Mars Micro Balloon Probe

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Background

The Mars Micro Balloon Probe (MMBP) is a project to create a low-cost airborne Mars photographic probe with a trans-Mars injection (TMI) mass an order of magnitude less than that of any Mars balloon probe designed to date. This can be done by approaching the gondola design in a spirit of ruthless minimalism, reducing it to a single instrument coupled with a computer, UHF radio transmitter/receiver, and a primary battery power supply suitable for a one day flight. In addition, large mass savings and greater simplicity and reliability can be achieved by replacing the traditional complex high pressure hydrogen or helium inflation gear coupled with superpressure or overpressure balloons with a novel self inflating zero-pressure balloon using ammonia or water vapor for lift. Combining these innovations, it is possible to create MMBP units with a total TMI mass, including entry system, on the order of 10 kg. Such light weight systems would be prime candidates to fly as hitch-hiker payloads on any of the numerous Mars missions planned for the near future. This would allow high resolution aerial photography to be performed on Mars without the loss of any of the surface or orbital science currently planned.

MMBP Solar Balloon Using Self-Inflating Lift Fluids

Conventional Mars balloon mission designs, such as MAP and the French Mars balloon, have incurred large penalties in both mass and complexity through their requirement to carry large amounts of high pressure life gases, such as helium or hydrogen, in heavy compressed gas cans, and then perform an automated inflation of the balloon while the system is descending on a parachute on Mars. In order to eliminate such mass and complexity, a group at Jet Propulsion Lab has been developing a solar balloon, in which a metalized coating is used to raise the interior of a bag to high temperatures, thereby allowing it to use hot CO_2 as a lift gas on Mars. The advantages of doing so can be striking, as this procedure eliminates the need to transport compressed lift gases to Mars.

An alternative approach suggested by Pioneer Astronautics is to place a liquid in the bag that will vaporize at Martian temperatures and pressures, thus filling the bag with a high temperature gas with a molecular weight lower than CO_2. The benefits of using such a positive lift fluid in a solar balloon is seen quite readily in Figures 1 and 2. In Figure 1, we show the payload that can be floated at various altitudes on Mars using an 1529 m^3 commercial off-the-shelf polyethylene balloon manufactured by the Raven company if coated with nickel and inflated variously with CO_2, methanol, ammonia, or water. These balloons are quite lightweight, with an effective surface density of about 6-8 g/m^2, and would reach a temperature of about 340 K on Mars. It can be seen that the water filled balloon can float 12 kg at the surface, or 4 kg at 7 km, which means that such a system could be used to land an 8 kg payload on the surface and then ascend to perform an all-day aerial photographic float at 7 km with a 4 kg gondola. In contrast, the CO_2 balloon could only deliver a 3 kg payload to the surface, and can float no gondola at 7 km altitude.

If, on the other hand, we choose to use gold coatings to maximize balloon temperatures, we can no longer employ lightweight polyethylene balloons (they would become non functional at gold's 380 K) and instead must employ Mylar or Kapton systems, requiring netting reinforcement at greater cost. A comparison of the performance of water against CO_2 as a float gas using this balloon technology is shown in Figure 2.

