BEAGLE 2 - A RETROSPECTIVE LOOK AT THE BEAGLE 2 LANDER MECHANISMS FOLLOWING EVIDENCE OF SUCCESSFUL DEPLOYMENT

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ABSTRACT

Beagle 2 was a British led Mars lander that was transported to Mars by the European Space Agency's 2003 Mars Express orbiter. With extreme requirements on mass and available space the lander was equipped with an impressive array of instruments aimed at detecting the presence of life, past or present, on or below the surface of Mars, as well as studying the Martian environment. To support these instruments the engineers at Airbus, Stevenage developed a collection of compact lightweight mechanisms to deploy the lander to its on-surface configuration and then undertake the planned experiments. These mechanisms, together with the instruments were all tightly packed within the 600mm diameter lander that weighed only 33.2 kg.

This paper revisits the design of the mechanisms and examines in particular how successful the mission was from the mechanism perspective and how close it came to fulfilling the prime mission objective.

Keywords: Beagle 2, Solar Array Hinge Mechanism, Lid Deployment Mechanism, Robotic Arm, Instrument Arm, Lightweight Clamp band.

1 INTRODUCTION

1.1 Background

On 19th December 2003 Beagle 2 was spun-up and ejected from Mars Express on a ballistic trajectory towards Mars. It was due to land in the Isidis Planitia basin 6 days later on Christmas day, deploy itself and make contact with Earth via one of the spacecraft orbiting the red planet. No signal was received and Beagle 2 was officially declared lost on 6th February 2004 after a number of unsuccessful attempts to make contact.

In 2015 high resolution images from NASA's Mars Reconnaissance Orbiter of the targeted landing area coupled with new methods of image post-processing involving stacking images to achieve improvements in the resolution of the combined images identified an artefact that has subsequently been accepted as the partially deployed Beagle 2 lander with nearby objects being identified as the ejected heat shield, main parachute, rear cover and pilot chute used during the controlled descent and landing sequence.

Interpretation of the latest MRO images point to a partially deployed lander with at least 2 of the 4 solar panels fully deployed. In order for the lander to have progressed to a configuration with some solar panels fully deployed the Entry, Descent and Landing sequence and deployment from the air bags must all have executed correctly. For the lander to have then progressed to a point where some, if not all, of the solar panels deployed then the initial operational sequence must also have been correctly initiated and partially executed with the mechanisms involved operating correctly or partially. Failure to fully deploy all 4 of the Solar Array panel would have obscured the patch antenna mounted in the lid of the lander preventing all communications.

