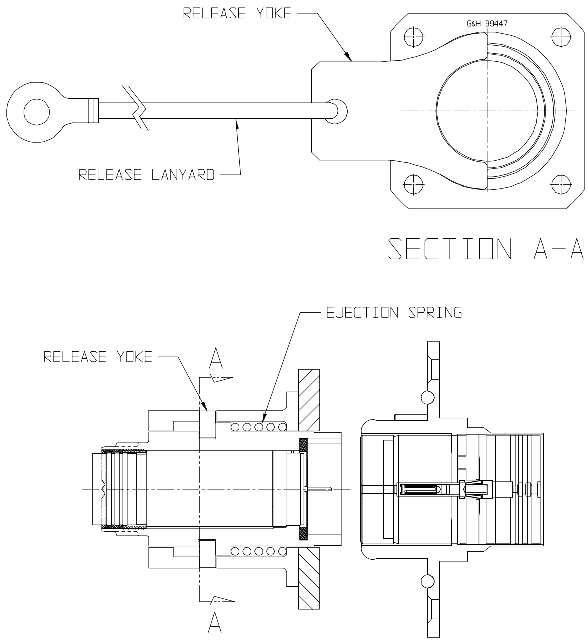


Figure 3.  Initial concept of a retractable umbilical connector

A retaining fork offered greater capability in withstanding the shock and vibration of launch, thus providing a more reliable means of positive retention. However, as all movement within the SUEM was radial and not axial, it would require the fork to move in a radial direction.  The original plan of using one of the SUEM's pyrotechnic protractors to directly initiate separation of the connector had to be abandoned as it might adversely affect the actuation of the SUEM.  It was decided to tie the release fork directly into the SUEM's structure itself as show in Figure 4.  This meant that both the SUEM rotation and connector separation would commence simultaneously.  The total time required to complete this event from initiation to the start of spin up and ejection was estimated to be 120 milliseconds.  In addition, the force available for retracting the fork was estimated to be 100 N.  Allowing for safety margins, this would leave the umbilical connector with only about 12 milliseconds to fully separate in order to prevent binding or tip-off during spin up and ejection of Beagle2.

