THERMAL DESIGN OF A LUNAR PENETRATOR

Samuel Nouvellon(1), Lucy Berthoud(2), William Rickwood(3)

(1)University of Bristol, Queen's Building, University Walk, Bristol, BS8 1TR, United Kingdom,
Email: sam.nouvellon@hotmail.co.uk
(2)University of Bristol, Queen's Building, University Walk, Bristol, BS8 1TR, United Kingdom,
Email: lucy.berthoud@blueyonder.co.uk
(3)University of Bristol, Queen's Building, University Walk, Bristol, BS8 1TR, United Kingdom,
Email: willrickwood@hotmail.co.uk

ABSTRACT

The thermal design of a lunar penetrator intended to operate for up to one year in polar cold traps without use of Radioisotope Heater units is analysed and discussed. Local temperatures in polar cold traps can reach 35 K. Various different designs and materials are assessed, with factors such as mass of the subsystem, power requirements and complexity taken into account. The passive thermal control incorporates elements to reduce both conductive and radiative heat loss. With further design features based on shape memory alloys and low power microheaters, the payload can be kept operational for up to 18.8 or 30.75 days, depending on the level of complexity. As of yet, no practical method of extending the lifespan of the penetrator to a year has been found without resorting to the use of RHUs.

1. INTRODUCTION

Due to a recent revival in interest in the Moon, from both a scientific and a human exploration perspective, there has been an increase in missions and concept studies linked to our nearest celestial neighbour. However, most of the lunar geophysical data dates from the Apollo era, and scientific understanding of the Moon and the origins of the Solar System would be greatly increased by in-situ experiments [1] [2] [3][4]. Penetrator probes appear to be highly suited to this type of mission. A number of penetrator designs have been proposed for planetary exploration over the years, from Russia's Mars 96 to JAXA's Lunar-A [27]. Some have flown, such as Deep Space 2, but no penetrator mission has been fully successful as of yet. However, they remain attractive in the field of space science as they are relatively simple spacecraft, ideally suited to tasks that require a multitude of probes canvassing a wide area. They are also less expensive to build than soft landers. In this context, the British National Space Centre's MoonLITE mission concept proposes to send a low-cost orbiter and four penetrators to be fired into the surface of the Moon at different locations. These would create a network of seismometers for lunar seismology studies, perform other geochemistry and lunar heat flow measurements, and possibly detect volatiles at poles [3]. One of the stumbling blocks in its development is the problematic thermal design for operation in a polar environment.

The purpose of this study is therefore to assess whether it is possible to maintain the payload of a MoonLITE-class penetrator operational for up to a year while avoiding risky and expensive solutions, and if so, what are the requirements for such a capability. For low cost missions, Radioisotope Heater Units (RHU) and other nuclear devices are prohibitively expensive and present planetary protection issues, while the hard impactor's nature excludes fragile or large thermal systems, therefore these options were disregarded. The launch date was assumed to be in the near future, so only existing technologies were to be considered. After evaluating the optimal design for passive thermal control, the study will consider some of the technologies available and, if necessary, will make recommendations as to how these may be used to optimise the thermal capability of the spacecraft. While no experimental testing was performed for this study, the penetrator was modelled first using core heat transfer principles and then with ESATAN-TMS to demonstrate the reliability of the results and increase their accuracy. This paper aims to assess whether conventional thermal control is adequate for a typical low cost penetrator mission and how to achieve an optimum thermal capability within these constraints.

2. MISSION PARAMETERS

Two penetrators have been proposed in a lunar context: JAXA's Lunar-A and the UK's MoonLITE. The latter's goal was to be deployed at various locations, including the poles where temperatures in the cold traps may be as low as 35 K [5]. Furthermore, MoonLITE's smaller size presents more of a challenge for the thermal subsystem as it is unlikely that a RHU can be fitted inside the casing, and the lower mass reduces the thermal capacity of the probe. Therefore, the MoonLITE mission parameters were chosen as a template on which to base the following study as they are likely to represents the more extreme design case.

The original MoonLITE mission was to be composed of a lunar orbiting probe and a total of four penetrators whose purpose was to be fired into the surface of the Moon in order to study its internal structure [4]. A key component of the scientific payload is the creation of a network of seismometers that would enable the study of the geological processes of the Moon [3].These are required to run for up to a year, the heat flow measurements are performed over several lunar cycles, while the other systems are merely required to operate for one half of a lunar cycle, or approximately two Earth weeks [4]. These include volatile detection, regolith material and thermal properties, etc. A lunar cycle is 29.5 Earth days in duration.

A prototype of the lunar penetrator was built and tested by Qinetiq for the Mullard Space Science Laboratory (MSSL) at University College London in May 2008: the penetrator was able to withstand the impact into a simulated lunar soil environment [6].

