BEAGLE 2 INDEPENDENT REVIEW REPORT

Document number: BEA-EST-RP-4121

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1 Foreword

The Beagle 2 Lander was confirmed as a Mars Express payload by the ESA Science Programme Committee in November 1999. Phase C/D commenced immediately thereafter. The Director of Science requested an Independent Review to be conducted in order to evaluate the progress of the Beagle development and also assess the current status of key Lander elements. The review was carried out between 25th and 29th September 2000 at Astrium-Ltd premises in Stevenage with visits to Open University and Martin-Baker Aircraft Company. The review was based on a data package provided to all review team members in early September. A full report on the findings and recommendations of the complete review board has been produced. The Review Board Members wish to thank participants from Astrium-Ltd, Martin-Baker Aircraft, Leicester University, Open University, RAL, and subcontractors for their co-operative participation which enabled this review to be carried out in an expeditious manner.

A very special acknowledgement must be given to Elizabeth Novelli for her contribution. Without her patience, stamina and dedication this report would not have been possible. Each of the review board members extends to her their personal thanks for her secretarial support.

2 Terms of Reference

This review was directed at the Beagle 2 probe to be carried to Mars on the Mars Express Spacecraft.

The terms of reference provided to the Board included:

Assess the Beagle 2 overall design concept, including its interface with Mars Express;

Determine the maturity of the system design, including the status of significant documentation ;

Determine the design status of the major subsystem. For this Review, the Gas Analysis Package (GAP) was treated as a major subsystem and was reviewed by both engineers and scientists with appropriate credentials.

Assess the completeness of the test program plans and documentation.

Verify the completeness of internal and external interface designs and documentation.

Review the management structure and determine its suitability to implementing Beagle 2, and the status of schedule, mass and power reserves.

Assess the status of the payload including the accommodation of structural, thermal, power, data handling and software needs.

3 Review Participants

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4 Executive Summary

4.1 Summary findings and recommendations

Beagle 2 has only become a Space Science project to Mars through the drive and enthusiasm of Colin Pillinger and his team. They have had to initiate work and studies in advance of formal acceptance and funding. As a result a Consortium arrangement has been set-up to manage the project. Although this differs from the normal project hierarchy of project manager and subcontractors the joint system team under Mark Sims, made up of engineers from the principal academic and industrial organisations who have made financial contributions in kind to this project, is demonstratively working. The Review Board accepts the management and engineering organisation for BEAGLE 2 because of the motivation and the enthusiasm of the project members. However, it is fragile and could break down in times of financial stress.

Early during the review it quickly became apparent that the mass of the probe/lander was critical as the nominal mass was at the prescribed budget with no headroom for growth due to development problems. The project team was fully aware of the criticality of the mass budget and were controlling the mass breakdown at a level of 10g. Mass was being trimmed wherever possible. Based on the experience of the Pathfinder airbag development the review team considers that the airbag design for Beagle 2 is marginal and it is probable that the mass of the airbags would increase. Any further increase in mass of the landed system results in an increase 1:1 of mass for the rest of the EDL (Entry, Descent and Landing) system. It is strongly recommended that, if possible, the Mars Express project creates a mass margin, which can be allocated when the need for mass increases can be demonstrated from test results on the airbags or from other essential survival or science needs. Mass margin should not be released in the advance of proven need.

The second most critical aspect on the project was schedule margin. It is believed that the existing contingency is inadequate for a project with major new payload developments, development of a re-entry system and designing for the Mars environment. The need to meet the required launch date is clearly recognised but additional schedule contingency can be found for Beagle 2 by changing final integration of the flight model Beagle 2 at the launch site rather than contingency in Europe prior to transportation to the launch site. 6 to 8 weeks could be gained if air transportation of Beagle 2 to the launch site was arranged.

Additional contingency can be found by not sending the flight model payload and electronics for the 50 day period allocated for a vibration test on Mars Express. This would allow time for end-to-end testing on the Lander equipment which is considered essential by the review board.

Although no detailed plans exist for planetary decontamination of equipment on Beagle 2 it is considered that this can be satisfactorily achieved by the project after discussions on this subject, provided implementation is promptly started.

With regard to financial needs on this project it is considered inevitable that additional funds will be needed to overcome development problems. Although the total available funds from the different sources is not known to the Review Board further request for funding can be expected in order to complete the project.

Conclusions:

Each of the topics from the terms of reference has been reviewed and the detailed findings and recommendations are included in the report.

It is considered that if each of the findings is satisfactorily addressed then it is the conclusion of the Review Board that the design maturity of the system and subsystems is satisfactory at this stage of the project, with the exception of the airbags and few other noted activities. Particular attention has been paid to the GAP experiment. The long experience of the Open University team on development and use of mass spectrometers, together with the supporting industrial suppliers, should mean that a working flight model experiment can be completed within the needs of the project schedule.

With regard to the system test programme, this was found to be complete in that each major test was identified in the schedule with a reasonable time allocated. The need for early airbag testing has been highlighted but the use of Plum Brook for airbag tests is limited by other users. The use of an alternative facility in Europe which can be done with a relatively modest expenditure is necessary e.g. mechanical test facility at ESTEC shall be seriously pursued.

5 Management and Risk Assessment

The management structure of Beagle 2 is complex reflecting the nature of the Consortium. There are multiple lines of accountability or authority. The line of accountability for the industrial participation flows through the Industrial Manager who appears to be answerable only to his corporate management. There is no unique line of accountability for the scientific participation. Management directives can only be effected through consensus among the four managing partners. Given the modus operandi of the consortium there may be no other workable management structure. It appears to be effective largely because of the good will and shared commitment of the consortium partners to the Beagle 2 Project. At best the arrangement is fragile, and can work only as long as the shared interest of the parties does not collide with the corporate interests of the participating entities.

Overall, the project planning and co-ordination seems complete and thorough for this stage in the development cycle. The Project Manager has an extraordinary grasp of the planning schedule, and uses it as an effective tool for overall project co-ordination although, as noted in Section 7, there was some evidence that not all of the Astrium-Ltd core team may be fully coordinated with the rest of the system team.

Although the project has produced a risk management plan, risk management, in the classical sense, is virtually non-existent in the Beagle 2 Project environment. This is not because of a lack of understanding of risk management or a lack of understanding of the need for it. Management of risk requires the availability of margins in a project and the ability of project management to allocate margins in order to mitigate risk. As discussed elsewhere in this report mass margin is zero, if not negative. Likewise, other dimensions of margin such as volume, power, schedule and funding are significantly less than normally seen in projects at the Beagle 2 state of development. In the absence of margins, there is no effective means to mitigate risk; thus it will grow, and it will grow in an unmanaged way.

In the judgement of the review board the Beagle 2 Project is challenging but eminently doable. The members of the industry and scientific teams are exceptionally qualified and fully capable of executing the work required. However the absence of margins have led to unsuitable design choices in many cases as delineated in later sections of this report and should be corrected. The alternative is to proceed with very high-risk posture, which would not be suitable to the high profile enjoyed by the Beagle 2 Project.

Aggressive and immediate action should be taken to increase the mass allocation (or descope Beagle 2 functionality) to correct the deficiencies identified in this report, and to make allowance for future mass growth that will almost certainly occur during the upcoming development and test activities.

6 System Level Summary Assessment

The Beagle 2 team presented a potentially viable, innovative system for the gathering of surface science from Mars. Astrium-Ltd, the engineering prime contractor, is an established and capable aerospace firm with extensive experience in the design, manufacture and operations of Earth orbiting satellites and other spacecraft. The assembled team, including Martin-Baker aircraft and other subcontractors, is a talented and capable group with a clear focus on the common goal of Beagle 2 success. The team has a significant challenge in that the development for a planetary Lander is a significant departure from the normal experience base.

6.1 System

6.1.1 Overall Design Concept

The Beagle 2 design that was presented is a very innovative well conceived approach to meeting the science goals, as they are currently understood, within the constraints imposed on the project. The status of the science and mission requirements is nebulous as the goals appear to be the only high level guidance that the project is responding to.

6.1.2 Maturity of Design

The design maturity of the Beagle 2 system elements varies from CDR level to pre-PDR level. The majority of the elements are well along in the design process and many have functioning breadboards with engineering units planned in the near future. A prominent exception to this status is the development of the airbags. ILC Dover has been under contract for only about 2 months and the status of their effort is judged to be pre-PDR. Our assessment is that Martin Baker Aircraft is very capable of performing the Entry Descent and Landing system (EDL) work. However we are concerned that the planned development testing in the airbag program is inadequate and should be augmented to ensure a low risk product.

6.1.3 Status and management of technical margins

Mass:

The mass margin is essentially zero. The project has very effective mass management mechanisms in use, but it is unlikely that the delivery mass will be within the allocation. A normal project at this stage should have on the order or 10% margin to insure delivery within the allocation.