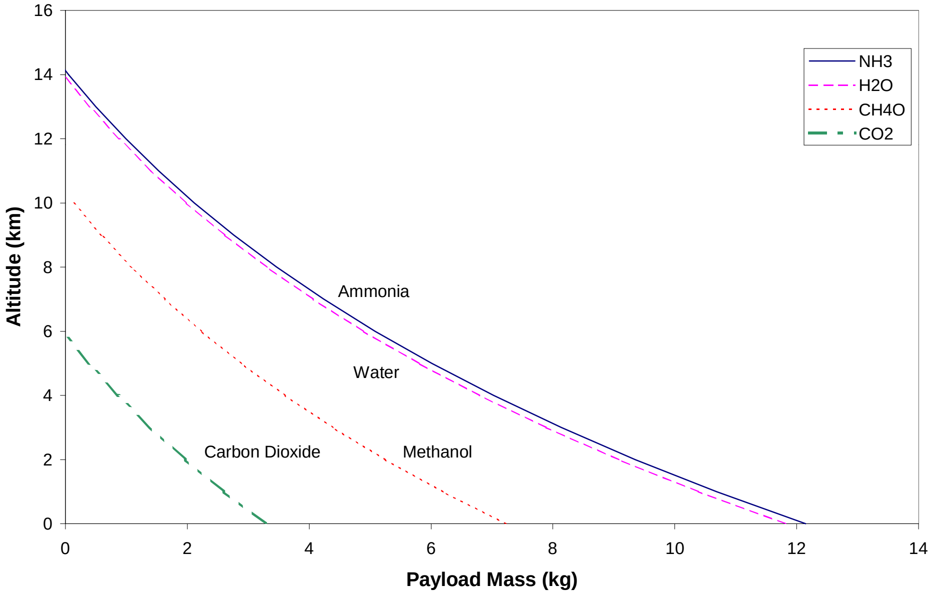

Figure 1. Steady-State Altitude vs. Payload Mass for 1529 m^3 COTS Balloon (Coated with Nickel: $\alpha_s = 0.4$, $\varepsilon = 0.1$)

It can be seen that the performance improvement offered by the use of water in this system is even more dramatic. Finally, since water can perform well in the 340 K environment provided by metallized polyethylene technology, we could compare the performance of water in an metallized polyethylene balloon with CO_2 in a gold-coated mylar balloon of areal density 13 g/m^2. In this case the payload advantage of the water system was found to exceed an order of magnitude over what a CO_2 system could carry with a balloon of equivalent volume.

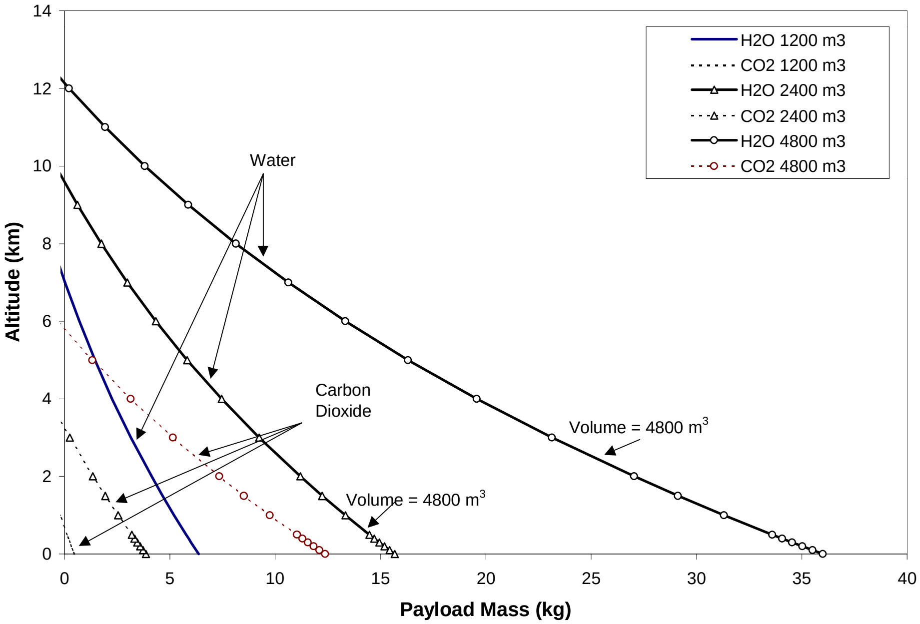

Figure 2. Comparison of the payload capabilities of water and CO_2 filled Mylar gold coated balloons (13 g/m^2 surface density). The 1200 m^3 balloon using water vapor for lift has nearly double the payload capacity of the 2400 m^3 balloon using CO_2 for lift.

So we see that although use of an indigenous Mars gas for lift may seem initially attractive, the limited lift capability of the relatively heavy carbon dioxide severely reduces the overall capability of the balloon probe. Although solar heating allows carbon dioxide-based balloons to have positive lift capabilities, the benefits of solar heating are greatly increased if the balloons are filled with lighter lift gases – including such easy to manage fluids as water and methanol. Thus, while it is true that the use of any positive lift fluid introduces an added degree of complexity compared to a pure solar-heated balloon using atmospheric gas for lift, studies done under the present program show that the potential performance improvement offered by employing such a lift fluid in solar balloons is so large that an investigation of the feasibility of such a system is clearly justified.

PHASE 2 HARDWARE AND EXPERIMENTAL WORK TO DATE

EOSS 41-43 Balloon Flight Tests

Pioneer Astronautics and the Edge of Space Sciences (EOSS) Flight #43 (8/26/00) culminated in the successful demonstration of inflating a small Mars balloon at 30 km (98 kft) altitude, using only 40 cc (a little over an ounce) of methanol. Prior to that, EOSS-41 (6/18/00) and EOSS-42 (7/16/00) tested much of the equipment needed for the successful EOSS-43 deployment test. Dr. Jack Jones (JPL) witnessed our successful test, and there was extensive coverage of the experiment on space.com, spaceref.com, and CNN.com.