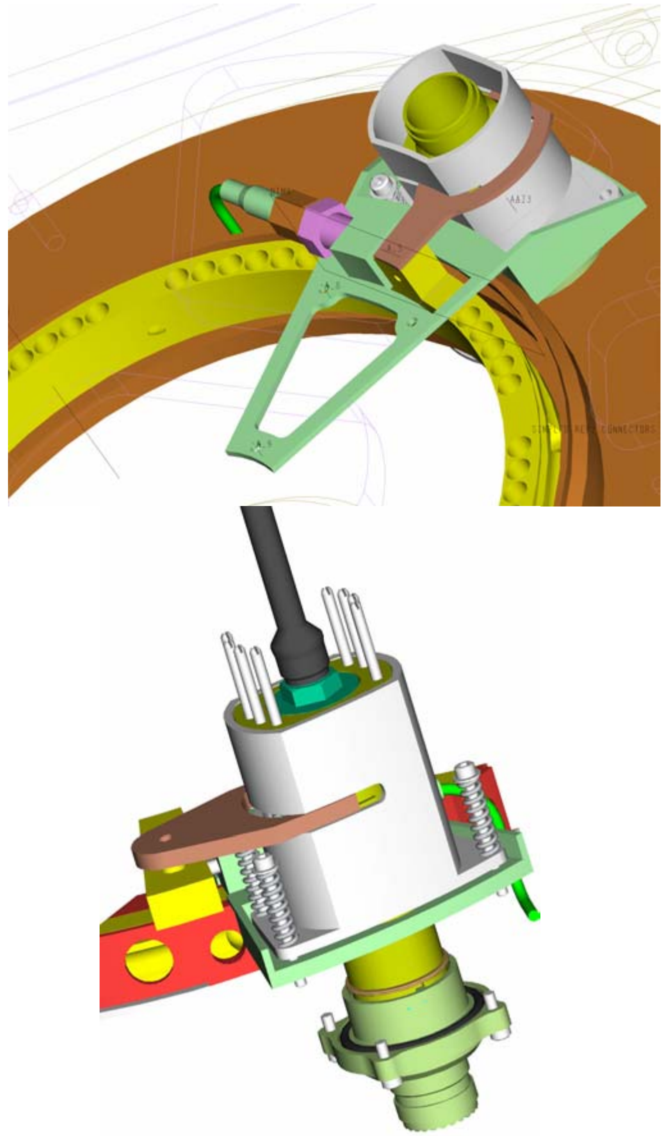

Figure 4.  Umbilical connector location relative to the SUEM

To meet the aforementioned requirements, eight heavy-duty coil springs were added within the plug housing to provide the force and stroke necessary to instantaneously separate the connector halves.  Furthermore, the sliding friction between the fork and the connector plug was minimized by the use of a solid dry lubricant (molybdenum disulphide) to meet the force requirement. To prevent chattering during vibration, four spring-loaded adjustment screws for mounting the plug housing was added to the SUEM mounting bracket (see Figures 5 and 6).  These springs provided a pre-load on the plug and compensated for any axial movement in the system. Finally, the plug was designed with an integral backshell to provide both strain relief and a means for termination of the shielding.

The connector receptacle would be directly mounted to the Beagle2 structure. An o-ring was incorporated to provide sealing in addition to the flight-proven deadfacing to meet the mission requirement of preventing ingress of any foreign particulate and thermal and electrical protection during entry and final descent. This form of deadfacing had successfully flown on such launch vehicles as Delta III, Atlas V, and National Missile Defense Interceptor.

Figure 5. Umbilical connector plug and receptacle, respectively

Figure 6. Actual Beagle2 umbilical connector

## ANALYTICAL AND EXPERIMENTAL RESULTS

The release of the umbilical connector was critical to SUEM spin and ejection operations with just a small window for success. The predicted events in the release sequence were summarized below:

| | |
|---|---|
| T = 0 second | Protractor initiation and start of rotation of locking ring. Umbilical locking clamp starts to release |
| T = 2 ms | Release mechanism locking shear wire breaks |
| T = 5 ms | Locking balls start to release ejection spring and umbilical locking clamp is released |
| T = 7 ms | Locking balls fully released and Lander ejection commences its ejection and spin up |
| T = 12 ms | Umbilical connector fully released |
| T = ~120 ms | Full ejection of Beagle2 Mars Lander |

The umbilical connector separation dynamics were modeled to determine worst-case release times and margins of safety. Using published data, the theoretical friction loss and force available were calculated and plotted as a function of separation distance in Figure 7.

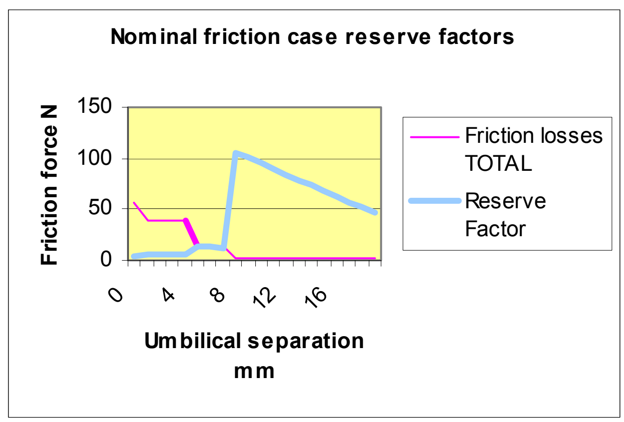


Figure 7. Nominal Friction Reserve factors

The objective was to have a minimum safety margin of 3 over the worst predicted friction losses, and the analysis showed a factor of about 3.8. Under these same conditions, the nominal separation time was 5 milliseconds to clear the mechanical envelope of the separating halves of the umbilical connector. This correlation was demonstrated in Figure 8. Additional benefits of this design were also noted at this time. Since the umbilical connector was spring-mounted to the SUEM, this enabled some misalignment capability during integration. This would also serve to accommodate any sway during ejection.