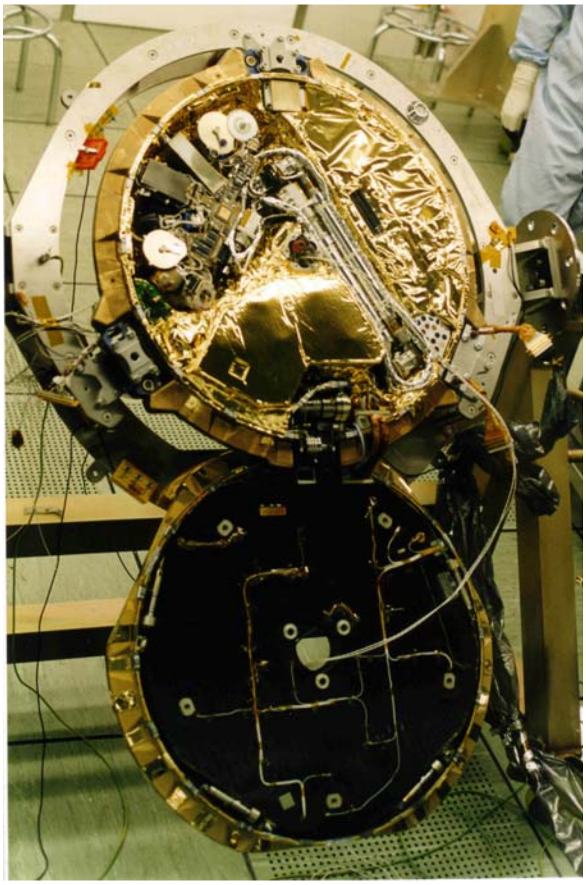

Figure 1: Beagle 2 Prior to Closure

1.2 Beagle 2 Overview

Beagle 2 lander was a lightweight lander consisting of 2 shallow bowl-shaped halves incorporating a number of compact, lightweight, bespoke mechanisms that were all designed, developed and qualified by Airbus under the scope of the Beagle 2 programme. These included a lightweight clamp-band - used to secure the 2 halves of the lander together; a main hinge - used to deploy the lid and self-right the lander, opening it up to allow experiments to be performed and 4 solar array panel hinges - used to deploy the solar panels, and a 5 degree-of-freedom robotic arm - to deploy instruments onto the surface. This paper revisits the design of these principle mechanisms and re-evaluates the decisions made during the design process with regards to the robustness of the design; paying particular attention to the decision not to incorporate any redundancy into the designs because of the severe constraints on accommodation space available, the need to minimise mass and conform to strict power limitation requirements.

A review of the mass summary file shows that every single item was fully accounted for and savings of a few grams were considered as potential mass savings.

2 BEAGLE 2 MECHANISMS

2.1 Top Level Summary

As mentioned above The Beagle 2 lander had 4 distinct mechanisms in the final stages of the landing sequence that were designed, developed and qualified specifically for the mission.

The mechanisms were:

a) Clamp Band Assembly (CBA)
b) Main Hinge Deployment Mechanism (MHDM)
c) Solar Array Release Devices
d) Solar Array Hinge Mechanism (SAHM)
e) Robotic or Instrument Arm

Because of the severe constraints on mass and volume each of these mechanisms were, in effect, potential single point failures; there was no redundancy built into any part of the mechanism and they all had to function correctly, in sequence, for the mission to succeed.

2.2 Individual Mechanisms Overview

2.2.1 Clamp Band Assembly

The CBA consisted of 3-off 20mm wide x 0.81mm thick titanium straps, connected by 2 turnbuckles to tension the band and apply the clamping force required to keep the 2 halves of Beagle 2 together during AIT, launch, cruise and EDL, and a single release device designed to release the band tension and allow the 2 halves of the lander to separate exposing the instruments within the clam shell to the Martian environment. Further details of the CBA can be found in Ref [1] but the provides a summary of its mechanical details.

In addition to the items highlighted above the CBA incorporated 18 V-shaped Clamp Blocks, used to transfer the CBA tension into a clamping force at the lander lid and base interface. Due to weight constraints there were no ejection springs or catcher system instead we relied upon the tension in the band, the position of the turnbuckles and the dynamic behaviour of the band upon release to flick the band away from the lander.

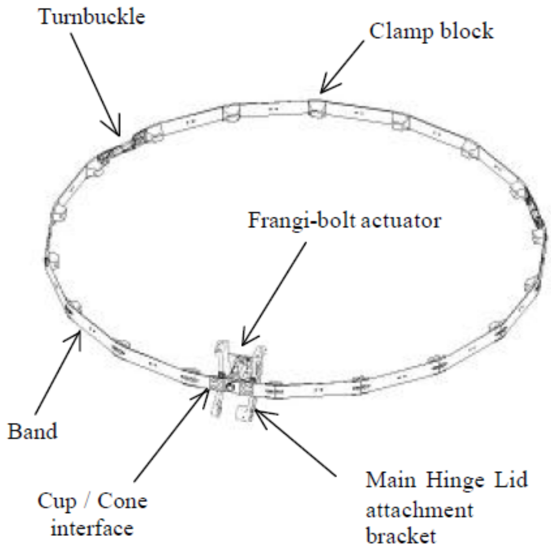

Figure 2: Clamp band Assembly (CBA)

Characteristic	Performance Achieved
Mass	0.456 kg
Dimensions	620mm diameter, band segments 20mm wide x 0.81 thick
Tension - nominal	2159 N
Operating temperature range	-30 °C to 30 °C
Non-operating temperature range	-58 °C to +125 °C
Frangibolt Release Voltage	18 V- 24 V

Table 1: CBA Characteristics

Should the dynamic behaviour be insufficient to fully un-wind the CBA, operation of the MHDM and the shape of the lid and base interface brackets would ensure that the band would fall clear permitting the lander to open. Release of the CBA was by means of a Frangibolt incorporating a memory metal actuator to stretch a notched Titanium bolt until it failed allowing the then free ends of the band to fly away from the Lander. Again due to weight constraints there was no redundancy in the release device, if it failed to operate the band would fail to release. Typically a Frangibolt would be designed to have redundant heater coils used to generate the heat to stretch and break the bolt. This however would have required redundant wiring and additional circuitry. Adding a second redundant Frangibolt actuator would have cost 25grams. Many clamp bands have fully redundant release devices but this would have added around 100 grams to the mass budget after allowing for the offset caused by the deletion of one of the 2 turnbuckles. Additional circuitry and wiring would have further increased the mass penalty.