Schedule:

The project manager maintains a project master schedule that contains key elements pertaining to every part of the project. The doing organisation have more detailed work schedules keyed to the master schedule by which they plan and execute their work. All of the work is scheduled on the basis of a 5 days – 37 hours work/week. There are discrete schedule margin entries in both the master schedule and the detail work schedules. The overall schedule margin appears barely adequate, but given the 37 hours / week planning basis, should be adequate with the application of moderate overtime. For the work planned as noted elsewhere in this report, the planned activities are well short of what will be required in certain areas. The schedule margin could be improved if the first delivery of the flight probe was changed to delivery of a test article that would satisfy the Mars Express test requirements. This would allow additional testing and characterisation of the flight Lander before sterilisation and re-assembly.

Power:

The combination of the power expected from the solar array and the capacity of the battery should result in good power margins. The exact power margin will depend on the landing conditions and the operations planning. Some concern was expressed relating to the solar array degradation due to dust and radiation near the end of the nominal mission. The Beagle 2 model for predicting this degradation appears less conservative than the NASA models.

6.1.4 Status of Documentation

The Project documentation appears to be in good shape in most areas to implement the project. Among the exceptions are the highest level science and mission requirements. The absence of these high level requirements documents makes it very difficult to put together a design verification program and/or a credible descope plan. A document tree showing the flow down of requirements was not provided. In some cases where equipment specifications were not available, it appeared that it is planned to write the equipment/performance specification after testing the breadboard unit.

6.2 Entry Descent and Landing System

The Martin Baker EDL team is a strong and motivated team with a large amount of corporate knowledge and experience. The team is without question capable of performing the tasks they are responsible for. In general the status of the EDL technologies is mature with the exception of the airbag and gas generator systems. The team has made the assumption that a large amount of heritage in airbag design will be garnished from the Pathfinder experience. This assumption has been internally reinforced by their selection of the same contractor used to build the Mars Pathfinder airbags. It is the feeling of the review board that this is not a valid assumption. It is also the opinion of the board that the EDL system development plan is not robust. Due to financial constraints the team has chosen not to perform high fidelity multi-body dynamic drop and separation tests.

6.2.1 Mars Express Interface

The Mars Express (MEX) interface has 5 major elements: Environments, Mechanical Interface, Thermal Interface,Ejection Dynamics, Electrical Interface. The modal requirements set on the Beagle 2 Lander are stringent and are driving the mechanical design of the probe structure. The first transverse and first axial mode requirements have been specified at >45Hz and >85Hz respectively. As a result, the Spin Up and Eject Mechanism (SUEM) and the aeroshell separation mechanism designs have been forced to use hyper-static interfaces which inherently reduce the reliability of the systems in order to increase the overall probe stiffness.

Beagle 2 is a spacecraft on the Mars Express orbiter yet the Beagle 2 team may not have felt empowered to request changes to the Mars Express requirements. As a result it appears that the Mars Express / Beagle 2 system is not optimised and there is an inefficient use of mass. It is the opinion of the Board that a lighter overall system could have been devised but at this stage of the Mars Express programme with the structure in fabrication only limited possibilities may now exist.

6.2.2 Aeroentry

While advantage has been taken of the Huygens heritage for the initial design of the aeroshell, modifications have been implemented to alleviate the aerothermal environment at the front/back cover aeroshell interface. This has resulted in significant departures from the original Huygens front shield design/OML. The initial assessment of the hypersonic aerodynamic performance has accordingly been revised by utilizing state-of-the-art modelling with significant redundancy and by taking into account the deltas due to CO2 atmosphere. In addition, complementary testing is planned to provide a required anchor point. Low supersonic and transonics are being characterized by similar numerical means. The modifications to the original aeroshape are also expected to be beneficial in this regime, in particular for the dynamic stability of the probe. A thorough numerical assessment of this topic has been implemented in the relevant Mach range, as well as an experimental characterization.

The aeroheating level assessment is being performed by both engineering correlations and high level numerical modelling, complemented by experimental characterisation of the backcover heating. Due to previous experience on Huygens and ARD, it is felt that the present Thermal Protection System (TPS) design is satisfactory.

Further optimisation of the TPS thickness is being actively pursued, but could prove premature since other, system-driven, variations of the ballistic coefficient might arise during the next stages of development. It is recommended that no particular emphasis is placed on this topic until overall mass figures and final aerodynamic coefficients/uncertainties are consolidated. Both the quality and the quantity of the work performed are outstanding.

6.2.3 Parachute

Based on the discussions with Martin Baker engineers, the review board did not feel it necessary to review the detailed progress of the two parachute developments. Martin Baker has extensive experience with terrestrial parachute systems. Martin Baker was the provider of the Huygens probe EDL system which was principally a dual parachute system. The lead engineer for the Huygens parachute is also the lead engineer for the Beagle 2 EDL system.

6.2.4 Airbag Subsystem

The airbag subsystem is at a pre-PDR state of development. To date no prototypes have been tested or built. The current airbag development program is extremely success oriented and is relying heavily on Mars Pathfinder heritage to save development time. The board feels that the Beagle 2 airbag system is sufficiently different from the Mars Pathfinder airbag system that it is difficult to claim any design heritage.

It is the board's opinion that the current airbag test program is not adequate. The board's opinion, based on Pathfinder experience, is that a minimum of about 18 impact tests spaced out in 3 test series will be required. It is also the board's opinion that the planned use of the NASA Glen Plum-Brook station drop test facilities developed for Pathfinder poses a major schedule risk to the project. Beagle 2 requires unconstrained access to a low pressure impact facility, they will *not* have this at Plum-Brook. The board recommends immediate investment into the development of such a facility. The criticality of a robust airbag test program is accentuated by the design of the airbag release system. The success of the airbag release system (and therefore the Beagle 2 mission) requires that the airbag bladder do not sustain *any* damage whatsoever during landing.

"design robustness" and "graceful degradation" are claimed to be baselined approaches however implementation of these concepts was not evident from presented design.

Overall avionics architecture is more or less established but different parts of the electronics design seem to be handled pretty much independently from one another.

6.3.1.2 Power

Solar Arrays:

Solar cells technology and manufacturer have changed quite recently with Spectrolab providing triple junction GaAs cells/photovoltaique assembly to Astrium-Ltd for panels deployment system design and development.

Solar array design status appears to be at a very conceptual level and although no schedule criticality was claimed, design and validation should be followed very carefully.

In order to limit the risks, a step by step test program is due to start before the end of this year.

Battery:

Although the same Li-Ion battery technology is used for Mars Express, Beagle 2 operating conditions at very low temperatures (-30C) require a thorough performance evaluation test program.

Early performance testing was initiated at AEA manufacturer more than a year ago and more representative life testing is to be initiated before the end of this year.

The battery capacity has been increased recently and the development status of this item looks to be well controlled.

Common electronics:

Some of the key elements like the processor board and power supplies have been breadboarded and tested separately however some other electronics are yet only at a conceptual level. From the preliminary FMECA available, some items show that above 80% of failure modes can cause a loss of mission, and although this was expected due to the single string approach, implementation of design robustness does not appear at component level by e.g. local redundancies to cope with the most dramatic failure modes, high reliability electronic parts.

Electro Magnetic Compatibility

Although partial EMC requirements seem to exist in different documents, an EMC specification should be produced and used as input for EMC analysis to be performed before the end of the year and in order to adequately prepare EMC test campaigns.

Power/energy budgets and modelling:

A power and energy balance modelling tool has been developed and already includes a number of features concerning battery and solar array performance predictions versus environmental conditions and surface operations activities.The model is to be improved as solar array and battery performance data are consolidated, however it seems possible to perform some fairly representative simulations already.

6.3.1.3 Command and Data Handling

Data Handling System specification was not yet available although architecture definition based on the use of the ERC32 Processor seems well established. Lack of specification as seen in other areas shows a bottom up design approach rather than top-down but the processor board has already undergone a design iteration of the breadboard. This area looks under control.

6.3.1.4 Communications

Progress status of the Telecommunication package with DERA newly developed transceiver appears to be on track. Beagle 2 Lander to Orbiter communications are at UHF and compatibility testing with CCSDS - Proximity-1 Protocol is baselined.

Early compatibility tests of the NASA'01 link scheduled for November this year and January next year will significantly increase the level of confidence in this new design.

6.3.2 Software

Two experienced contractors, Logica and Science Systems Ltd, have started work with a division of responsibilities agreed. The work is being managed by Astrium Portsmouth with the ESA standard PSS 05 being the guideline for software methodology and control. The first issue of the Lander Software Requirements Document (SRD), will be reviewed in October followed by the Architecture Design Document. It was stated in the presentation on this work area that further payload requirements will be supplied over the next months. During the Mars surface operations it is only planned to operate one payload instrument at a time so the progressive coding of the software is not seen as a problem. From a schedule point of view the need is to have a timely input flow of requirements.