The sub-scale Mars balloon was carried aloft by a large, 3000g rubber balloon, shown during pre-launch in Figure 3 and immediately after launch in Figure 4. Attached on nylon string beneath the lift balloon included the parachute, EOSS beacon with cut-down device, Pioneer's

GPS, a Sony CCD-TR517 camcorder looking down, the Pioneer experiment, and the EOSS Shuttle with GPS and ATV looking up. The ground station that recorded telemetry and live TV is shown in Figure 5.

Figure 3. EOSS-43 Flight Preparations

Figure 4. EOSS-43 Launch

Figure 5. EOSS-43 Ground Station with Jack Jones (JPL), Mike Manes (EOSS) and Robert Zubrin (Pioneer Astronautics)

EOSS-43 rose at an average ascent rate of 6.87 m/s (1350 fpm) as shown in Figure 6. It was launched on a Saturday morning at 9:20:34 am MDT from Byers, Colorado. Two GPSs were flown on this flight to record balloon altitude and position in real time. One GPS operated from liftoff to 16.950 km (55.6 kft) altitude, at which time its battery was depleted. The other GPS unlocked at 10:28:28 am at an altitude of 29.4 km (96.349 kft), just in time for deployment of the experiment at 10:28:43 am at 97 kft. The experimental Mars balloon inflated in 67 seconds, and maintained full inflation until the main lift balloon burst at 10:35:59 am at an altitude of 107 kft, thus completing this experiment. Future tests will involve inflating Mars balloons while descending in order to simulate Mars re-entry.

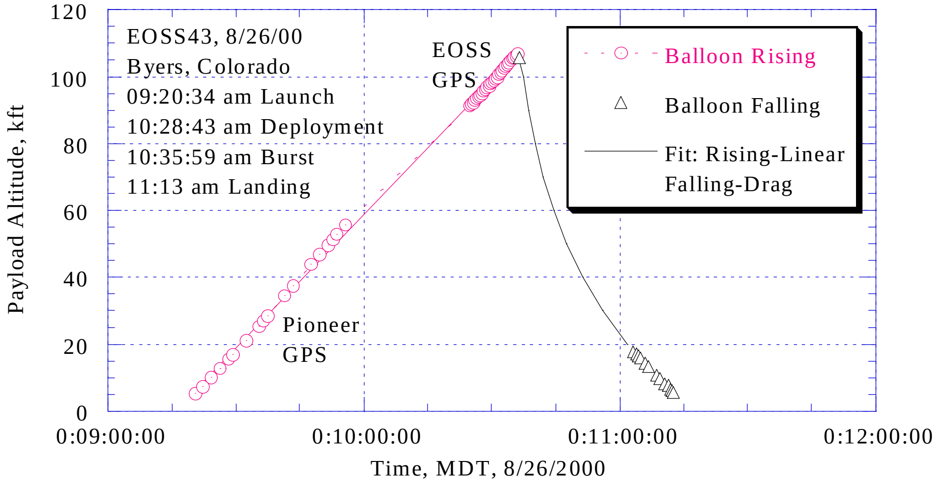

Figure 6. Altitude History of the EOSS-43 High Altitude Balloon

This experiment used a small, ~0.6 m^3 (~20 ft^3) black polyethylene balloon filled with only 40 cc (a little over a liquid ounce) of methanol. This black balloon will absorb sunlight quite nicely and its specifications are shown in Table 1. It was folded inside PVC end caps which were pressurized to one Denver atmosphere (absolute). That is, it was packed and sealed, as shown in Figure 7, using weather-stripping at Denver's working pressure. The strings holding the cap ends together would have been cut at 25 km or 82 kft (0.025 atm), initiated by barometric pressure electronics, at which time the can would deploy away from its top; however, this action was not completed until 97 kft was reached which more accurately simulated Mars conditions. The top of the can (still attached) was holding the uninflated black balloon. Upon exposure to sunlight, the balloon was heated to vaporize the methanol and inflate the experimental balloon.