The MoonLITE penetrator has the following design parameters [4] [7] [8]:

Table 1. MoonLITE penetrator design parameters

Length	*0.56 m*	Total mass	*13 kg*
Diameter	*0.12 m*	Payload mass	*7 kg*
Outer shell material	*Aluminium alloy*	Impact velocity	*300 m/s*
Outer shell thickness	*6.5 mm*	Deceleration	*10,000 - 15,000 g*
Approximate operating depth	*> 0.8 m* *3.9 m (test firing)*	Maximum angle of impact	*<8° from vertical*

While no detailed design of the penetrator has been made available yet, the following assumptions were made based on current industry practice or on other similar spacecraft, such as Mars 96, DS-2, Lunar-A or the Jovian moon penetrator concept:

- For geochemistry and volatile detection experiments, the payload would be required to run for a minimum of two Earth weeks to experience the full range of temperatures and their associated environmental conditions. The target lifespan is of one year for the seismometers [4].
- The temperature range tolerated by the battery and the payload electronics was from -40ºC to 50ºC, or 233 K to 323 K [9][10].
- The payload would require 0.06 Watts of power [7] from the lithium-ion battery, which would have a capacity of 500 W-hrs [12].

3. OPERATING ENVIRONMENT

For the purpose of this study, the penetrator depth was chosen as 2 m below the surface. The penetrators are deployed at different points, including the equator and the poles. The lunar regolith can be divided into two layers. From the surface to about 2-3 cm below, the regolith is powdery and loosely packed, which implies a low density. Beyond that depth, it becomes denser and there is the possibility of encountering larger rocky components [5]. The properties of the lunar soil were sourced from a series of measurements conducted at the surface of the Moon using equipment left by the Apollo missions [13].

Table 2. Lunar regolith thermal properties

	Density (kg/m^3)	**Thermal conductivity (W/mK)**	**Specific heat capacity (J/kg.K)**	**Thermal gradient**
Upper 3 cm	1500±50	0.0009-0.0016	1000	n/a
Below	1740	0.011-0.02	1000	1.6

Since the most extreme temperatures will be experienced at the equator and at the poles [5], it was assumed that if the penetrator could be designed to survive in both cases, then it would be able to survive in all the intermediate temperatures. However, it was found that while the temperatures vary significantly between day and night at the surface, at depth the environment rapidly becomes isothermal, as illustrated in Table 3.

Table 3. Lunar regolith temperatures

	Surface Temperature		**At depth**
	Maximum	Minimum	**(> 0.4 m)**
Equator (0º latitude)	395 K (*122 °C*)	100 K (*-173 °C*)	256 K (*-17 °C*)
Pole (90º latitude)	200 K (*-73 °C*)	70 K (*-203 °C*)	140 K (*-133 °C*)

Of particular interest is the deployment of the system in a polar cold trap, where the likelihood of finding water ice is significantly higher than in other locations [3], due to the fact that these have been permanently in shadow for several billion years. It is suggested that the temperature there is about 35-40 K [5], and that this value hardly varies with depth. As these are the most extreme conditions the penetrator may encounter, they were chosen as the design cold case.

Table 3 indicates that the penetrator would be able to survive at the equator without the need for thermal control, thus removing the need for a hot case.

4. PENETRATOR DESIGN

Heat transfer can occur in three different ways: conduction, convection and radiation. On the Moon, the lack of air or any other fluids means that convection was ignored for this study. Using basic equations from heat transfer theory, a simple model of the penetrator was used to analyse the heat flow out of the probe and select the best approach for the passive thermal protection.

The penetrator is assumed to be subdivided into two main components.

- The payload is a cuboid (a box) with dimensions 0.4 m x 0.088 m, and with a mass of 7 kg. The payload contains mainly electronic devices, which are composed of Printed Circuit Boards (PCB). These are based on the material FR-4 [14], a glass fibre set in an epoxy resin [15]. The conductive heat paths were therefore assumed to run through this material, since the metallic parts are mostly isolated from one another for electrical reasons. The payload is assumed to be a single entity generating 0.06 Watts of heat.
- An aluminium outer casing protects the payload from the external environment. As described in Table 1, it is 6.5 mm thick.

4.1. Internal layout/design

Assuming the penetrator is completely buried in close-packed lunar regolith, the maximum lifespan of the penetrator would be a few seconds at most, beyond which the payload temperature would fall below 233 K. Even with a 3.2 cm thick layer of high performance insulating material, such as Silica Aerogel [9] [16], this only increases the lifespan of the payload to 2 hours.

To reduce the severe heat loss, the penetrator interior was redesigned as a vacuum flask. Now, the payload is held away from the aluminium outer casing by a number of struts which reduce the overall surface area in contact with the outer shell. The new layout was assumed to be as follows:

- The payload is fixed to the aluminium shell by 8 struts: three at the front, one at the top, and four around the side walls (see Fig. 1). The shell is also a box, for ease of modelling. The electronics inside the payload are protected from the impact shock by sublimation-based shock absorption systems designed for the MoonLITE mission [17].