In common with the Lander electronics, the onboard processor is not redundant and further work needs to be done to look at recovery/work around for potential failures in the electronics, processor and instruments which the processor can initiate if problems occur.

Because of the sterilisation programme of the flight Lander prior to final delivery, the opportunity exists to introduce the flight PROMs and software at a late stage in the programme. This would allow more time to refine the software taking into account knowledge from the instrument and probe/Lander testing.

Although the work in software has only recently built up with the needed labour resources no significant problems are seen at this time so long as requirements are received in a timely manner.

The risk associated with not investing in a robust airbag test program as early as possible is mass growth that can not be accommodated by the rest of the system. For each gram of mass added to the landed system there will be approximately 1 gram of mass added to the rest of the EDL system to accommodate it. It is the board's opinion that the airbag subsystem can be made to work reliably and within schedule, if and only if a robust drop test program is implemented very quickly.

6.2.5 Separation

The Entry Descent & Landing System (EDL) contains several major separations that occur during the EDL sequence: Probe/Launch latch release, Probe separation from the MEX, back-cover separation and heatshield separation. In general, the launch frequency, and separated mass constraints placed on the Beagle 2 force design choices that compromise the robust operation of these separations.

6.2.5.1 Probe / Launch latch release

The design of these latch release mechanisms has been driven by the probe first mode frequency requirements of 45 Hz. This requirements has caused the choice of a hyper-static cup-cone interface that includes titanium on titanium contact. It is the opinion of the board that the design of these separation joints is not robust.

6.2.5.2 Probe/MEX separation

Probe/MEX separation is powered by the SUEM, which is a previously flown heritage design. It is the opinion of the Board that this system is mature and does not represent undue risk to the mission.

6.2.5.3 Back-cover/Lander separation

Back-cover/Lander separation involves another hyper-static (order 42) joint. As above this kind of design is considered non-robust. Further, there are no push-off springs at the separation joints. Further, the cone angle for the cup-cone faying surfaces, is close to the bare metal locking cone angle. It is the board's opinion that this joint must be redesigned.

6.2.5.4 Heatshield/Lander separation

Heatshield/Lander separation occurs after the back-cover separation. The separation joint is initially secured by the same pyro-cut bolts that restrains the back-cover. After the release of these bolts only aerodynamic forces located the heat shield. There is no control of the heatshield during the time between the back-cover separation and the heatshield separation. Additionally there are no push-off springs at these joints. It is the board's opinion that this joint must be redesigned to directly control the position of the heatshield until separation, powered by separation springs, occurs.

6.2.6 Thermal

The maturity of the thermal design has increased significantly since the System Engineering Review Team (SERT) review in October 1999.

6.3.3 Structures & Mechanisms

The Lander has a carbon fibre composite structure with titanium fittings. The board believes that the structural design and analysis team is competent and that the design is basically fit. The extreme mass constraints on the structure, imposed by the Mars Express launch requirements, however, result in a structural design that requires moment restraint at the launch latch and back-cover/heatshield / Lander separation joints in order to meet the Mars Express frequency requirements. This is a potential source of mission failure. It is the Board's view that changes in the current structural design, allowed by the addition of increased structural mass, would enable a robust redesign.

The Lander has several mechanisms, for release of the lid/base joint, opening the Lander lid, deployment of the solar arrays. These mechanisms are in the following states of design maturity.

6.3.3.1 Lid/Base Release Mechanism

The lid and base are held together by a clamp band. The basic design of this clamp is sound but the release of the clamp poses a threat to the opening of the Lander Lid. Further, the clamp design includes titanium on titanium contact, which is inherently dangerous if the surfaces are not treated properly. It is the Board's opinion that the clamp should be redesigned to reduce the threat to the lid opening and to remove the titanium to titanium contact.

6.3.3.2 Lander Lid Opening

The Lander lid deployment mechanism does not currently have sufficient torque margin. The gear drive should be redesigned to increase transmission strength to a level that provides torque margins at the very least to the current ESA levels and removes the possibility of transmission damage at the drive motor stall torque. Moreover the hinge is sensitive to damage when hitting the surface of Mars.

6.3.3.3 Solar Array Deployment

The design of the solar array deployment mechanisms is at a pre-PDR level. The board was unable to adequately review these mechanisms because of the immature state of the design.

6.3.4 Instrument Arm

A systematic list of requirements for the instrument arm does not exist, although it seems that, at least a number of instruments and tools which it carries, do have stringent positioning requirements in order to operate properly. The XRS (X-Ray Spectrometer), for instance, needs to be positioned in contact with a soil or rock sample and be perpendicular to its surface within a few degrees. The arm designer expects that such requirements cannot be met due to design constraints imposed on him (e.g. the resolution of the stereo camera system).

Based on the design information obtained, it appears that the arm hardware design, including hold-down mechanisms and drive electronics, is appropriate. The arm joint mechanisms, however, have been designed in such a way that gear drive damage can occur at the stall torque. This should be remedied. It must be noted, that the reach of the arm is very limited, (due to its small length in combination with its location inside the Lander base). Accordingly the chances of being able to find a rock within reach, on which the envisaged scientific operations can be performed, are limited.

The onboard software for the arm is planned to be kept very simple by shifting the generation of position commands for its five joints to the Ground Support Equipment. For this GSE only conceptual ideas exist at this stage. The resulting performance of the arm as a subsystem will depend partly on this. Consequently there is a significant uncertainty about the ability to position the arm correctly within a reasonable time. The Beagle 2 team is aware of these uncertainties but cannot quantify them and expects to solve this by adapting the surface operations to limitations that will occur in the future. End-to-end testing of the hardware and software for operations of the arm at a point in time where hardware adaptations are still possible is recommended.

6.3.5 PAW Tools

The review team received only very limited information on these items. This information was insufficient to review them properly and to obtain a reasonable amount of confidence. Moreover there is a concern about the dust protection of various items.

6.3.5.1 PLUTO/Mole

The mole is a very important device for providing soil samples to the GAP. Unfortunately the review board could not obtain any substantial design information other than a verbal description by the project manager, supported by video images of an early prototype of such a device. From the information presented the review board concluded that the mole design may be insufficiently mature to rely upon. Moreover its development schedule is questionable.

There is a reversible mole under development which, if ready on time, will be the baseline unit, but the schedule is tight. The backup mole is uni-directional. Either unit has a winch on its tether to retrieve it. The lack of a cable cutter is a risk of a science mission failure due to a possible mole hang-up which could prevent arm motion and PAW operations. Either a cable cutter or careful science sequencing is recommended.

6.3.5.2 Corer / grinder and Wide Angle Mirror

Similarly to the mole very little information was available on the Corer / Grinder, which is needed to access pristine samples in rocks, and on the wide angle mirror, including its tilting mechanism, which is essential for taking surfaces images before the instrument arm is deployed. It may be difficult to protect the delicate mechanisms for opening/closing the jaws of the Corer/ Grinder from dust and soil particles. No information on the way how this is intended to be achieved has been provided.

6.3.6 Instruments

The prime instrument for achieving the key science objectives is the Gas Analysis Package (GAP), findings relevant to this are in Section 6.4. The PAW carries a suite of instruments for supporting measurements to characterise local geology and mineralogy.

These are:

The X-Ray Spectrometer (XRS) which will carry out an elemental chemical analysis of rocks and soils, together with precise measurement of K for isotopic dating in conjunction with the Ar measurements of GAP.

The Mössbauer Spectrometer will identify soil oxidation and magnetic phases of rock types and relative environmental conditions by measurement of Fe carbonates.

A pair of cameras will be used to prepare a digital elevation map for controlling the robotic arm . These will also identify local petrology and optical properties of the atmosphere.

A microscope will be used to investigate rock texture, coarse mineralogy and microstructures.

Beagle 2 will also carry a suite of Environmental Sensors for measurement of the wind, oxidising gases, atmospheric pressure, air temperature, deposition of dust, UV flux and high energy particles. The environmental suite also includes accelerometers for reconstruction of the entry trajectory.

The XRS and Mössbauer Spectrometer contributions to the prime objectives of Beagle 2 are clear. The cameras play an essential role in establishing local terrain mapping for guiding the PAW to key locations and surveying local petrology. The contribution from the microscope is less clear and it is not clear that the relative complexity of its operation justifies the science return. Also it is not clear that the environmental sensors make a significant contribution to the key mission objectives.