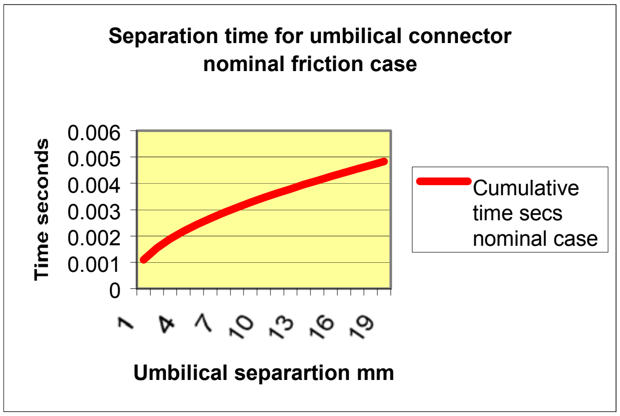


Figure 8. Separation time for nominal friction

Although the umbilical connector was a derivative of devices that had been used in previous space applications, no data was available that illustrated performance after long-term thermal vacuum exposure. In order to demonstrate this, a connector pair was taken from the flight connector batch to carry out a number of release tests under thermal vacuum before subjecting to a long-term thermal vacuum test.

One major concern was the tribological performance on some of the components. The release fork was fabricated from aluminum alloy and hard anodized to provide some wear resistance. It was then coated with a solid dry lubricant per MIL-L-46010. The mating surface of the housing was nickel plated and similarly dry-filmed. The electrical contact pins and sockets are gold plated to MIL-G-45204 over a beryllium copper substrate. The main concern was the possibility of cold welding of similar surfaces after 6 months in space.

The tests were conducted at the European Space Tribology Laboratory (ESTL). ESTL designed a special test fixture to simulate the release of the fork at a speed of about 3.5 m/s. The test fixture used an electrically operated solenoid to release spring energy that acted on the fork to release the umbilical connector at the required speed. A photo diode was used to record the separation time and load cells were used to measure the release clamp activation force. Provision was also made to enable electrical resistance checks to verify continuity of the contacting pins and sockets. The test fixture and set up is shown below in Figure 9.

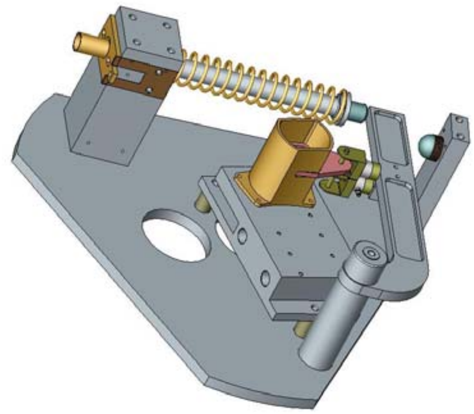

Figure 9. Test setup with the umbilical connector

One umbilical connector was selected from the flight unit lot and a total of 15 separation tests were conducted. The first test was performed in ambient air as a datum point. This was followed by 14 additional release tests in vacuum (< 1.5 x $10^{-8}$ torr) at a temperature of -40 °C. The final test was conducted after 6-month continuous exposure to vacuum. The connector was then vacuum-baked in its de-mated condition at 125 °C for 72 hours prior to the vacuum release tests to ensure the worst condition for separation by out-gassing volatiles that might otherwise act as a boundary lubricant.

For the long term vacuum test, the umbilical connector was cycled 10 times between +30 °C and -40 °C before final soak at -40 °C for the duration of the 6-month test

During vacuum test, circuit continuity was also monitored by connecting all circuits in a 'daisy chain' arrangement. The result is tabulated in Table 1. As shown, the electrical resistance was not affected by long-term vacuum exposure or repeated operation of the umbilical connector.

| Test | Resistance (Ohm) | Test | Resistance (Ohm) |
|---|---|---|---|
| Air | 0.452 | Vac 8 | 0.409 |
| Vac 1 | 0.415 | Vac 9 | 0.406 |
| Vac 2 | 0.406 | Vac 10 | 0.416 |
| Vac 3 | 0.415 | Vac 11 | 0.407 |
| Vac 4 | 0.412 | Vac 12 | 0.400 |
| Vac 5 | 0.414 | Vac 13 | 0.403 |
| Vac 6 | 0.418 | Vac 14 | 0.402 |
| Vac 7 | 0.403 | Vac 15 | 0.409 |