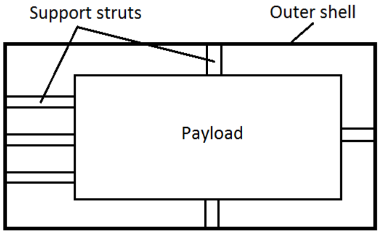

Fig. 1. Penetrator interior schematic

- The penetrator is assumed to be vertical, so that the deceleration loads are also vertical and run solely through the front struts. There is no sideways component, as these ideal conditions are obligatory for a successful penetrator landing. The front struts are 5 cm in length, while the rest are 1 cm in length.
- Its maximum operating temperature is 323K (50 ºC) and its minimum operating temperature is 233K (-40 ºC), based on the available design data. On arrival, the penetrator is at 323 K (50 ºC).

4.2. Conduction through the struts

The conduction heat paths are now exclusively through the struts. From Fourier's Law, there are two approaches to reducing the heat flow through the struts. Firstly, the struts must be designed to minimise cross sectional area and increase their length; secondly, the material from which the struts are constructed must have a low thermal conductivity. However, the struts must still be able to withstand the impact, especially those at the front where the load is at its highest. The mass of the penetrator is 13 kg, its deceleration has a maximum value of 15,000 g, and the Moon's gravitational acceleration is 1.63 m /s^2. The force on the front struts was calculated to be 318 kN.

For the initial strut design, a basic conduction model was constructed using Fourier's Law. Assuming steady one-dimensional conduction, for the time being, the model was built in analogy to electrical conduction which dictates that the heat flow out of each strut can in fact be added up in a similar fashion to Ohm's Law. Thus, assuming no radiation, the total heat transfer due to conduction is [18]:

$$\dot{Q} = \sum -kA\frac{dT}{dx} = \sum mC_p\frac{dT}{dt} \quad (1)$$

For every temperature drop of 1 K, the temperature gradient at that point is calculated and applied to a fixed time-step. Using this basic method, it was deemed possible to compare the suitability of various materials for the manufacture of the struts.

A preliminary selection of materials was undertaken, based on criteria derived from the assumptions cited previously:

- Density (ρ)
- Thermal conductivity (k)
- Specific heat capacity (C_P)
- Compressive strength (L_C)
- Minimum required cross-sectional area for front struts (A) (derived from ρ and L_C)

Table 4. Mechanical and thermal properties of candidate materials for struts [19]

Material	**ρ (kg/m^3)**	**k (W/m.K)**	**C_P (J/kg.K)**	**L_C (MPa)**	**A (cm^2)**
Aluminium 7000 (T7452)	2790	158-171	963	372-434	8.6
Titanium Ti-6Al-4V	4490	7.1-7.3	560-570	1100-1150	2.9
PEEK/IM Carbon Fibre*	1550	4.3-6.3	930	945-1200	3.4
Glass fibre S-grade†	2490	1.2	735	4000-5000	0.795

*Polyether Ether Ketone composite/Intermediate Modulus Carbon Fibre
†10µm monofilament

The time taken for the payload to cool down from 323 K to 233 K solely through conduction is plotted here:

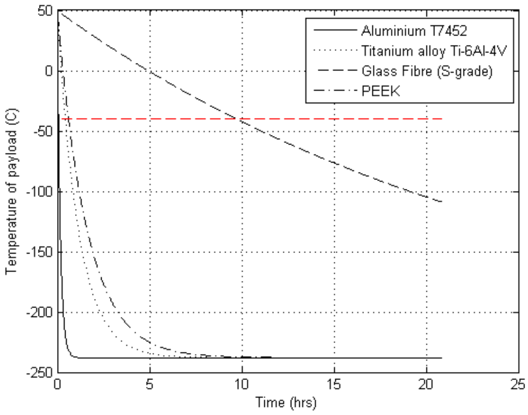

Fig. 2. Penetrator payload temperature decay assuming conductive heat loss only
Note: the red dotted line denotes the minimum operating temperature

S-grade glass fibre has the best performance in minimising heat loss, the payload taking approximately 9.73 hours to drop below -40 C.

4.3. Radiation between payload and outer casing

The heat loss due to radiation from the payload to the rapidly cooling outer shell was incorporated into the initial model. If the radiation is within the spacecraft, the sum of the view factors to the surrounding components is equal to 1 [20].

Taking into account radiative heat transfer, equation (1) is now rewritten [18]:

$$\left(\sum -kA\frac{dT}{dx}\right) - \sigma\varepsilon A\left(T_{emit}{}^{4} - T_{abs}{}^{4}\right) = \sum mC_p\frac{dT}{dt} \quad (2)$$

Several methods of minimising radiation are available in the form of coatings or coverings that have a low emittance ε.