Table 1. Experimental Balloon, Small, Black Polyethylene

Uninflated size :	0.9 m x 3 m (2.95 ft x 9.84 ft)
Mass:	62 grams
Inflated size (estimated):	~1/2 mil thick x 0.57 m (1.9 ft) D x 2.1 m (6.9 ft) L
Estimated volume:	0.6 m^3 (20 ft^3)

Figure 7. The Pioneer Astronautics Experiment with Experimental Balloon Inside the Can and Firing Box Above

Figure 8 shows the balloon inflated at an altitude of 30.9 km (101.4 kft), taken from a Sony camcorder looking down at eastern Colorado farmland. Figure 9 shows the same balloon looking up against the main lift balloon and the blackness of space from the ATV link. Finally, Figure 10 is a collage of several frames taken after the main balloon burst at approximately 10:36 am from an altitude of 32.6 km (107 kft), when the camcorder briefly viewed above the horizon to show the Earth’s atmosphere and space.

Figure 8. The Inflated Experimental Black Polyethylene Balloon Above the Colorado Plains

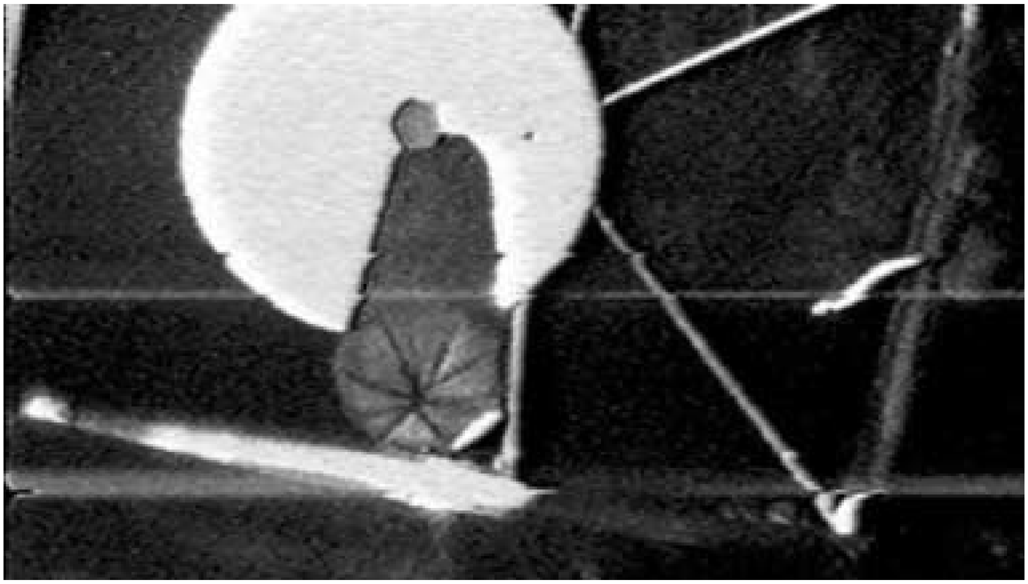

Figure 9. The ATV View of the Inflated Black Balloon

Figure 10. The Inflated Mars Balloon in Free Fall from the Edge of Space

Temperature and pressure data were also logged on a one ounce Onset HOBO datalogger. Figure 11 shows that outside air temperature dipped to –70°C in agreement with radiosonde data taken earlier that day, and that the inside of the electronics box was kept above –20°C.

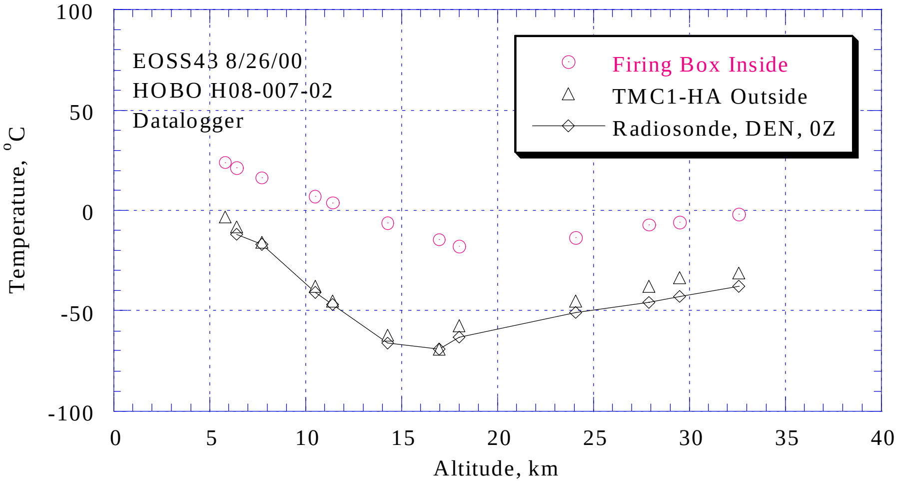

Figure 11. EOSS-43 Temperature Data

Theoretical Background

The amount of methanol required to fill this black balloon near the intended deployment altitude of 24.5 km (80 kft), at an ambient pressure of 30 mb (0.03 atm), and at an approximate balloon temperature of $0^{o}C$ (273K) is given by the perfect gas law:

$$m = PVM_{w}/RT = (0.03\text{atm})(0.6\text{x}10^{6}\text{cc})(32.04\text{g/mole})/(82.1\text{x}273\text{ K}) = 26\text{ g} \qquad (1)$$