If the CBA failed to open then the mission would be lost and none of the other mechanisms or the instruments installed on the Instrument Arm would be able to perform their separate function

2.2.2 Main Hinge Deployment Mechanism

The Main Hinge Deployment Mechanism (MHDM) was designed to open the lid of the Lander once the CBA had successfully deployed. Because of accommodation constraints the Hinge consisted of motor gearbox assembly incorporating a 201420:1 multi stage gearbox consisting of a 5 stage planetary gearbox, a spur gear stage and a harmonic drive. Drive from the output stage of this assembly was passed to a secondary output drive via a tensioned wire rope. The secondary output stage was necessary to accommodate most of the mechanism internally in the Lander base, where it was protected from landing impacts (and from damaging the airbags) by the external protective cladding, and to move the axis of rotation outboard to generate the necessary clearance for the lid during deployment. Full details of the MHDM can be found in Ref [2] but the following table provides a brief summary of the main technical details of the mechanism.

Characteristic	Performance Achieved
Mass	0.987kg
Dimensions	140mm(w)x140mm(d) x110mm(h)
Max. output torque	71Nm
Back-driving torque	10.7Nm
Max. rotational speed	0.3 /s
Supply voltage	12V
Drive current	100mA (max.)
Position feedback	10k , 1% linearity
Operating temperature range	-40 °C to +30 °C
Non-operating temperature range	-100 °C to +125 °C

Table 2: MHDM Characteristics

The Main Hinge was designed to cope with the Lander landing either way up and in fact lid downwards was the worst case as the base consisted of 24.3kg or 73% of the total 33.2 kg of the Lander mass. Lifting this mass required a total factored output torque of 71Nm, hence the need for the very large gear box ratio. Such a large ratio resulted in a deployment time of approximately 10 minutes for the full 180 degrees rotation required to fully deploy the lid.

As with the CBA if the Main Hinge Mechanism failed to operate then the mission would be lost as the next in sequence Solar Array Hinge Mechanisms would not be able to deploy the Solar Panels, which were required to generate power for the remainder of the mission

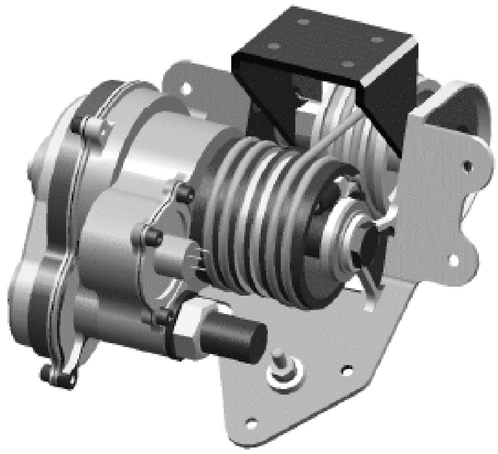

Figure 3: Main Hinge Mechanism

.Once again there was no redundancy built into this mechanism. It is almost impossible to build redundancy into the mechanical parts of such a hinge mechanism but there would have been redundant bushes, where possible, to offset the effect of a seized bearing but nothing else apart from a margin of safety designed into the mechanical structural parts against the predicted loads.

It is common practice with motors to have redundant drive motor coil mounted on a common motor drive shaft but lack of available space and mass prevented such a basic solution being implemented into the design. The Maxon motor employed in the MHDM weighed only 25 grams but the additional wiring and circuitry would have added to this, as would additional structure to support the increased length of the cantilevered motor.

2.2.3 Solar Array Release Devices

The stack of SA panels was secured to the lid of Beagle 2 via 5-off Frangibolts. As with the clamp band, these worked by the action of a heater stretching a notched bolt until failure. All 5 devices had to work to release the stack of SA panels and allow them to be deployed. Again no redundancy was employed because of lack of space and available mass budget. Secondary Frangibolt heater elements would have weighed 25 grams each plus the additional wiring and circuitry. The increased length of the notched bolts would have added around another 50 grams in total.