Table 5. Properties of candidate materials for radiative insulation coatings [21] [20]

Surface covering	**Effective Emittance (W/m^2)**	**Mass per unit area (kg/m^2)**	**Mass penalty (kg)**
Polished Aluminium	0.08	n/a	n/a
Gold coating (0.1 mm)	0.04	1.93	0.301
Polished beryllium (0.1 mm)	0.01	1.85	0.289
MLI – 40 goldized Kapton layers	0.005	4.4	0.686

*Multi Layer Insulation

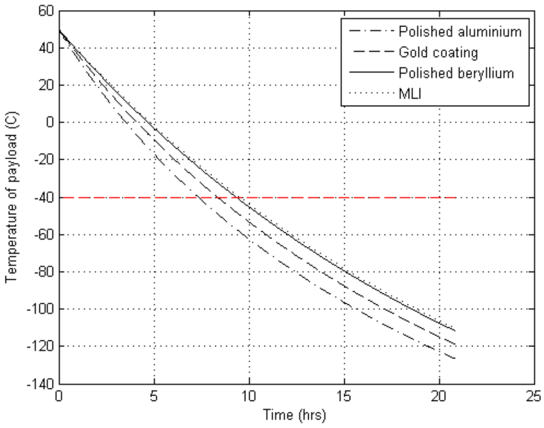

Fig. 3. Penetrator payload temperature decay, assuming radiative heat loss through payload walls and conductive heat loss through S-grade glass fibre struts

Combined with S-grade glass fibre struts, the MLI offers the longest payload lifespan: close to 9.5 hours of operation in a polar cold trap. However, MLI is fragile and it cannot be guaranteed to withstand the very high deceleration during impact. A tear in the thermal blanket could reduce the lifespan by up to an hour if the aluminium inner casing is exposed. With time being such a valuable resource, this could significantly hamper the penetrator's capabilities. Furthermore, the bulkiness of the blankets adds extra mass and reduces the volume of the vacuum gap [22].

Polished beryllium achieves much the same performance, but with less than half the mass, assuming a 0.1 mm coating thickness. Unfortunately, beryllium requires a highly complex and expensive coating process which may conflict with the low-cost nature of the probe. Therefore, taking into account performance, mass and complexity, a gold coating is considered to be the best practical option for radiation insulation, and the payload's lifespan is therefore 8.34 hours.

5. PENETRATOR MODELLING AND DESIGN OPTIMISATION

Once the design of the penetrator's vacuum flask was completed, a more reliable model was developed using ESATAN-TMS (r2) in order to gather more accurate data on the penetrator's lifespan in the absence of any thermal control systems and verify the realism of the values that were obtained.

5.1. Design optimisation

In an effort to increase the penetrator's lifespan without the use of thermal control systems, the heat loss through the struts had to be reduced. This can be done by lowering the effective conductivity of the conduction paths via the inclusion of highly insulating material. Silica Aerogel has a wide application in spacecraft design due to its very good insulating properties, as detailed here:

Table 6. Aerogel material properties [23]

Material	Silica Aerogel†
Density	50 kg/m^3
Thermal conductivity	0.041 W/m.K
Specific heat capacity	214 J/kg.K
Compressive strength	4.0 MPa

†Isocyanate cross-linked nanostructured silica Aerogel

If a thin slither of insulating material is placed between the electronics and their aluminium payload casing, within the payload so that they benefit from sublimation-based shock absorbers [17], it is expected that the ultra-low thermal conductivity of these materials would increase the penetrator's durability in its freezing environment.

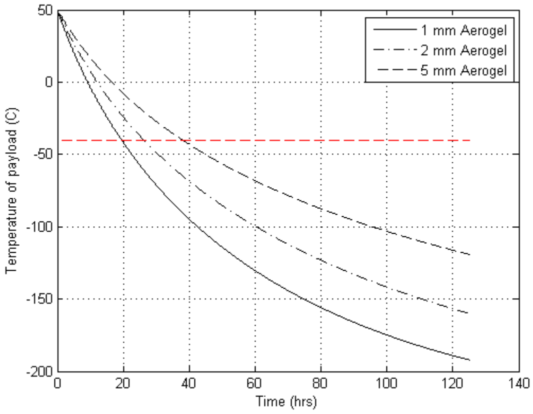

Fig. 4. Penetrator payload temperature decay for various Aerogel insulation thicknesses (gold radiation coating on payload)

As Fig. 4 shows, a thin 5 mm layer of Silica Aerogel increases the lifespan approximately 38.05 hours, mainly due to the fact that the heat loss through conduction has dropped from 19.08 W to 1.58 W at beginning of life (BOL). The mass penalty for a 5 mm layer of Aerogel within the payload is 39 g.

Note that if beryllium is used, its slight performance edge over gold as a radiative insulator (described in section 4) is greatly magnified by the use of Aerogel. Using 5 mm of Aerogel in a beryllium-coated payload increases the lifespan to just under 70 hours. In effect, the lifespan of the penetrator can be almost doubled with beryllium coating, although for a large increase in complexity and cost.