The Project Manager from Leicester University expects that the delivery dates for the PAW instruments will be met. All five PAW instruments have significant flight heritage, although the XRS has been repackaged so that only the sensor head has to be on the PAW (the electronics have been housed in the Lander Base Section).

Test Planning is the responsibility of each instrument PI. The PI test schedules were not reviewed. The PAW instrument mass estimate is about the same as the mass allocation.

The instrument electrical energy requirement is driven by the operating sequence which was not available for review. The power consumption information provided suggests that the batteries have enough capacity to support PAW instrument operations.

There are two issues of significance. One has to do with the positioning of the PAW to the point of interest and is dealt with in Sections 6.3.4, and 6.7. The other issue deals with the lack of mass margin. As discussed above, the PAW instruments may have capability beyond the focus of establishing whether conditions for life exist or were ever suitable. It is recommended that the present complement of PAW Instruments and Environmental Sensors be reviewed from the point of view of descopes to obtain mass margin (although it is recognised that the potential gain is limited) and simplify the overall system and operations.

In conclusion there are no significant issues, except mass margin, that preclude the PAW Instruments and Environmental Sensors from meeting performance and schedule requirements.

6.3.7 Thermal

Since the October 99 SERT Review the maturity of the thermal design has increased significantly due to well-focused efforts in the areas of thermal modelling, identification of major design uncertainties and quantification of sensitivities to major design parameters. A development test program has been formulated and partly executed to reduce the design uncertainties and verify design sensitivities. In addition, research involving detailed study of Martian environmental data (Viking, Pathfinder) and climate modelling have produced a more complete Martian environmental model. This has resulted in the formulation of realistic thermal load cases for Beagle 2 and has even made a contribution to Mars environmental modelling at the international level.

Extensive trade-off activities since the SERT have resulted in a streamlined design of the Lander. The most significant developments in the design since the SERT : a) adoption of a simplified battery thermal design in which the phase-change material has been replaced by conventional heaters b) replacement of "Tinox" solar absorber by a lighter Germanium absorber c) use of experimental data collected in development tests to improve modelling of solar absorber dust-induced degradation d) quantification of maximum heater energy needed by the Lander per Martian day-night cycle (80 Whr).

The design thus features a Basotect foam main insulator and a solar absorber to supplement heater power supplied by 8 heater circuits. The design is highly sensitive to dust-induced degradation of the solar absorber but it is assessed that adequate testing and modelling of the effect is being performed.

The main findings from the Lander thermal design are:

1) The chosen solar absorber-based design is feasible but introduces important operational constraints on payload operations because payload temperatures stay within operational limits for a limited time during a typical day/night cycle; the consequence is that scientific return in terms of "science-hours" has to be assessed and operations planning becomes a critical tool in maximising the scientific return.

2) The thermal and vacuum/CO2 compatibility test programs for the battery, transponder and robotic arm joints/motors are essential in order to provide evidence supporting the temperature requirements which have been used to assess the thermal design.

3) Progress in the understanding of dust-induced surface degradation has been significant and has been fed into the related analysis required for solar cell degradation estimations

Heater Line Reliability Strategy : it is recommended to implement a high level of redundancy in the battery heater control software because of the criticality of this item.

4) The Lander antenna location has not yet been decided; this issue needs to be resolved in order to enable assessment of thermal impact (i.e. shading on solar absorber, heat leaks through antenna mounting).

6.4 GAP (Gas Analysis Package)

6.4.1 The GAP Team

Prof. Pillinger and his associates at Open University (O.U.) have an excellent background to support the development of the GAP instrument, and to analyse and interpret the flight data. The O.U. team is augmented by several industrial organisations with whom they have worked with in the past.

6.4.2 Measurement Approach

The GAP has two modes:

1) Atmospheric samples are measured with the mass spectrometer (MS) inlet open to the gas sampling manifold. There is an abundance of sample in this mode.

2) The static mode is used for the small gas samples produced by the heating of Martian soil or rock specimens. When a heating step is completed, the evolved gas is processed using chemicals in the manifolded section to reduce the samples to the desired species, then that processed sample enters the MS, and the inlet valve is closed so that sample gas can be continually ionized until sufficient spectra are obtained. Analysis of the solid samples includes both pyrolysis and combustion. At each of about ten temperature steps going up to 1000K, a pyrolysis sample is analysed and then a combustion sample is analysed.

6.4.3 Hardware

6.4.3.1 Heritage

The hardware components have significant heritage from the Rosetta program, as well as numerous laboratory research programs. None of the major assemblies (e.g., mass spectrometer) have direct heritage.

6.4.3.2 Sample Handling and Distribution System (SHADS)

SHADS is an assembly derived from Rosetta hardware, and is supplied to OU by MPae. This assembly contains the sample ovens and carousel, and has a significant degree of heritage. The solid samples are deposited into this assembly from the mole, or the corer-grinder, or the spoon.

6.4.3.3 Vacuum Pumping

The GAP measurement requires working with gas pressures between Mars atmosphere and high vacuum. This is a challenge to the pumping design. A bellows pump is being developed as a first stage, and the high vacuum is obtained with an ion pump. The ion pump is powered by a supply of about 1400 volts.

6.4.3.4 Manufacturing Status

Breadboards exist for all of the major components. QM assemblies are being manufactured. The method of assembling the unit into the Lander has been designed and appears quite practical.

6.4.3.5 Contamination

It appears that most of the hardware, and maybe all of it, is heat sterilizable. The experimental technique is designed so that some organic contamination can be tolerated.

6.4.4 Robustness

The measurement technique is tolerant of valve leakage during the approximately one year from last operation on Mars. The valve seats may chatter during launch and touchdown, but again, the measurement technique can tolerate this. The system design does not accommodate running the ion pump during storage and cruise.

The primary calibration gas is stored in solid form, so it is not likely to be affected by the valve leakage.

6.4.5 Test Planning

Component testing is well understood, but the Qualification and Acceptance test planning is not well advanced.

6.4.6 Resource Status

6.4.6.1 Mass

The mass estimate is very close to the mass allocation, so there is no significant margins.

6.4.6.2 Power

The GAP is designed to consume less than 60 watt hours per measurement. The flight battery is capable of providing 190 watt hours per sol, so it appears that power is not presently an issue for GAP.

6.4.6.3 Schedule

The Qual unit is required to be delivered to the Lander in March 2001. That schedule appears achievable as long as there are no significant problems or failures that occur during assembly and test.

6.4.6.4 Cost

Cost was not reviewed.

6.4.7 Issues/Concerns

6.4.7.1 Test Planning

The test planning seems to be late relative to the hardware status.

6.4.7.2 In-flight Vacuum Pumping

The MS will not be pumped for almost a year. There is no known problem with this, but it may take a long time to achieve an acceptable vacuum pressure once on Mars. It seems preferable to provide auxiliary power to GAP during all of the period of time until operations start on Mars, with the exception of launch , coast and the first sol.

6.4.8 Recommendations for GAP

6.4.8.1 High Voltage Supply to Ion Pump

The qualification plan should incorporate an accelerated life test of the HV Supply to provide assurance of the vacuum container integrity. This should include more than the anticipated operational temperature cycles and over larger temperature ranges than expected on Mars.

6.4.8.2 Continuous Ion Pumping

Modify the MS and system design to provide continuous ion pump operation, for as much at the time as possible.

6.4.8.3 Thermal Design

The GAP instrument thermal design is marginal; this instrument is predicted to exceed minimal non-operational temperature limits at night during a large part of the mission; temperature limits of the GAP pressure sensors, mass spectrometer and power converter need to be experimentally verified in case the components have hidden temperature margins; in parallel, a more in-depth study of the GAP thermal design needs to be undertaken since at present the study has only been done at Beagle 2 system level.

6.4.8.4 Test Planning

Accelerate the test planning for Qual to avoid any false starts in the test program.

6.4.9 Conclusion

The GAP can be provided to the Lander at an acceptable time, unless the mass budget is not met.

6.5 Planetary Protection

Planetary Protection at System Level:

The status of Beagle 2 planetary protection (PP) at the system level is uneven. The highest level planning document, the Planetary Protection Plan, is well developed and complete. The contents include a complete set of the COSPAR PP requirements for a Category IV A Mars Lander and listing of the top-level issues. These issues are typically adequately understood. If the project properly executes the Plan, it will satisfy the COSPAR PP requirements. However, as verbally amended by project PP personnel, the current PP Plan's intention no longer significantly exceeds COSPAR requirements. The current issue of the PP Plan calls for a complete terminal sterilisation of the Lander, with the implication that this process was a science contamination control approach (See Contamination Control below). In discussion, however, the Beagle 2 PP personnel have described sterilisation at the subsystem level as the approach to meeting the COSPAR spore burden requirement. This motive and approach are sensible and appropriate.