Table 1. Connector electrical resistance

Separation time and force for the umbilical connectors were also recorded and shown in Table 2 and Figure 11. Overall, the connector separation consistently meets the target time frame and force limit.

| **Test** | **Air** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
|---|---|---|---|---|---|---|---|---|
| Release clamp time | 4.9 | 4.2 | 4.5 | 4.6 | 4.5 | 4.6 | 4.5 | 4.5 |
| Electrical separation time | 7.4 | 7.9 | 7.9 | 6.9 | 7.5 | 7.5 | 7.7 | 7.5 |
| Umbilical separation time | 11.7 | 12.0 | 12.1 | 11.7 | 11.9 | 12.2 | 12.1 | 12.1 |
| **Test** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** |
| Release clamp time | 4.0 | 4.5 | 4.5 | 4.4 | 4.3 | 4.4 | 4.5 | 4.3 |
| Electrical separation time | 7.5 | 7.6 | 7.5 | 7.5 | 7.2 | 7.5 | 7.1 | 7.4 |
| Umbilical separation time | 12.4 | 12.4 | 12.4 | 12.0 | 11.7 | 12.5 | 12.0 | 12.4 |

Table 2. Umbilical connector separation time (milliseconds from T = 0)

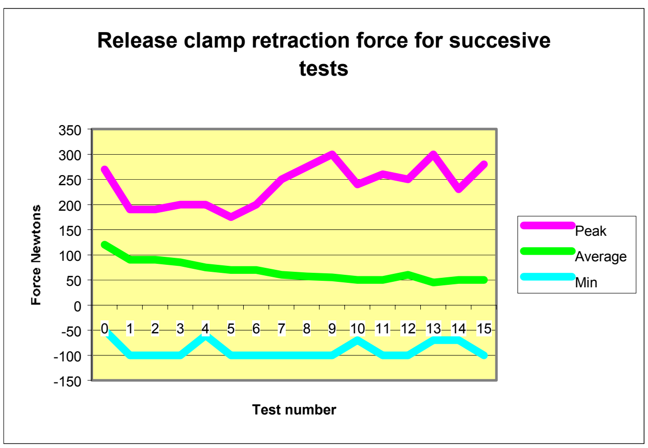


Figure 10. Release clamp retraction force during successive releases

It can be seen from Figure 10 that the release force was slightly higher in air than the first vacuum test number. This was probably due to out-gassing of water from the solid dry lubricant. There was also an emerging trend where the peak force was fairly constant over the first 5 or 6 releases and then started to increase. This could be attributed to wear debris. The average force, on the other hand, became asymptotic at 50 N, half of the predicted retraction force of 100 N. The peak forces were larger than anticipated but still well within the 1900 N of total retraction force available from the protractors.

A final visual examination of the contact surfaces of the release clamp showed evidence of normal wear. This was expected and not to be of concern to the functioning of the actual flight connector that would have at most 3 releases prior to launch.

## CONCLUSION

A total of 92 successful umbilical releases were eventually made during the course of this program. The actual umbilical separation showed good correlation with the dynamic model predictions with release times of approximately 8 ms. This release time was also examined in the context of the Beagle2 rotation after this elapsed time and was found to be of an inconsequential amount and easily accommodated by the spring mounted preload system. In addition, the electrical tests conducted prior to each release also showed good repeatability.

In general, the Beagle2 Umbilical Connector functioned as designed. Empirical tests and theoretical calculations gave the team extremely high confidence for a successful release from Mars Express at its rendezvous point with Mars in December 2003.

## ACKNOWLEDGEMENTS


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We would like to acknowledge the support of Martin-Baker Aircraft and Insys, Ltd. for their assistance in defining the connector requirements and integrating it into the structure of both spacecraft and the SUEM.

Finally, we would also like to acknowledge the testing of the Umbilical Connector carried out by the European Space Tribology Laboratory (ESTL); in particular the valuable support and advice given by Dr. Emyr Roberts and Richard Watters during the course of this program.


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