5.2. Lunar regolith heat storage on impact

A potential method of using the kinetic energy from the impact involves using the lunar regolith itself as a heat storage medium. The very low thermal conductivity of the regolith, as low as 0.011 W/mK at depth, would mean that the heat generated during the impact would only dissipate away slowly. Thus the immediate environment around the penetrator would receive up to 585000 Joules of energy from the penetrator. Assuming a 1 m^3 environment and using the data provided in Table 2, this in fact only raises the local temperature to around 35.5 K, which is negligible for this study.

Other means of storing the kinetic energy, such as flywheels, were analysed and discarded due to complexity and mass.

5.3. Design summary

In summary, the thermal design of the lunar penetrator was set as follows:

- The payload is held within a vacuum flask, minimising conductive heat losses.
- Conductive heat transfer is through the struts that fix the payload casing to the shell. These are made from S-grade glass fibre, a high strength material already used in space applications.
- To reduce heat losses due to radiation, the payload casing is covered in polished gold or beryllium coating.
- The interior of the payload is lined with 5 mm of silica Aerogel, an ultra-light insulating substance.

The design of the penetrator alone gives the payload a maximum lifespan of 1.6 days or 2.9 days, with gold and beryllium coatings respectively.

6. ESATAN-TMS MODELLING

ESATAN-TMS (Thermal Modelling Suite) is a software tool that is used within the spacecraft industry for thermal analysis. It allows the creation of a model through the use of basic “shells” that can be discretised as nodes. Radiative and conductive heat transfer calculations can then be performed by the program, thus providing a good assessment whether the original model used in this study was sufficiently correct and accurate.

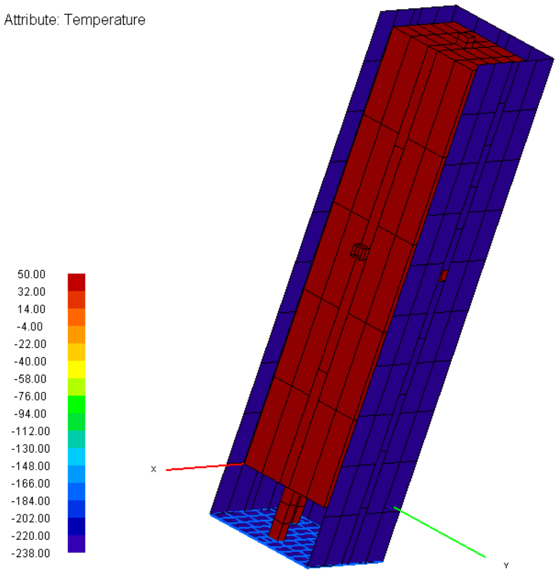

Fig. 5. Penetrator temperature distribution at t = 0 (inc. cooled outer shell cut-away)

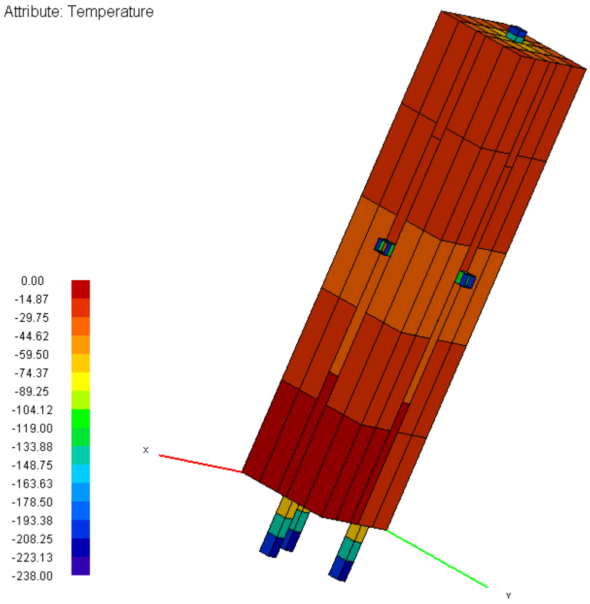

Fig. 6. Penetrator temperature distribution at t = 4 hrs (no Aerogel insulation, gold coating)

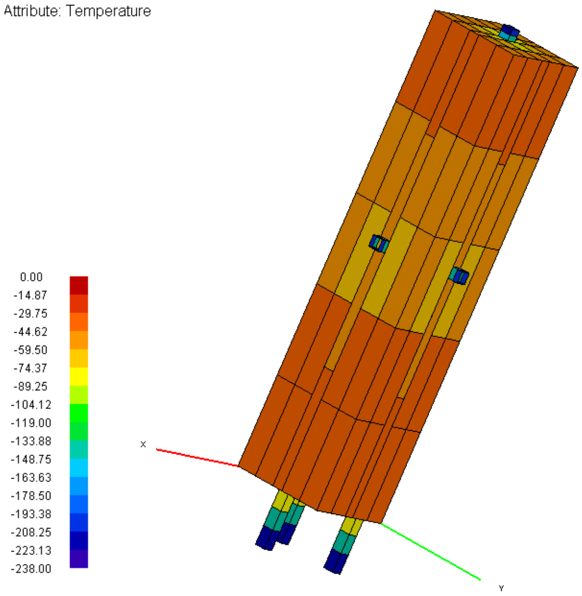

Fig. 7. Penetrator temperature distribution at t = 8.5 hrs (no Aerogel insulation, gold coating)