There are, however, a number of concerns regarding the implementation of the Plan. Apparently, the start of implementation has been delayed. Given that there are several long lead time issues to be worked, this delay may cause schedule problems later. Some of the issues, which interact with the design and development of the probe and its payload, may lead to insoluble conflicts. Ultimately, such issues may compromise the project's ability to meet COSPAR PP requirements. Therefore, the PP implementation phase should be started or significantly ramped up immediately.

An important implementation process to be planned early is the systematic method for the estimation of the total spore burden on the Beagle 2 probe. This approach must include the identification and listing of all components with exposed (PP accountable) surfaces. The exposed areas for each such component must be given in finer detail for surfaces to be treated separately (or recontaminated and re-treated). The microbial reduction treatment of surfaces should also be considered. At this point, a preliminary sub-allocation of the maximum allowable number of spores to each component should be drafted. Finally, a sampling plan for the fractions of exposed areas to be sampled (e.g. how many swabs), should be established to provide an adequate statistical estimate of the total spore burden from the actual microbial assay data. The complete preparation of this part of the PP implementation before the start of assays, will enable timely estimations of the probe's spore burden and monitoring of status versus the spore budget. It will thus provide a method to identify contamination problems early enough for effective intervention.

Planetary Protection Issues for Generic Subsystems:

One long lead time item that is important for all subsystems is the need for a detailed implementation plan for the specific decontamination or sterilization methods for each spacecraft component to be treated. The development of this plan requires a cooperative effort between the PP personnel and the hardware designers. A preliminary version of this plan is needed for hardware design, assembly, integration and verification planning, and planetary protection.

Planetary Protection Issues for Specific Subsystems:

The entry heating analysis of the backshell is extremely important because it may leave part of the accountable surfaces outside the protection of the aeroshell. This issue affects the spore allocation for the Lander and probe, as well as the biological cleanliness requirements on the interior of the launch vehicle fairing and even the launch site contamination control.

In the Planetary Protection Plan, there is a pending decision on sealing the aeroshell during ground operations after probe final assembly or continuously purging the interior of the aeroshell with HEPA filtered gas. The purge option should be clarified and the port identified (e.g. special separate port or the depressurization vent port). In either option, special GSE with its own HEPA filtration is required. The details of the GSE purge system requirements and the intended use should be added to the Contamination Control (CC) Plan, with appropriate cross-references to the PP Plan (and vice versa).

Contamination Control:

The current issue of the Planetary Protection Plan in fact goes beyond COSPAR requirements for a category IVA Mars Lander by the intentional inclusion of contamination control requirements for the benefit of science instruments. As noted in the document itself, the approach would exceed COSPAR requirements. However, these requirements and the specifications in the Contamination Control Plan are not as well-considered and complete as the Planetary Protection Plan. During discussion, it became clear that the degree of contamination control for science instruments may have been over-specified. For example, the PP Plan indicated a complete terminal sterilization of the Lander is required. In discussion, the Beagle 2 PP personnel have described sterilization at the subsystem level as the PP approach.

In addition, adequate contamination control requirements on the probe system are not in place for use by design engineers, including outgassing requirements for material selection. These requirements should be derived from the susceptibility to contamination of the various instruments. These factors must be offered by the project scientist. Note that best effort requirements are not requirements for the purpose of this process. The derivation and establishment of acceptable system requirements should be based on an iteration between science desirements and engineering feasibility. It is recommended that this process be started as soon as possible (since GAP may drive this process, see the Section 6.4, GAP).

6.6 Assembly Integration and Verification

6.6.1 Completeness

The proposed AIV plan is contained in the Design, Development and Verification Plan which is referenced in this report. This DDV document shows the various test models and the probe and Lander culminating in a Flight Model probe which is cleaned for planetary protection on the final hardware build of instruments and equipment before delivery to the Mars Express Spacecraft. Review of the plan showed up the need to obtain the maximum value for the Beagle 2 development programme and in this regard discussions with the Mars Express project on the minimum build standard of the probe for spacecraft level vibration tests could result in better value. For example, the need for an end-to-end test of the GAP experiment on the Lander was emphasised by the review team and substituting the flight model instruments and common mode electronics with mechanical and electrical dummies would allow this testing to be carried out during the 50 days the probe/Lander is on the Mars Express spacecraft for a vibration test.

Overall the DDV document does include the major assembly, integration and test activities, but only in outline.

Astrium-Ltd should have no difficulty in detailing the activities usually found on spacecraft programmes such as launch vehicle vibration. Early development testing has been introduced for new activities and tests relating to entry, landing and surface environmental operation on Mars. At equipment level testing of mechanisms is the Mars environment is not apparent from the document and solar array sample testing over temperature seems lacking.

6.6.2 Schedule

The outline planning for the system level activities and tests contains reasonable time slots for each activity/test. There is a general concern by the board members that the allocated systems schedule is inadequate for a development programme of this nature with new payload instruments and Mars related entry, landing and surface operations. Equipment delivery delays will occur on new developments as well as during the Lander level compatibility tests. A possible period of additional contingency which would be made available is to integrate the flight probe with the spacecraft at the launch site rather than integrate in Europe to the launch site. This will create 6 to 8 weeks schedule contingency and possibly ease potential problems of transportation of radioactive sources on the spacecraft.

Planning of the cleaning for planetary decontamination of the FM equipment needs to be done at a more detailed level to check the feasibility of the assembly and re-integration of equipment.

6.6.3 Pre-launch, Cruise and Coast Phase Planning

A validation plan has been prepared for activities at the launch site, cruise and coast phases to ensure that these activities are tested in the system level test programme. This validation testing will ensure operations are within design limits and provide reference data for the actual operations.

6.7 Surface Operations

A draft version of a mission operations plan is in preparation and is intended to be submitted to the PIs for approval. This should be done soon since it could have design implications, e.g. for the hardware and software of the instrument arm, PAW and Mole.

The lack of any documented functional requirements for positioning the science instruments on rocks and for positioning the sample acquisition mechanisms to deliver to SHADS/GAP (Sample Handling and Distribution System) may have very significant implications on the mission operations. There are not even good estimates of the expected positioning ability of the instrument arm subsystem, as currently conceived. As a consequence many more command cycles than planned may be needed for the acquisition of samples by SHAD.

Verification of the design of the arm hardware and software together with the instruments and tools should be accomplished by extensive end-to-end ground testing, using representative models of Martian surfaces before the flight design is finalised.

7 Detailed Findings Assessments and Recommendations

The following sections represent the compilation of the detailed thoughts and working notes of the review board members. The nature of these comments ranges from the specificity of a detailed design review to more general topics of management and management philosophy. While the Board was not asked to perform a detailed design review, and as such did not, it was necessary to probe into the specifics of the design in order to assess the health of the project. The finding and assessment sheets are formatted such that a factual , non subjective finding is made. This is followed by the Board's subjective assessment as to the potential impact of the finding, followed by a subjective recommendation for action. It is hoped that the Beagle 2 team may find useful the written documentation of the Board findings and recommendations.

System Findings

7.1.1

Findings/Observations:

There are no science and mission requirements, and therefore there is no traceable path to functional requirements and performance specifications.

Assessment:

No real ability to assess the design against the top level requirements.

Recommendation:

Produce a top level requirement document. Assess degree to which design captures the requirements.

7.1.2

Findings/Observations:

The Mars Express is largely single string and has many single point failures.

Assessment:

The mass constraints dictate this single string implementation.

Recommendation:

Formalize a program to implement robustness through high reliability parts, functional redundancy, soft failure management, acceptable degraded operations, etc.

7.1.3

Findings / Observations:

In the electrical system session it was said there was no document tree showing flow down of apportioned requirements to assemblies and the corresponding test verification.

Assessment:

7.1.1.1 None was provided

7.1.4

Findings / Observations:

High lateral and axial frequency requirements (45 + 85 Hz) imposed on Mars Express by Mars Express.

Assessment:
Drives entire Beagle design to use hyper-static interfaces increasing the risk of failure.
Recommendation:
Mars Express should consider relaxation of negotiation interface between Mars Express and Mars Express frequency requirements.

7.1.5
Findings / Observations:
There is no apparent mass margin at a time in the project when problems will be uncovered that will require mass increases for corrective action
Assessment:
If science de-scopes are required to help alleviate problems of mass growth, the process of approving such de-scopes will require time to implement the de-scopes
Recommendation:
Define both a minimum acceptable science mission, and a prioritized list of science de-scopes. Negotiate with ESA so that the Project Scientist and Project Manager(s) can exercise de-scopes that retain minimum acceptable science, and that can be acted on without seeking item by item approval by ESA.