2.2.4 Solar Array Hinge Mechanism

Beagle 2 had 4 Solar Array panels, roughly circular in shape and 590mm in diameter installed inside the lid. The SAHMs are much simpler mechanisms than the MHDM primarily because the solar panels were very light and the mechanism only had to cope with a single possible deployment orientation of the Lander. All 4 mechanisms were essentially identical but with slight geometric differences in the output flange to account for the way the 4 panels were stacked upon each other. The SAHMs consisted of a motor gearbox assembly and single pass spur gear set with a 3729:1 gear ratio plus structural interfaces to the Lander lid and the SA panels. With a deployment time of approximately 12 seconds for the full 180 degrees rotation the mechanisms had to be deployed in a specific sequence and time controlled to avoid clashes with other panels. The panels had to be rotated through at least 100 degrees to provide sufficient room for the next panel to deploy.

Full details of the Solar Array Hinge Mechanism can be found in Ref [2] but Table 3 provides a brief summary of the main technical details of the mechanism.

Characteristic	Performance Achieved
Mass	0.120kg
Dimensions	30mm(w)x100mm(d)x45mm(h)
Max. output torque	2.5Nm
Back-driving torque	0.17Nm
Max. rotational speed	15 /s
Supply voltage	12V
Drive current	100mA
Position feedback	10k , 1% linearity
Operating temperature range	-40 °C to +30 °C
Non-operating temperature range	-100 °C to +125 °C

Table 3: SAHM Characteristics

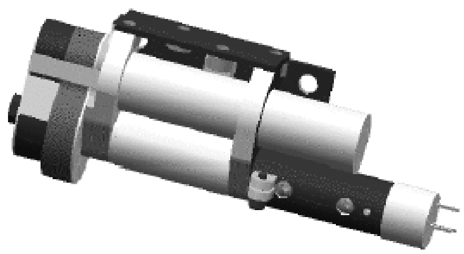

Figure 4: SAHM Mechanism

At this point it is worth comparing the difference in mass between the MHDM and the SAHM. Each SAHM weighed only 120 grams compared with 987 grams for the MHDM, which reflects reasonably well the difference in work required from the different mechanisms. The SA panels weighed around 0.750 kg each whereas, as stated, the MHDM had to potentially deploy the base and equipment within, which weighed 24.3 kg.

As with the other mechanisms all 4 SAHMs had to function correctly, not only to expose the surfaces covered with solar cells to enable the generation of power necessary for the mission to continue but also to expose the patch antenna mounted in the lid of the lander under the last SA panel. If the final SA panel didn't deploy then without the patch antenna exposed communications with Mission Control in Leicester, UK would not be possible and the Lander could not be commanded from Earth.

As with the MHDM there was no redundancy built into these mechanisms, constraints on available space and mass meant that the normal practice of having redundant motor coils could not be implemented. The SAHM used a different Maxon motor/gearbox assembly so a redundant coil would have added at least another 25 grams per hinge plus the impact of additional wiring and circuitry, plus any additional support structure to support the increased length of the cantilevered motor.

2.2.5 Robotic or Instrument Arm

The Instrument Arm is a 5-degree of freedom anthropomorphic manipulator with a multifunctional end effector (the PAW) permanently attached to the wrist joint. The PAW was a key element of Beagle2 as it comprised the instruments to examine Martian rocks and to take samples for analysis by the Gas Analysis Package (GAP) mounted in the base of the Lander.

Full details of the Instrument Arm can be found in Ref [2] but the following table provides a brief summary of the main technical details of the mechanism.

Characteristic	Performance Achieved
Mass	2.2kg
Degrees of Freedom	5
Maximum reach	0.709m
Max. output torque	25Nm
Back-driving torque	21Nm
Max. rotational speed	0.5 /s
Supply voltage	12V
Drive current	100mA (max)
Position feedback	10k, 0.1% linearity
Operating temperature range	-40 °C to +30 °C
Non-operating temperature range	-100 °C to +125 °C