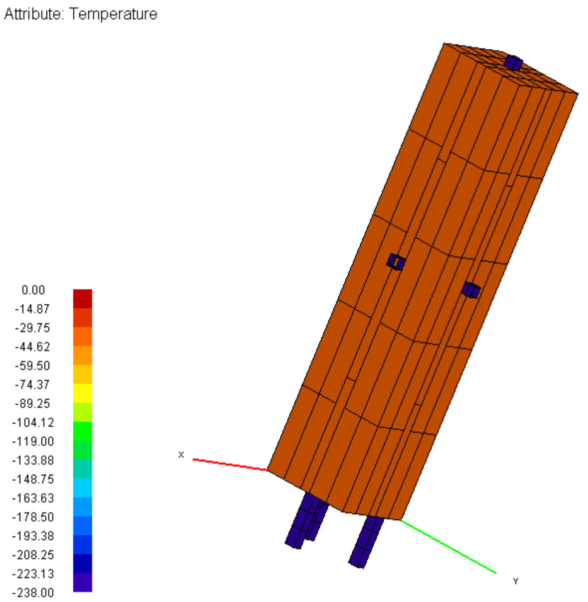

Fig. 8. Penetrator temperature distribution at t = 38 hrs (with Aerogel insulation at base of support struts, gold coating)

Table 7. Comparison of temperatures from both models

No Aerogel insulation

Model	1D simple model	3D ESATAN-TMS
0.5 hours	43.2	9.5
4 hours	1.3	-15.3
8.5 hours	-41.1	-45.2

Aerogel insulation at base of each support strut

Model	1D simple model	3D ESATAN-TMS
7 hours	25.8	-10.1
38 hours	-39.9	-41.8

The results obtained from ESATAN-TMS confirmed those gathered from the first model. The theoretical approach and its associated assumptions were therefore assumed to be valid, and the results were thus considered to be relatively accurate, although the ESATAN data suggested an initially faster rate of cooling, possibly due to a better representation of conductive-radiative couplings.

7. REMOVABLE STRUT

A simple approach to reduce the conductive heat flow out of the payload involves actually reducing the heat transfer out by severing a certain number of conduction paths. Indeed, once, the penetrator is buried in the lunar regolith, the number of struts used to keep the payload casing in place could be reduced without compromising the payload's integrity, since the struts themselves only act as supports now.

Shape Memory Alloys (SMA) are materials whose shape changes with temperature fluctuations. There has been some precedent for this type of technology in the space industry, notably from TiNi Aerospace Inc., whose products have been included on several past missions including two Lunar orbiters: LCROSS and Lunar Prospector. Notably, the company's P5-STD model [24] appeared to be most appropriate for a small penetrator. Its "Pinpuller" design, shown in Fig. 10, was envisaged as a replacement for the rear strut where the impact forces will be low.

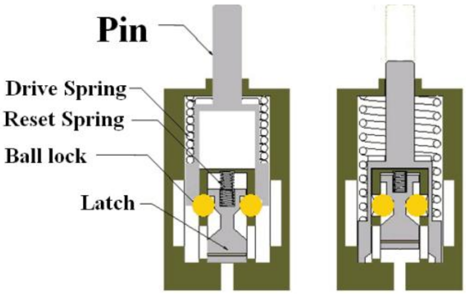

Fig. 10. SMA-based P5-STD retractable pin schematic [24]

Once the penetrator is safely buried and stable in the regolith, the reset spring retracts causing the latch to move upwards and close the ball lock. The movement of the balls away from their original position allows the compressed drive spring to expand and push the pin downwards. The drive spring is necessary due to the weak lunar gravity which cannot guarantee the pin automatically "falling".

The P5-STD model has a mass ranging from 23.9 and 328.9 grams, depending on the size of the device, and can retract the pin-strut by up to 1.6 cm [24]. If the strut itself is made out of low conductivity material such as S-grade glass fibre, this should limit significant radiation. Otherwise, covering it in a gold coating should prevent radiative heat loss.

The advantage of this system is that it is activated once the local temperature drops below a chosen level. Since the heat flow out of the penetrator is highest for conduction at high temperatures, it would be advantageous to drop the strut as early as possible, in other words at a high temperature: this was chosen to be 320 K to avoid premature activation.