7.1.6
Findings / Observations:
The detailed planning for contamination control of Mars Express has not been completed.
Assessment:
The implementation approach for contamination control may require hardware architectural changes which could have a significant schedule (and cost) impact.
Recommendation:
The plan should be developed as soon as possible and any hardware changes required should be implemented into the EM hardware.

7.1.7
Findings / Observations:
Mars Express requires delivery of flight hardware (FM1) to system level test at the beginning of 2002
Assessment:
Early delivery takes away valuable time from EDL development schedule
Recommendation:
Allow Mars Express to accept a model mass mock-up for system level testing

7.1.8
Findings/Observations:
During the successive presentations and splinter meetings on Avionics, some confusing information was provided in certain areas. Astrium Ltd. core team awareness of schedule and planning appeared somewhat deficient
Assessment:

The Atrium Ltd. core team may not always be in consonance with the rest of the Systems Team

Recommendation:
Consider the possibility of an integrated Core Project Team at the same location

7.2 Entry Descent and Landing Systems

7.2.1

Findings / Observations:
There has been a proposed change in the Mars Express / Beagle 2 thermal interface (by MEX) from ± 20° C. to ± 50° C.

Assessment:
If the change were to be made, both the Beagle 2 thermal and power designs are affected with a probable increase in Probe mass.

Recommendation:
Firm up the requirement ASAP so that cost, schedule and mass issues can be dealt with minimum adverse effects.

7.2.2

Findings/Observations:
The separation Band is not restrained after separation.

Assessment:
The separation Band could end up in a position which would compromise the successful opening of the Mars Express.

Recommendation:
The separation Band should be redesigned to provide a completely deterministic separation.

7.2.3

Findings/Observations:
"Mechanisms" environmental compatibility is not verified until PFM

Assessment:
Design heritage of Mechanisms has to be demonstrated if envirmental compatibility is deferred until PFM program

Recommendation:
Perform early environmental tests on DM mechanisms to test lubricant performance

7.2.4

Findings/Observations:
According to DD&V Plan, Transponder environmental compatibility is not verified until PFM Vacuum Test

Assessment:
Transponder Design does not have enough heritage to justify environmental compatibility test as late as PFM

Recommendation:
Perform environmental testing on Transponder QM

7.2.5

Findings/Observations:

The mechanical design makes use of many Titanium on Titanium separation joints.

Assessment:

Ti on Ti moving joints run the risk of seizure due to galling. Seized joint could result in loss of mission.

Recommendation:

Redesign the joints to eliminate the risk of galling.

7.2.6

Findings / Observations:

Beagle team is relying on Mars Express to do separation analysis.

Assessment:

Primary source of separation dispersion may come from Mars Express SUEM.
Mars Express team should feel 100% responsible for this separation event.

Recommendation:

Beagle 2 team should participate jointly in the separation with Mars Express.

7.2.7

Findings / Observations:

Beagle 2 team does not have intimate knowledge of Mars Express top floor mechanical layout and configuration.

Assessment:

Mars Express team may not be aware of issues that Beagle Team deems hazardous to mission success, e.g., deployables, thermal.

Recommendation:

Both teams should teams should be intimately familiar with both sides of the interface, and stay appraised of changes all the way through to launch

7.2.8

Findings / Observations:

Thermal spacer under SUEM feet carries launch load

Assessment:

Load paths through Glass Fibre reinforced plastic thermal insulator are not well understood and may involve loading the 0.010 inch thick AL face sheets on the Mars Express top floor end-on for primary load transfer.

Recommendation:

Remove the load path ambiguity

7.2.9

Findings / Observations:

The launch lock is hyper-static and in addition has Ti-on-Ti cup cone interface w/ Teflon lubricant

Assessment:

The hyper-static interface reduces reliability of loads prediction
The hyper-static interface is susceptible to high internal loads, which in turn could be a threat to lubrication therefore galling (Ti-Ti)
Tolerance of pattern could induce internal loads and moments into the Frangibolt
Recommendation:
Ideally eliminate over-constraint. If the 45 Hz min freq. requirements prevent this, float the cup or cone to eliminate tolerance problem during assembly, replace Ti with steel on 1 of 2 surfaces.

7.2.10
Findings / Observations:
Separation joint between back-cover and Lander has hyper-static cup/cone interface and no push-off springs.
Assessment:
15° cone angle is close to untreated locking angle. Hyper-static I/F may result in large internal loads.
Cup/cone separation may not occur. Failure of this separation is a mission failure.
Recommendation:
Re-design the joint to have large separation margin w/o lubricant.
Consider re-design of joint to yield statically determined joint.
Consider inclusion of separation spring at each joint.

7.2.11
Findings / Observations:
The Beagle 2 Team is relying on availability of Plum-Brook for performing 2 sets of drop tests
Assessment:
The team should assume that 2 sets will <u>not</u> be sufficient.
The team may not have access to Plum Brook since MER + payload fairings tests are happening during the same time period.
Recommendation:
Team should find their own impact test facility where they can have unlimited access to testing

7.2.12
Findings / Observation:
Airbag development is at pre-PDR maturity level
Assessment:
This situation represents a major risk to the project, which could require changes to the parachute, heatshield and other components of the Lander.
Recommendation:
Project must re-allocate resources to bring the airbag development to phase C/D ASAP.

7.2.13
Findings / Observations:
EDLS test program lacks combined subsystem dynamic deployment testing.
Assessment:

Large scale multi-component testing is not currently planned or budgeted. These tests are needed to illuminate the "unknown-unknowns" found in the component interaction.

Recommendation:

The EDLS test program should be augmented to include multi-component sub-system testing.

7.2.14

Findings / Observations:

The heatshield Lander separation joint is uncontrolled during separation event.

Assessment:

Between backcover separation and subsonic parachute deployment the heatshield is resting against the Lander by virtue of aerodynamic forces and its position and attitude are not controlled. This may result in binding or catching on the airbags, Lander structure, or other feature. these may prevent proper separation performance

Recommendation:

Redesign joint to include statically determinant separation interface <u>and</u> separation push-off springs. Preferred solution may require two separation devices, one for the back cover and one for the heatshield.

7.3 Lander Systems

7.3.1

Findings/Observations:

Auxiliary power supply is the most critical one of the Lander electronics since it is used for all essential users like the Processor. APS FMECA reports that over 80% of failure modes have a criticality of one and therefore lead to the loss of missions.

Assessment:

This raises a concern about the lack of robustness.

Recommendation:

Consider implementing single point failure tolerance in the most critical areas of the APS. As an example, using self-healing capacitors as opposed to Ceramic may take a little more volume but the same mass, and the risk of failure in short circuit is negligible.

7.3.2

Findings/Observations:

RF Communications from the Lander cannot be established until after the Lander has opened up on the surface of Mars.

Assessment:

If no transmission was ever received from the Lander then no information on the possible cause of failure would be available.

Recommendation:

That consideration to given to adding a UHF antenna on the upper shell of the Lander (possibly utilizing some of the balance mass) so that a short RF carrier could be transmitted at a predetermined time in the event normal communications were not established.

7.3.3

Findings/Observations:
Thermo-Mechanical verification of Solar Cell bonding on panel substrate is not performed by sample testing over temperature. Furthermore, cell T-Limits have not been defined.
Assessment:
Thermo-Mechanical verification of Solar Cells gluing technique is straightforward (Thermal Vacuum testing of a few cells is sufficient and should be.
Recommendation:
1 Obtain temperature predictions of Solar Cell/Glue/Substrate Assembly from existing thermal analysis
2 Perform early Thermal Vacuum testing of a few cells on a piece of substrate to Qual.
3 Perform TV testing of 3 flight panels to acceptance levels.
Levels

7.3.4
Findings/Observations:
Torque margin for Lander main hinge actuator is not up to ESA standards.
Assessment:
ESA torque margin standards, which are derived for orbital spacecraft, should be considered an absolute minimum for the design of any planetary system. Torque margins approaching 4 should be used for this and other Mars Express mission critical single point failure mechanisms.
Recommendation:
Re-manufacture gear drive systems to improve margins to the 3-4 range.

7.3.5
Findings/Observations:
Gear drives on several Lander mechanisms can be destroyed by application of maximum drive motor torque.
Assessment:
This is poor design practice with possible gear drive failure during testing.
Recommendation:
Remanufacture gear drives to survive the motor stall torque.

7.3.6
Findings/Observations:
Although FMECA and Part Stress Analysis have been produced for the two essential power supplies of the Lander, no Worst Case analysis is currently envisaged.
Assessment:
Verification that required performances by Lander Electronics and Instruments are met under applicable worst case conditions is a key analysis for validating the design.
Recommendation:
Carry out WCA

7.3.7
Findings/Observations:

Solar array deployment motors are supplied from the Payload power supply PPS which requires the Auxiliary Power Supply APS to be operational.
If APS remains operational for a Battery Voltage as low as possible (typically 15v), the PPS is switched OFF on Battery Voltage below 18v.