Table 4: Instrument Arm Specification

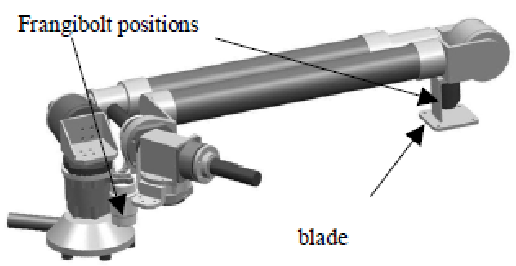

Figure 5: Instrument Arm - Installed Configuration

The IA was retained in its stowed configuration using a pair of Frangibolts, both of which had to operate to allow the IA to be released from the base of the Lander and perform its function. If the IA could not be deployed then none of the 7 instruments or tools mounted on the PAW could be used to sample the Martian environment in the vicinity of the Lander. As with the other mechanisms there was no redundancy within the IA or its Hold Down Release Devices; all had to function for the IA and the PAW mounted instruments to be used. In reality, however, if one of the 5DoF joints seized during on-surface operations then the IA could still have been used to a limited extent resulting in a degraded mission.

Adding redundant Frangibolt heater coils and increasing the length of the notched release bolt would have added around 80 grams to the mass budget plus additional wiring and circuitry. Adding redundant motor windings to each of the 5DoF would have been a much more difficult affair, if not impossible given the available space. This would have had the secondary effect of increasing the number of cables traversing the hinge lines resulting in increased resistance and probably larger motors to ensure that ECSS Mechanism operating margins were maintained.

Figure 6: Instrument Arm Assembled in Lander

3 LATEST MRO HiRISE IMAGES

In January 2014 the Beagle 2 team at University of Leicester announced that through a new analysis method and the painstaking work of searching through high resolution images by Michael Croon, a former member of the Mars Express operations team at ESA's Space Operations Centre, ESOC, in Darmstadt, Germany, working in parallel with members of the Beagle-2 industrial and scientific teams an artefact identified on the surface of Mars in the correct region that could possibly be Beagle 2.

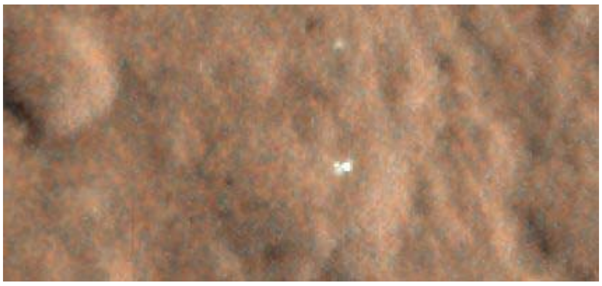

Figure 7: MRO HiRISE Image of Beagle 2

This artefact has since been accepted as Beagle 2 but because it is right at the resolution limit of the MRO cameras it is not possible to accurately determine exactly the deployed state of the Lander. There could be 2, 3 or 4 solar panels deployed but the evidence seems to favour at least 3 of the 4 as shown in Figure 8.

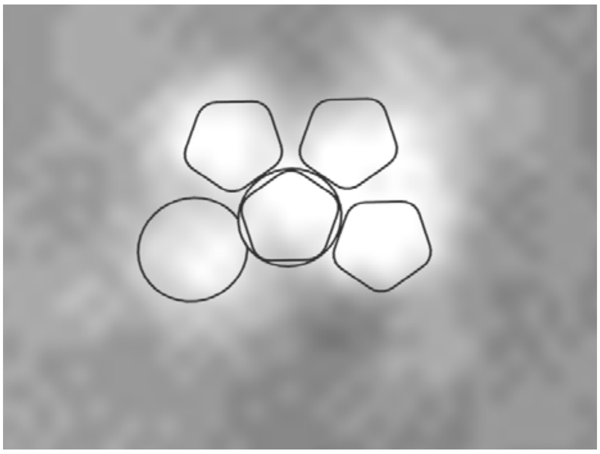

Figure 8: Interpretation of MRO Images Showing Beagle 2 on the Surface of Mars

From the inset images it can be seen that it is possible to fit a number of different deployed state configurations to the highly processed images. This prevents the team at the University of Leicester from accurately identifying the deployed configuration but it seems that not all the solar panels deployed and this would have prevented any communication via the obscured patch antenna mounted in the lid.

4 ASSESSMENT OF BEAGLE 2 CONFIGURATION

4.1 Overview

The following table assesses the status of each mechanism assuming that the configuration shown in Figure 8 is correct.