At atmospheric pressure and room temperature, methanol is a liquid with a density of 0.79 g/cc, so 33 cc of methanol will have a mass of 26 grams. As the balloon continues to ascend, a positive pressure will enable the balloon to inflate. Allowing ~21% margin, 40 cc (1.35 oz, or 32g) of methanol was used.

The amount of time required to inflate this balloon could have taken a half minute to several minutes depending on the cross-sectional area the uninflated balloon presents to the sun. Methanol’s heat of vaporization is ~290 cal/g which varies slightly with temperature. Therefore, the minimum amount of heat required to vaporize 32 grams of methanol is:

$$Q = m\,\Delta H_{v} = 32\text{g x }290\text{ cal/g x }4.18\text{ J/cal} = 39\text{ kJ} \qquad (2)$$

The solar flux at altitude is about 1.4 kW/m^{2} = 1.4 kJ/m^{2}-s. If we assume we can absorb 70% of this energy across 1 m^{2}, allowing for some convective losses, or 1 kJ/m^{2}-s, then it would take 39 seconds to vaporize 32g of methanol. In reality, due to cosine effects and uncertainties in how the balloon will deploy, as well as thermal mass of the balloon itself, it could take longer. On EOSS-43, it took about a minute.

Convective cooling is a concern at the possible lower 80 kft deployment altitude. An estimate suggests 20-30% heat loss due to free convection and more due to forced convection. Free convection heat transfer in terms of Nusselt number (Nu) is frequently experimentally correlated in terms of the product of Grashof number (Gr) and Prandtl Number (Pr), also known as the Rayleigh number (Ra). Pr ~0.7 for air flow. The Grashof number based on diameter of a sphere or a horizontal cylinder is given by:

$$Gr = D_b^3 \rho^2 g\left(T_b / T_{atm} - 1\right) / \mu^2 \qquad (3)$$

where D_b is balloon diameter (meters), ρ air density (kg/m^3), g=9.8 m/s^2 on Earth, 3.7 m/s^2 on Mars, T_b balloon temperature, T_{atm} atmospheric temperature, and μ air viscosity (kg/m-s). At 24.5 km altitude, from the U.S. Standard Atmosphere Supplements, 1966, for 45^o N July model atmosphere, we obtain:

$$Gr = (0.57)^3 (0.0464)^2 (9.8)\left(300K / 224K \ \ -1\right)/(1.46x10^{-5})^2$$

$$= 6.2x10^6$$

so that

$$Ra = GrPr = 4.3x10^6$$

The Nusselt number correlation for free convection about a sphere is given by:

$$Nu = 2 + 0.453\ (GrPr)^{0.25} = 23 \qquad (4)$$

and for a horizontal cylinder,

$$Nu = 0.53\ (GrPr)^{0.25} = 24 \qquad (5)$$

The heat transfer coefficient h_c is then given by:

$$h_c = Nu(k / D_b) \qquad (6)$$

where k = 0.02 W/m-K the thermal conductivity of air at 224K, such that h_c = 0.81 W/m^2-K for a sphere and 0.84 W/m^2-K for a cylinder. The heat loss rate from this balloon can then be estimated from the surface area of a sphere or a horizontal cylinder:

$$Q_{sphere} = 4\pi (D_b / 2)^2 h_c (T_b - T_{atm}) = 63 \text{ W} \qquad (7)$$

$$Q_{cyl} = \pi D_b L h_c (T_b - T_{atm}) = \pi(0.57\text{m})(2\text{m})(0.84 \text{ W/m}^2\text{-K})(300\text{K}-224\text{K}) = 229 \text{ W} \qquad (8)$$

as compared to the estimated 1000 watts heat input into the balloon if it were completely inflated. We are of course estimating balloon temperature, but it is apparent that convective losses are a concern below 80 kft and that higher balloon deployment altitudes are desirable. At the EOSS-43 deployment altitude of 97 kft, the free convective cooling loss from a horizontal cylinder should drop to 137 watts.