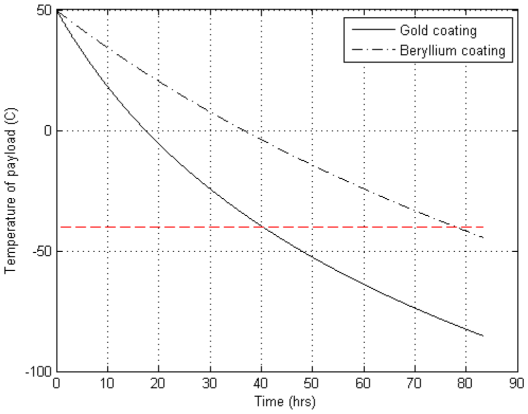

Fig. 11. Penetrator payload temperature decay with 7 struts

By removing the top strut soon after impact, the penetrator's lifespan was increased to 40 hours with gold coating on the payload casing, and close to 78 hours with beryllium coating.

8. HEATER ACTIVATION

As the temperature approaches -40 °C, the heat flow out of the payload reduces to approximately 1 W. Due to the low payload power requirements, the battery still retains much of its original 500 W.hrs capacity. The heat loss can be compensated by using microheaters fed by the battery, which are modelled as a single node at the centre of the payload [21] [22].

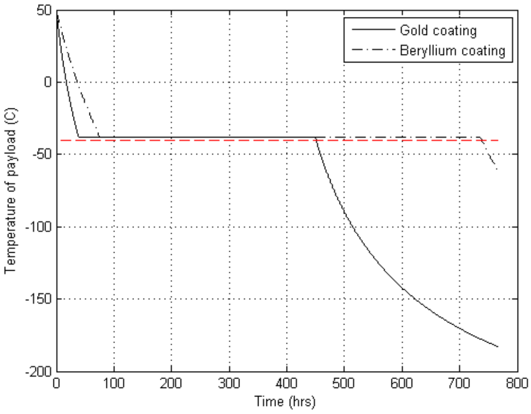

Fig. 12. Penetrator payload temperature decay with activation of microheaters when temperature drops below -35°C

The payload's operational lifespan is extended to 18.8 days if using gold coating, and 30.75 days if using beryllium coating.

Considering the science requirements demanded from MoonLITE, as described in section 2, an 18-day operational life would allow most of the short-term experiments to be completed, while a 30-day lifespan would allow geological heat flow analysis to be performed over one lunar cycle. In the latter's case, the experiments conducted in an initial 15-day phase may be repeated to analyse the change in material and magnetic properties over the lunar cycle.

The year-long seismology experiments are certainly not achievable, although some possibilities remain if the lunar transit spacecraft – or an orbiter – is then crashed into the surface of the Moon, similarly to SMART-1. The subsequent seismic waves would be recorded by the penetrators placed at different locations on the Moon.

Table 8. Summary of payload lifespan at each design level

Design level		**Maximum payload lifespan**
Aluminium casing		< 1 second
Vacuum flask, S-grade glass fibre struts	Gold coating	8.34 hours
	Beryllium coating	9.50 hours
Aerogel insulation (5mm)	Gold coating	1.6 days
	Beryllium coating	2.9 days
Retractable strut	Gold coating	1.67 days
	Beryllium coating	3.25 days
Microheaters	Gold coating	18.80 days
	Beryllium coating	30.75 days

9. CONCLUSION

This study has shown that it is possible for the sub-surface MoonLITE lunar penetrator to operate for at least two terrestrial weeks in a polar cold trap where the local temperature is 35 K, without the use of nuclear devices such as Radioisotope Thermal Generators (RHUs) or complex mechanical systems. By designing the penetrator as a vacuum flask where the payload casing is held in place by 8 glass fibre struts and coated in gold for radiation limitation, the penetrator lifespan is increased from a few seconds to a maximum of 1.6 days if heat losses are minimised via the application of highly insulating Aerogel. Further gains in lifespan were achieved through the inclusion of a shape memory alloy mechanism that removes one of the conductive heat paths, and microheaters that compensated for the heat loss when the payload temperature drops below a certain level. This pushed the payload lifetime up to 18.8 days. The use of beryllium coating instead of gold nearly doubles this value to give 30.75 days of operations, at the expense of manufacturing complexity and costs. The mass of the entire proposed thermal subsystem is under 0.53 kg.

The technology downselection was performed using a model derived from first principles of heat transfer theory. Validation of the method used and of the results was confirmed with ESATAN-TMS software. However, the local environmental conditions at the polar cold trap were found to be too extreme for the penetrator to survive more than a month, let alone a year as required for the seismology experiments posited for the MoonLITE mission.

To achieve this target, it would appear that the inclusion of a RHU onboard would be necessary, although this would certainly cause planetary protection issues, especially if volatiles which may be useful to a renewed human presence on the Moon were to be discovered in those regions. The use of a RHU would therefore certainly require a redesign of the penetrator. It is recommended that further study would include experimental testing of the penetrator's thermal capability to validate the design and refine the accuracy of its performance data. Additional impact testing would also be needed to ensure that the vacuum flask design is capable of withstanding the forces of impact.

Other issues include the thermal control of the penetrators during their transfer to the Moon, where the heat transfer dynamics are similar to those experienced by a satellite: this would presumably require active thermal control provided by the microheaters, fed by the main spacecraft, to maintain the payloads in an operational state and ensure that the systems are kept at 323 K up to the point when they are fired at the lunar surface.