Assessment:
Since Solar Array deployment is essential even if the Battery is almost fully discharged, SA deployment Motors shall be supplied whatever the Battery Voltage.

Recommendation:
Solar panels have to be deployed.

7.3.8

Findings / Observations:
The plan is to hard wire all of the boards around the battery and they will have to be unsoldered in the event of problems on a board and to install the flight battery.

Assessment:
Schedule will be extended with this approach if rework is required and may compromise the previously sterilized (decontaminated) assemblies

Recommendation:
Consider some of the modern miniature connectors or as a minimum use connectors through the test program and solder only after the flight battery is installed.

7.3.9

Findings / Observations:
The small size of the sample cup in the mole makes it sensitive to electrostatic adhesion of sample to inside of cup

Assessment:
May not be able to get sample out of mole

Recommendation:
Re-evaluate or re-design the sample extraction system / mechanism to eliminate the sensitivity to electrostatic forces and need for gravity.

7.3.10

Findings / Observations:
All instruments supplied from the same dc/dc converter

Assessment:
A single instrument failure shall not be able to permanently fail the dc/dc converter

Recommendation / Request for info:
Failure propagation risks from the instruments to the power supply should be carefully addressed.

7.3.11

Findings / Observations:
The complete descent / deployment sequence of the probe relies on timer for wake-up and on the processor that could be reset by an Electro Static Discharge (ESD)

Assessment:
No ESD test is currently included in the planning.
Recommendation:
This should be studied furthered.

7.3.12
Findings / Observations:
1) Except the transceiver, none of the Lander electronics is embedded in boxes for mass saving reasons.
2) There is no EMC specification although it seems from discussion that some requirements on instruments and power supplies do exist.
3) A fairly complete EMC test program has been accounted for in the schedule
Assessment:
1) Lander electronics susceptibility to electromagnetic environment is increased
2) Lack of EMC specification for the Probe/Lander is definitely a risk factor increase
3) A step by step EMC test program will certainly reduce the risks but may induce a number of re-design iterations.
Recommendation:
An EMC specification should be produced with adequate levels against which CE, CS, RE, RS tests will be performed.
This EMC specification shall be used as an input to the Lander EMC analysis yet to be performed.

7.3.13
Findings/Observations:
Current MEX plans require the SUEM to be removed from MEX after environmental testing but prior to separation testing.
Assessment:
Removing the SUEM from MEX prior to performing the separation test will completely invalidate the results of the separation test, since the purpose of the test is to determine the effect of the environment test on the MEX-SUEM interface.
Recommendation:
Either perform the SUEM separation test while still attached to MEX, or don't do one at all.

7.3.14
Findings / Observations:
The "dirty" side of the PAW has to be designed to work reliably in the presence of dust and the soil particles. No evidence was shown that this requirement has been taken into account in the design of the tools.
Assessment:
A number of mechanisms in the PAW may be quite sensitive to dust. Without proper sealing the mechanisms may fail.
Recommendation:
Seal all mechanisms from dust.
Perform as soon as possible tests with development models of sealed tools in a test chamber with Mars soil stimulant (e.g. at DLR Cologne).

7.3.15

Findings / Observations:

The review team has seen very little information on the mole and the corer/grinder.

Assessment:

The achievement of the scientific objectives depends to a large extent on the correct operations of these tools.

Recommendation:

The design and performance of these items should be peer-reviewed as soon as possible.

7.3.16

Findings / Observations:

The requirements for positioning in terms of orientation / perpendicularity on surfaces by the PAW instruments and tools are not documented.

Assessment:

It is unclear to what extent the instrument arm will be able to position the instruments and tools in such a way that they can be operated properly.

Recommendation:

Establish the requirements for positioning of the arm on the sample sources.

7.4 Gas Analyzer Package

7.4.1

Findings / Observations:

One of the mass savings actions taken by GAP was to put the high voltage power supply in a pressurized package, rather than potting it.

Assessment:

A leak in the pressurized package would likely result in a failure on the Mars surface by way of arcing or corona discharge. This would result in a complete failure of GAP, and possibly to the Lander

Recommendation:

The high voltage unit should be qualified at the component level, including an accelerated life test with appropriate temperature cycling.

7.4.2

Findings / Observations:

Planning of the GAP test program is late.

Assessment:

Proceeding into tests without a plan is risky

Recommendation:

A test plan should be defined and agreed ASAP

7.5 Planetary Protection

7.5.1

Findings / Observations:
The Lander assembly sequence is preliminary, pending sterilization procedure definition
Assessment:
Planetary Protection is also dependent on assembly sequence, so that leaving one matter resolution until after the other, is a threat to successful planetary protection
Recommendation:
1) AIV should produce more detailed description of FM1 disassembly and FM2 assembly (to the level of assembly) preferred by the project, in the absence of PP.
2) Planetary protection group should review item 1 for recontamination issues
3) Planetary protection group should promptly issue a preliminary assessment of further disassembly required for sterilization

7.5.2
Findings / Observations:
Schedule period 7/12/00 through 11/28/02 including 25 day contingency.
Assessment:
The period is too short for required disassembly, microbial reduction, assays, re-assembly because there is no clear time for assays, logistical problem of disassembly/assembly timeline granularity vs sterilization facility scheduling, and no clear time for liveliness tests and re-cleaning if spore numbers are too large.
Recommendation:
1) Sterilize components that have protected surfaces before FM1 assembly, as required. Suggest airbags, parachute, GAP, etc.
2) Perform some assays on FM1 (as is) to establish a worst case for FM2 decontamination approach feasibility
3) Plan now well before July 2002. Consider softness of disassembly schedule in detail vs sterilization facilities or processes availability include time for assays
4) Consider some liveliness test post PP process.

7.5.3
Findings / Observations:
No system currently in place to account and trace PP-accountable spacecraft surfaces and attendant contamination
Assessment:
Will compromise ability to identify and effectively remedy contamination problems and determine bioload
Recommendation / Request for info:
Establish a system that accounts for all PP-accountable spacecraft surfaces and tracks attendant contamination
(Recommendation made to and accepted by the Mars Express Team at the PP session)

7.5.4
Findings / Observations:
Implementation of planetary protection activities has not yet started .
Assessment:
May create schedule difficulties and compromise an otherwise good plan's implementation

Recommendation / Request for info:
Consider enabling an earlier start

7.5.5
Findings / Observations:
The current sterilization plan is to process the entire PAW and MOLE at one time, just prior to final assembly of the flight probe, by either heat or ETO.
Assessment:
It will very likely be impossible to find a single process that will be compatible with all materials and components.
Recommendation:
Identify the best technique for each assembly and determine the most efficient order and sequence to perform the decontamination operations and assembly.
Consider separate processing of instruments, prior to PAW assembly.
Note: *it may be necessary, for schedule reasons, to make an EM PAW to integrate with spacecraft and process the flight PAW separately, keeping it clean until final assembly of Beagle.*

7.5.6
Findings / Observations:
The Mars Express PP team's overall attention to, and organization for PP implementation is commendable
Assessment:
There is excellent appreciation for most issues involved in the implementation of PP requirements. The Mars Express PP plan properly executed, will more than satisfy COSPAR requirements.
Recommendation
None

7.5.7
Findings / Observations:
There is no definition of the CC requirements applicable to the design and fabrication of the Lander components.
Assessment:
Unless the particulate and molecular contamination from the Mole and other Lander components are properly controlled they will compromise the scientific objectives of the GAP
Recommendation / Request for info:
Specify science CC requirements as soon as possible then derive and accept requirements (including material selection) for the mole and other relevant Lander components.

7.5.8
Findings/Observations:
The plan is to hard wire all of the boards in around the battery, which will have to be unsoldered in the event of problems on a board and to install the flight battery.
Assessment:
Schedule risk with this approach is high and this may compromise the previously sterilized

(decontaminated) assemblies.
Recommendation:
Consider use of miniature connectors.

7.6 Assembly Integration and Validation

7.6.1
Findings/Observations:
DLM Lander is used for airbag drop testing.
Assessment:
DLM Lander seems to have more value to the mechanical Team by doing thermal and other tests.
Recommendation:
Do not use the DLM Lander for airbag testing.

7.6.3
Findings / Observations:
There is no planned system level end-to-end test of surface operations including a sequence from finding a rock through gas analysis of the sample, and down-linking the data.
Assessment:
This kind of test may uncover any number of problems that would otherwise not be uncovered in the presently planned testing. The schedule penalty may not be significant, because many planned subsystem tests at the system level would be subsumed in the end-to-end test.
Recommendation:
Establish a set of measurement protocols to be used in landed operations, and test these protocols during system testing. Perform end-to-end testing using the instrument arm DM, the instrument DM's, PAW DM in combination with a Lander DM as soon as those models are available, such that hardware and software modifications may still be possible.