Forced convective cooling is a greater concern as the inflation occurred while the balloon was rising at a speed u of 6.87 m/s (1350 fpm), and future tests will be conducted while the balloon is dropping at 30 m/s to simulate Mars reentry. Forced convection is correlated in terms of Reynold’s number, which for a sphere or cylinder is based on diameter as a characteristic length:

$$Re_D = \rho\, u\, D/ \mu = (0.0464\ \mathrm{kg/m^3})\ (6.87\ \mathrm{m/s})\ (0.57\ \mathrm{m})/1.46\times10^{-5}\mathrm{kg/m\text{-}s} = 12{,}400 \qquad (9)$$

at 80 kft. One can correlate the Nusselt heat transfer coefficient for a sphere in air in terms of Reynold’s number:

$$\mathrm{Log}\ Nu = 0.61\ \mathrm{Log}\ Re_D\ - 0.52 \qquad (10)$$

or Nu = 95 at 80 kft. This Nusselt number can be further modified by the factor $(Pr/Pr_{air})^{0.4}$ for flow other than air, such as on Mars. Applying Equations (6) and (7) for a sphere, we obtain

$$h_c = 3.3\ \mathrm{W/m\text{-}K}$$

$$Q_{sphere} = 4\pi (D_b / 2)^2 h_c (T_b - T_{atm}) = 265\ \mathrm{W}$$

Estimating the loss for a horizontal cylinder using Equation (8), assuming the same heat transfer coefficient as a sphere, would give a forced convective heat loss of:

$$Q_{cyl} = \pi D_b L h_c (T_b - T_{atm}) = \pi(0.57\mathrm{m})(2\mathrm{m})(3.3\ \mathrm{W/m^2\text{-}K})(300\mathrm{K}\text{-}224\mathrm{K}) = 900\ \mathrm{W}$$

basically as much as the heat input. At the higher deployment altitude of 97 kft for EOSS43, these losses would drop to 144 W for a sphere and 500 W for a horizontal cylinder. In reality, the cylindrical experimental black balloon on EOSS43 was nearly vertical during deployment, so heat losses will be in-between that for a sphere and a horizontal cylinder.

Development of Metallized Mars Balloons

The substantial convective cooling of metallized Mars balloons due to free convection at float altitude and the even higher heat losses due to forced convection while dropping in the Mars atmosphere during eventual Mars deployment led to a re-examination of metallized balloons. It was recognized that although aluminized balloons would have an adequate steady-state temperature once float was achieved, there might not be enough solar heat absorption from aluminized films (α_s ~10%) to overcome the convective cooling during Mars re-entry. Residual heat is required to vaporize the inflation fluid and inflate the balloon before crashing into the Martian surface. It was known that gold coatings can provide enough solar absorptance, but because of its low emittance, would eventually get hot enough on Mars to melt polyethylene and possibly exceed the temperature limits of Mylar, which would then require the use of a polyimide such as CP1 or Kapton. There are a number of other coatings, such as nickel, titanium, steel, etc., which have a modest solar absorptance higher than gold and yet have a high enough emittance that suitable balloon temperatures can be achieved on Mars.

There are a number of balloon film and coatings options that may be viable for a Mars balloon. These are shown in Table 2. From a handling perspective, 1/3 mil polyethylene is attractive, and the areal density would be 7.6 g/m^2 plus that of a coating. Mylar can be handled down to 0.1 mil, and is available at less than a micron, provided it is reinforced. Orcon can apply their scrim reinforcement on as thin as 0.12 mil Mylar, usually on the metallized side. Allowing for 67 denier polyester yarn reinforced in both directions at 2 yarns/inch, the reinforcement weight would be 1.2 g/m^2 for the yarn and 0.8 g/m^2 for the space adhesive, plus 4.2 g/m^2 for the Mylar, plus coating weight and heat seal tape weight. Using Raven balloon weights for their 1/3 mil polyethylene balloons will therefore give us a reasonable weight for a Mars balloon even if it were made of reinforced ultra-thin Mylar film. Kapton cannot be made any thinner than 1/3 mil and would result in substantial weight impact even before reinforcement.