10. ACKNOWLEDGEMENTS

The author wishes to acknowledge and thank Dr Lucy Berthoud, William Rickwood, Dr Roger Moses and Dr Mike Tierney of the University of Bristol; Dr Chris Chaloner and Nick Cavan of SEA Ltd; and Yannick Melameka of ESATAN-TMS Support for their help and advice throughout the duration of the project.

11. REFERENCES

[1] Smith, A. And Crawford I. A., et al. "Lunar Ex – A proposal to cosmic vision", *Exposition on Astronomy,* 2009

[2] Gao, Y., Phipps, A., Taylor, M., Clemmet, J., Parker, D., Crawford, I. A., Ball, A. J., Wilson, L., Da Silva Curiel A., Davies, P., Sweeting, M., Baker, A., "UK Lunar Science Missions: MoonLITE and Moonraker", *DGLR International Symposium "To Moon and beyond"*, Germany, 2007

[3] Crawford, I. and Smith, A., "MoonLITE Science Requirements" *ML/RQ/001,* 2008

[4] BSNC, Science & Technologies Faculty Council, "MoonLITE - Mission Requirements Document", Isue 2, *ML/RQ/001,* 2008

[5] Surkov, Y. A., and Kremnev, R. S., "Mars 96 mission: Mars exploration with the use of penetrators", *Planetary and Space Science,* 46, 11-12, pp.1689-1696, 1998

[6] Vasavada, A. R., Paige, D. A., Wood, S. E., "Near surface temperatures on Mercury and the Moon and the stability of ice deposits", *Icarus,* 141, pp.179-193, 1999

[7] Gowen, R., "An update on MoonLITE", *UK Penetrator Consortium, EGU Vienna,* 2009

[8] Smith, A., Sweeting, M., et al, "MoonLITE and LunarEx penetrator missions to the Moon", *Asia Oceania Geosciences Society, Bangkok,* 2007

[9] Gowen, R., "Progress of MoonLITE Penetrators", *Lunar Exploration Analysis Group 2008,* Lunar and Planetary Institute, Florida, US, 2008

[10] S. Vijendran, J. Fielding, J. Köhler, R. Gowen, P. Church, P. Falkner, A penetrator for the Jupiter Ganymede Orbiter Mission, *Proceedings of the 7th International Planetary Probe Workshop: Barcelona, Spain,* 2010

[12] Smith, A., Gowen, R., Gao, Y., Church, P., "Technical Trade Study for a Lunar Penetrator Mission", *International Lunar Exploration Working Group (ILWEG), 9th Conference, Sorrento,* 2007

[13] Bates, J. R., Lauderdale, W. W., and Kernaghan, H., "ALSEP Termination Report", pp. 134-136, *NASA Reference Publication 1036,* 1979

[14] Bulletti, A., Capineri, L., Materassi, M., Dunn, B. D., "Surface Resistivity and Characterization of New Printed Circuit Board Electronics for Use in Spacecraft Electronics", *IEEE Transactions on Electronics Packaging Manufacturing,* Vol. 30, No. 2, 2007

[15] Plastics International, FR-4 Glass/Epoxy Material Specification Sheet

[16] Calemczuk, R., De Goer A. M., Salce, B., Maynard R., Zarembowitch, A., "Low Temperature Properties of Silica Aerogels", *Europhysics Letters,* 3 (11), pp. 1205-1211, 1987

[17] Hopf, T., Kumar, S., Karl, W. J., Pik, W. T., "Shock protection of penetrator-based instrumentation via a sublimation approach", *Advances in Space Research,* 45, pp. 460-467, 2010

[18] Rogers, G., and Mayhew, Y., "*Engineering Thermodynamics: Work and Heat Transfer*", 4th edition, Pearson Education, 1992

[19] Granta Design Ltd, *CES Edupack 2010,* version 6.2.0

[20] Fortescue, P., Stark, J., Swinerd, G., "*Spacecraft Systems Engineering*", 3rd Edition, pp.355-364, John Wiley and Sons Ltd, 2003

[21] Panetti, A. and McMordie ,R. K., "*Space Mission Analysis and Design*", 3rd edition, Wertz, J. R., and

Larson, W. J., (Eds), 11.5, pp. 428-458, Microcosm Press, 1999

[22] D.G. Gilmore (ed), "*Spacecraft thermal control handbook"*, Volume I: Fundamental Technologies (2nd Edition), AIAA/Aerospace Press, 2002

[23] Roy, S., Shimpi, N., Katti, Atul., Lu, H., Rahman, M., "Mechanical Characterization and Modelling of Isocyanate-Crosslinked Nanostructured Silica Aerogels", *American Institute of Aeronautics and Astronautics, 2006-1770, 47th AIAA/AMSE/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference,* 2006

[24] TiNi Aerospace Inc, available at: www.tiniaerospace.com , accessed on 07/03/2011