Mechanism	Assessment of Status from Images
CBA	Operated: There is evidence that the lander has opened therefore the clamp band must have functioned correctly for the Lander to have opened.
MHDM	Operated: There is evidence that the lander has opened therefore the MHDM must have functioned correctly and opened the Lander.
SA Release Devices (5)	Operated: The fact that at least 2 SA Panels appear to have deployed indicates that all 5 Frangibolts operated correctly allowing the SA panels to be deployed.
SAHM #1	Indications are that the first panel has fully deployed. This would have allowed the next panel to deploy and also for power generation to have commenced, supplementing the power stored within the on-board battery.
SAHM #2	Indications are that the second panel fully deployed as well. This would have allowed the next panel to deploy and supplemented the amount of power being generated also supplementing the power stored within the on-board battery.
SAHM #3	Indications are that the third panel deployed as well. If not this would have prevented the next panel from deploying. Analysis and modelling of the images shows that Panels 1, 2 and 3 each rotated by at least 130 degrees, more than sufficient for the next panel to deploy. 130º was the default angle for initial deployment before ground command unless illumination threshold check by software was not met in which case panel would continue to 160º.
SAHM #4	Likely that this panel hasn’t deployed. Critically this would have prevented the patch antenna mounted in the lid from being uncovered and allowing communications with Earth to commence.
IA	Without the ability to communicate with Earth the IA did not have the opportunity to confirm its status and the resolution of the images is insufficient to infer any information regarding its status.

Table 5: Status Assessment

4.2 Summary Assessment

From the above table it can be seen that at least 10 out of the 12 mechanisms supplied by Airbus, Stevenage operated correctly. The status of the IA cannot be determined and the status of the remaining solar panel hinge is uncertain.

4.3 Impact of Adding Redundancy

Throughout this paper mass and available space have been cited as reasons for not providing any form of redundancy in any of the above mechanism; they all had to work in the planned sequence for the mission to succeed. Although the numbers quoted for the mass of each of the redundant items are small they all add up and if all implemented would have added around 500 grams in additional parts. To this would need to be added any addition support structure to carry the additional mass, especially critical in the case of the extended lengths of the cantilevered Maxon motors. To this would have to be added the mass impact of additional wiring and circuitry. In total this could have added around 0.550 kg to the total mass of the lander or just over 1.5% of the total mass.

To put it simply on a mission where there wasn’t any spare mass budget, even an additional 0.55 kg could not be tolerated and the decision was made early in the design process not to have any redundancy. With the level of information currently available it is impossible to tell if additional redundancy would have allowed the final SA Panel to deploy, assuming that it has not, or whether there was some other fault; wiring problem, insufficient power, snag on the SA Panel Release Devices, excess stiction between the SA Panels, impact damage or some other fault that prevented the patch antenna from being exposed.

5 CONCLUSION

Beagle 2 was known to be a high risk programme from the outset. The limited access to funds throughout the programme as reported in Ref [3] was identified as a potential contributor to the ‘failure’ of the mission as it may have prevented many of the problems that develop in any programme from being properly solved early in the development. This can lead to problems being buried in the design, which are then more costly to rectify later in the programme or simply go undiscovered because there is insufficient time or money available to fully debug every aspect of the build. These concerns as expressed in Ref(3) were focused on the high risk elements of entry descent and landing and have been proven to be unfounded. Beagle 2 did not crash land as had been assumed. With the minimal time to design develop, build, test and deliver Beagle 2 in just 4 year, without the benefit of the usual project Phases A and B, required an unconventional approach. The development risks may equally apply to the lander mechanisms.

At this point in time it is impossible to tell exactly why Beagle 2 failed to contact Earth over the Christmas/New Year period in 2003/2004. But if the fourth Solar Panel has not deployed, had additional redundancy been built into the SAHM motors then all 4 may well have deployed and Beagle 2 would have completed its planned operations on the surface of Mars.

Although Beagle 2 is sometimes identified in the media as a failure the evidence is that the Entry Descent and Landing System succeeded in providing a controlled descent to the surface of Mars and significant parts of the Lander and, in particular, the Mechanisms all worked as designed and functioned correctly as planned. It is perhaps unfortunate that it is almost inevitable that in a system with no redundancy that some point in the chain, where everything has to work, something is not quite right and the system does not have sufficient operating margin to ensure operation.

6 REFERENCES

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7 ACKNOWLEDGEMENTS

Figure 1, Figure 7 and Figure 8 used with permission of Leicester University.