Some of the coatings can add substantial weight to the balloon, especially if it is decided to apply them on both sides. For now, it is assumed they will be single sided coatings applied on the outside surface only. It may be desirable to reduce the thickness of the coating for weight and/or optical property considerations. Table 3 shows predicted optical properties, and steady state Mars balloon temperatures as a function of thickness for several candidate coatings. Aluminum coatings only have a solar absorptance of ~0.10 and may not allow absorption of enough solar heat to overcome convective cooling rates during the Mars descent/deployment phase. Although Sheldahl typically references aluminum coatings with optical properties of α_s=0.12, ε=0.03, one of our aluminized Mylar rolls from Sheldahl had measured opticals of α_s=0.09 and ε=0.02 in exact agreement with our prediction for 100nm of aluminum. Titanium should have acceptable opticals, but like aluminum can tend to oxidize while in storage. Nickel or chromium should also have good properties, are stable, and are frequently used as bond layers for subsequent coatings. Ni-Cr alloys (nichrome) can have substantially higher emittance because its electrical resistivity increases over an order of magnitude higher than the pure elements of Ni or Cr by themselves. Good electrical conductors give lower emittance than poor electrical conductors and dielectrics. There is a large class of steels, including stainless steels, which should also be suitable for a Mars balloon application, and should have excellent chemical resistance to nearly all possible inflation fluids including ammonia. Finally, gold is a viable candidate with excellent corrosion resistance and reasonable opticals. Being an excellent conductor, gold has an extremely low emittance that can be easily degraded by dust or other contaminants in the Martian atmosphere.

Table 2. Weights of Candidate 1529 m^3 (54 kft^3) Mars Balloons

Material	Density, g/cc	Areal Density, g/m^2	Mass of Mars Balloon, kg (lbs)
Films			
PE, ¼ mil	0.9	5.7	4.7 (10.3)
PE, 1/3 mil		7.6	6.2 (13.6)
PE, ½ mil		11.4	9.3
Mylar, 0.1 mil (2.5μ)	1.4	3.6	n/a
Mylar, 1/5 mil		7.1	5.8
Mylar, ¼ mil		8.9	7.3
Kapton, 1/3 mil	1.4	11.8	9.7
Coatings			
Al, 100 nm	2.7	0.3	
Ti, 100 nm	4.5	0.45	
Cr, 100 nm	7.2	0.7	
Ni, 100 nm	8.9	0.9	
Au, 100 nm	19.3	1.9	
ITO, 500 nm	7.1	3.6	

Table 3. Predicted Solar Absorptance α_s and Total Emittance ε for Candidate Coatings

Coating\Thickness		10 nm	20 nm	50 nm	100 nm
Al	α_s	0.18	0.12	0.09	0.09
	ε	0.07	0.04	0.02	0.02
	α_s/ε	2.6	3	4	4
	T, Mars				310 K (37^{o}C)
Ti	α_s	0.52	0.49	0.43	0.43
	ε	0.36	0.27	0.15	0.09
	α_s/ε	1.4	1.8	2.9	4.8
	T, Mars			316 K (43^{o}C)	347 K (74^{o}C)
Ni	α_s	0.48	0.46	0.38	0.37
	ε	0.31	0.22	0.11	0.07
	α_s/ε	1.5	2.1	3.5	5.3
	T, Mars		298 (25^{o}C)	325 K (52^{o}C)	352 K (79^{o}C)
Au	α_s	0.16	0.18	0.19	0.2
	ε	0.04	0.02	0.01-0.02	0.01-0.02
	α_s/ε	4	9	10-20	10-20
	T, Mars	310 K (37^{o}C)			377-417 (>104-144^{o}C)

Astral Technology Unlimited (ATU), Northfield, MN, sputtered 50 nm of a nickel-vanadium (93Ni-7V) coating on 0.2 mils of Mylar for Pioneer, and attempted deposition on 0.35 mil polyethylene used by Raven Industries to manufacture intermediate sized balloons. Dunmore recommended using Astral for specialized coatings. Sheldahl would not quote on this project despite several requests to do so; technically, they cannot do roll-to-roll processing on less than 0.25 mil film, although Astral Technology has demonstrated coatings on 0.9 micron (0.035 mil) Mylar. Astral was not able to sputter nickel on the thin polyethylene substrate, despite the use of substrate cooling drums in the deposition zone, as the polyethylene melted. It is conceivable that with considerable development, and multiple passes of thinner coatings through the machine, this might be accomplished. Metallized Products (MPI) routinely evaporates aluminum on 1.25 mil polyethylene, but will not do coatings other than aluminum and would not quote on attempting aluminum on 0.35 mil polyethylene, although they offer aluminized 0.25 mil polyester.