7.7 Surface Operations

7.7.1
Findings / Observations:
Currently a draft mission operations plan exists for the first 50 days of the surface operations, which was prepared based on inputs from the PIs. However, the PIs have not yet to review this draft plan.
Assessment:
In order to avoid discrepancies between the PI's expectations on one hand and the capabilities of the Lander on the other hand this plan needs to be consolidated.
Recommendation:
Provide a draft mission operations plan, covering the entire baselined surface operations period, to the PIs for approval.

Attachment 1.

BEAGLE 2 INDEPENDENT REVIEW PARTICIPANTS

Name	Organisation
J. Casani	NASA/JPL
C. Pillinger	Open University
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G. Parker	NASA/JPL
A. Steltzner	NASA/JPL
T. Rivellini	NASA/JPL
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R. Horttor	NASA/JPL
P. Stabekis	Lockheed-Martin
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Glen Johnson	SSL
Judith Pillinger	Open University
Ian Praine	
Ian Wright	
Jenny Stelwart	
Andy Spry	Isotron
Dennis Leigh	Instruments development

Attachment 2.
BEAGLE 2 INDEPENDENT REVIEW
BIOGRAPHIES

Jack BARENGOLTZ

Dr. J. Barengoltz is a Principal Scientist at the Jet Propulsion Laboratory, which he joined in 1970. For the past 25 years, he has worked in the fields of contamination control and planetary protection. His experience has included the projects: Viking, Voyager, Galileo and Mars Observer. He was the contamination control lead for the wide field planetary camera 2. He was also the planetary protection lead for Mars Pathfinder, Mars '98, and Mars '01. Dr. Barengoltz also participates in the drafting of NASA Planetary Protection Regulations. A regular co-author of papers on the subject; he is a recognized expert in the field.

Thierry BLANCQUAERT

Background in electrical and power systems engineering.
Started at Aerospatiale on Ariane 5 electrical and power systems design and validation. At ESA Technical Directorate since 1992 on Huygens electrical and power systems, XMM power system and R&D. Currently involved on ATV (Automated Transfer Vehicle) power system design and SMART-1 electrical and power system development.

John CASANI

John Casani retired in 1999 after 43 years with the Jet Propulsion Laboratory. He spent the majority of his career in systems engineering and project management. He was Project Manager for three major space missions at JPL: Voyager, Galileo, and Cassini. He held senior project positions in many of the early space programs, including Explorer, Pioneer, Ranger, and Mariner. He is a recipient of several NASA awards, including the Distinguished Service Medal, the Exceptional Achievement Medal, and the Medal for Outstanding Leadership. He received the AIAA Space System Award and the von Karman Lectureship, the National Space Club Astronauts Engineer Award, and the AAS Space Flight Award. He received a BSEE and an Honorary Doctor of Science degree from the Pennsylvania and on an honorary degree in Aerospace Engineering from the University of Rome. He is a Fellow of the AIAA and is a member of the National Academy of Engineering and the International Astronautics Academy.

Cesar Gómez-Hernández

Thermal Engineer working in the ESA Technical Directorate. Professional activity centres on thermal design of space-borne earth observation instruments and detector cooling techniques using passive radiators and active refrigerators. Involvement in ESA programs has included work on ISO (Infrared Space Observatory, launched in 1992), ENVISAT (Environmental Satellite, launch 2001) and INTEGRAL (International Gamma Ray Observatory, launch 2002).

Dave HALL

Assistant Director, Space Science, British National Space Centre (BNSC). 25 years experience in development and construction of ion and electron spectrometers for studies in magnetospheric physics. Head of the Space Plasmas Group at the Rutherford Appleton Laboratory for 5 years during which the Group diversified its interests into instruments for planetary missions. Since 1995, on secondment to BNSC with duties including acting as UK representative for the International Mars Exploration Working Group and the Rosetta Steering Committee.

David LINK – MBE

ESTEC Consultant

40 years engineering and management experience in the Aerospace industry on equipment, subsystems and spacecraft projects. Projects range from scientific to commercial communication programmes. Project Manager Giotto and Inmarsat 2; Project Director and then Director of Science and Radar Observation at Matra Marconi Space.

Review responsibility : AIT and Pre-Launch operations.

Rafael C. MOLINA

Started at ESA-ESTEC in 1986, providing support in Aerodynamics and Aerothermodynamics. Has participated as support in the HERMES, HUYGENS and MSTP Programmes and actively contributed to the ARD and X-38 Programmes. Since 1996 Lead Aerodynamics and Aerothermodynamics Engineer in the CRV/CTV Study Office at ESA-ESTEC and responsible for related activities in the frame of the ARD Post-Flight Analysis.

David D. NORRIS

A JPL Interdisciplinary Principal Engineer with over 40 years experience in developing science instruments and spacecraft technology. Relevant experience for this review includes earth, lunar and planetary fields and particle experiment development, planetary and Hubble imaging system development, Viking GCMS instrument management, Viking Biology Instrument planning analysis. Co-inventor of Electro-Optical Ion Detector technology in mass spectrometry (EOID) Principal Investigator for U.S. National Institute of Health Grant for EOID technology demonstration, and Principal Investigator. for femtogram mass spectrometry applications to NASA Life Science missions.

Gary PARKER

Started at JPL in 1962 as part of the group that built the JPL Space Flight Operations Facility. Was a member of the JPL team that built the DSN station in Spain. Control System Analysist for a year then managed the Control Systems Development for Mariner 9, VO-75 and Voyager. Spacecraft Manager for the Magellan project. Integration and test Manager for the Cassini project then Managed the Planetary Flight Project Program Office at JPL. In that last position was responsible for 8 flight projects. Retired from JPL on 31 July 2000 now a consultant for SAIC.

Tom P. RIVELLINI

Senior Mechanical Systems Engineer, JPL. 9 years of experience at JPL, relevant experience for this review includes Mars Pathfinder Entry Descent and Landing System, Mars Pathfinder airbag subsystem design, Deep Space 2 Mars Microprobes Chief Mechanical Engineer and 2005 Mars lander prototype development. Technical interest include mechanical system design and configuration, structural design, landing systems, mechanical system testing.

Adam D. STELTZNER

Senior Mechanical Systems Engineer, JPL. 9 years of experience at JPL, relevant experience for this review includes slip ring anomaly analysis lead on Galileo, separation dynamisist on Cassini, stability analysis for entry, descent and landing on Mars Pathfinder and high speed entry vehicle development for the comet Nucleus Sample Return mission. Technical interest include mechanical system design and configuration, structural design, separation dynamics, mechanical system testing, analytical techniques and entry vehicle design and performance.

Michel van WINNENDAEL

ESA/Directorate of Technical and Operational Support, Automation and Robotics Section. Has been working on robotics at ESA/ESTEC since 1985; has been technical officer for various studies and development activities related to robotic systems for automated payload tending in orbital laboratories. Since a few years working mainly on planetary robotics, in particular planetary rovers. Covered robotics and mechanisms in the Beagle 2 SERT review in 1999.

Attachment 3.
BEAGLE 2 INDEPENDENT REVIEW
Datapackage Contents

Submitted documentation:

The following list of documents were submitted for review to all review board in early September:

- Management Plan plus three annexes/figures WBS, Organisation Chart and Product Tree
- Schedule as per June 2000
- Beagle 2 Technical Description (includes description of EDLS)
- Beagle 2 Payload Description
- Mass and Power Budgets. (Latter is Launch and Cruise only)
- Drawings showing Beagle 2 construction and entry system cross section
- Interface Control Drawings used with Mars Express
- Flight Operations Manual
- Design, Development and Verification Plan
- PA and Cleanliness Plans
- Planetary Protection Plan
- Planetary Protection Plan Appendices
- Planetary Protection Procedure
- Gas Analysis Package Description
- Beagle 2 NASA Telecomms ICD
- Beagle 2 Electronics Description/Diagrams based on Beagle 2 Consortium Meeting presentation

A partial list of additional documents provided at the Review includes the following:

- Beagle 2 Probe First Interface Thermal Mathematical Model
- Beagle 2 Probe Detailed Thermal Design and Analysis
- Beagle 2 Lander Phase B Thermal Design and Analysis Report
- Thermal Balance Test Specification and Procedure for Beagle 2
- Preliminary Results of Dust Coverage Trial
- Beagle 2 Airbag Conductance Measurement Preliminary Test Report
- Beagle 2 Lander Foam Conductivity Test Specification
- Common Electronic Power Supply Technical Description
- Electronics for Power Control
- Payload Power Interfaces
- B2 probe first interface thermal math model