In this trial run, Astral was able to coat 125 ft of the 0.2 mil Mylar in their smaller 2 ft wide sputter web coater. We used an existing Ni-V target as a new pure Ni target would have cost $3K. The vanadium improves sputtering efficiency. We also used 0.2 mil thick Mylar from their existing stock, although 0.1 mil may be more appropriate for a Mars balloon (Orcon can add rip-stop on Mylar down to 0.1 mil thick). Based upon this success, we would recommend purchasing a pure nickel target to sputter deposit on Mylar using Astral's 4 ft wide web coater for Mars balloon production runs; this width is also compatible with Orcon's rip-stop machine. Either width is probably acceptable for GSSL's new rip-stop process.

The measured optical properties for our Ni-V coating (on 0.2 mil Mylar with a black backer) are α_s=0.48 using Astral's DK-2A and ε_h=0.22 using their emissometer. These properties are higher than expected if we used a pure nickel target, and can probably be attributed to the alloying characteristics of the vanadium, which may be similar to nichrome. Solar transmittance was measured at 5% whereas pure nickel should only transmit 2% at 50 nm thickness. Future deposition runs should use pure nickel targets, possibly with up to 100 nm deposit, as it appears we will have to use Mylar to survive the deposition process. Mylar can also take the higher Mars operational temperatures which will result with a thicker deposit.

Because we have had concerns with emissometers in the past, we sent the same Ni-V coated Mylar to Atlas DSET Laboratories, Phoenix, AZ, for a total normal emittance measurement using their Gier-Dunkle DB-100, which is more commonly used in aerospace labs, and is based on a reflection principle rather than an emission principle. They measured $\varepsilon_n = 0.19$, or $\varepsilon_h \sim 0.21$, consistent with the Astral data. There is little doubt that $\varepsilon \sim 0.1$ can be achieved using a pure nickel sputtering target.

Convective Cooling Analysis of Metallized Mars Balloons

Figure 12 shows the capability of a 1529 m^3 Mars balloon for a payload of 2.73 kg (6 lbs). A balloon film with a nickel coating of 50 to 100 nm should attain a steady state temperature of 325-352 K (52-79^{o}C) accounting for free convection in the Martian atmosphere. Note that both ammonia and methanol can float this balloon at reasonable altitudes (5 to 9 km). However, at this same temperature, a pure "hot air" balloon using Mars CO_2 can only attain an altitude of about 1 km. This is inadequate for a Mars balloon mission of even 1 –day's duration, as the Martian topography is highly variable, and such a low flying balloon would run unacceptable risk of running aground. Of course, a higher temperature plastic could be employed, but even at 100 C, the flight altitude would only be about 3 km. Moreover, the higher temperature plastic would probably weigh more, thereby cutting into payload. Thus, in fact, to float the equivalent payload at equivalent altitude using a pure hot air approach, a much larger balloon would be required.

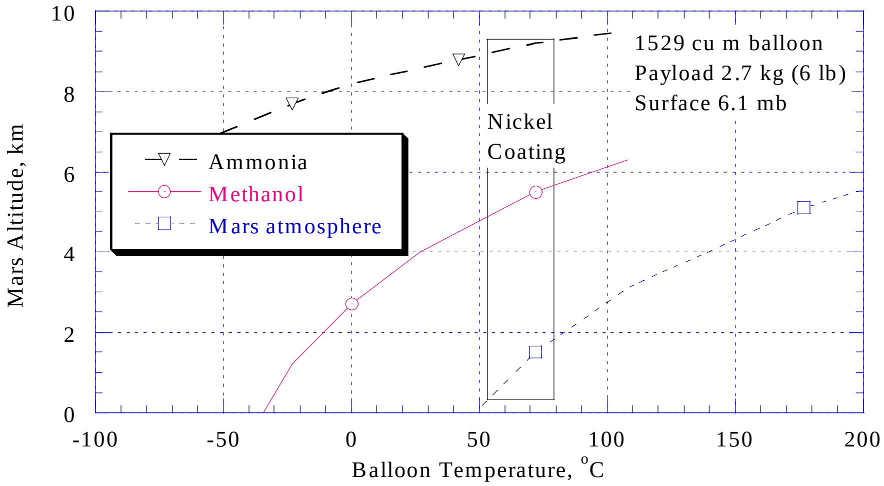

Figure 12. Altitude Capability of 1529 m^3 Mars Balloon with 2.7 kg Payload: Nickel Coating Provides a Steady State Temperature of ~70°C.