DESIGN, CONSTRUCTION, AND OPERATIONS
PLAN FOR THE MARSUPIAL ROVER

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ABSTRACT

An essential component of any currently-conceived human Mars mission is a pressurised, automated vehicle capable of safely and comfortably carrying a small crew of explorers distances of tens to hundreds of kilometres from the landing site. The design of such a sophisticated vehicle presents many technical questions and challenges. As a practical contribution to the needed design effort, Project Marsupial aims to make available to the MSA a practical, affordable, 4WD off-road vehicle which can be used for simulating exploratory sorties and for raising public awareness of the value of a Mars mission. Basic issues, design parameters and ideas for the Marsupial Rover - currently under construction in Western Australia - are described. A three-stage construction plan is then sketched out. Finally, a series of eight surface simulation operations for the vehicle are proposed.

INTRODUCTION

Mars Rover Concept

The best current Mars exploration plans require, in the equipment which must be delivered to the surface, one or more vehicles for carrying astronauts and equipment tens to hundreds of kilometres from the permanent base at the landing site for periods of up to days at a time [1, 2, 3]. Essentially land-going spacecraft, these vehicles should be able to provide several explorers with a comfortable, shirtsleeves environment for days at a time. They must be highly reliable, powered by an in-situ renewable resource and move with something like the speed and power of a good four wheel drive vehicle on Earth. Although such vehicles will be complex to develop and expensively massive to transport to the Martian surface, exploration work would be sharply curtailed without them, because it could only be conducted within safe walkback range of the lander. Apollo lunar EVA suits restrict walking speed to 6.4 km/h. Thus, a NASA safety margin of no more than 30 minutes walkback to base in the event of difficulty sets the maximum radius of an exploratory circle at 3.2 km [4]. On the moon, this limiting factor eventually become intolerable, and lunar rovers were sent in the later missions, extending this to a 10 km radius from the lander. A pressurised vehicle would dramatically expand the area over which scientific and exploratory work could safely be conducted, especially during an extended stay, since the centre of the radius of safety could then move over a much larger circle. While for reasons of safety the lander should descend to a safe, flat plain, many worthy features of the planet might be located in hilly, rocky or uneven ground, distant from the landing plain.

Most engineers imagining Mars rovers agree that the optimal power source for such a vehicle is methane and oxygen gas, which would already be generated in large quantities by automatic processing plants from in situ resources. This could be burned in an internal combustion engine, though because of the extreme temperatures produced by oxygen combustion (2000-2500°C), the mix would need to be diluted with atmospheric CO₂ to avoid melting. The simplest and most likely use to which the
An engine would be put in direct 4WD mechanical transmission to large wheels, although a case might be made for hybrid electric generation with electronic transmission to four electric motors on the wheels. Hydrocarbon fuels (including petrol, diesel and LP gas) yield among the highest available power-to-weight ratios, which is why they are used for ground vehicles the world over. A methane-oxygen Mars rover could have a between-refuelling range of 500 kilometers [4, page 3-114].

Yet the effective range over which the rover may operate is not likely to be limited by the duration of the vehicle itself, but by other factors. It must not, for example, exceed the range of a second, backup vehicle available to rescue the explorers in case of breakdown. This could be a second pressurised rover with the same range as the first, but due to the extremely high cost of delivery, this is much more likely to be a small, lunar-rover like vehicle, at least for the first expedition. The Design Reference Mission [2] for example, includes a requirement for several unpressurised teleoperated rovers (TROVs), with a possible range crew transportation range of "10's of kilometers" [4, page 3-114]. A TROV could accompany the pressurised rover either by being carried, by being towed on a trailer, or by having the TROV autonomously follow under its own power. A small, simple and cheap version could be folded up into a compact package and stowed on the roof of the pressurised rover.

Assuming an unpressurised TROV could sustain an average safe travel speed of 20 km/h, and that EVA suits can support life for 8 hours, the maximum safe radius of exploration appears to be 160 km. However, this oversimplifies the reality, since i) emergency reserves of consumables could be drawn from the TROV and ii) travel at night would probably be too risky in an unpressurised rover due to the cold and reduced visibility in all but the gravest emergencies. If nightfall was close, stranded explorers would generally be safer camping until morning. Without a second pressurised rover, then, the conservative safe exploration range should be limited by the available daylight hours, which at the equator is roughly 12.25 hours in all seasons [5], during which time an unpressurised rover could be driven back 245 km. During winter at the modest latitude of 60° there could be as little as 5 hours daylight (a driveback of only 100 km) or as much as 20 hours (driveback of 400 km if consumables permitted) in high summer. All this has implications for an analogue rover, because it sets limits to the range over which simulated journeys need to be conducted and because it shows the importance of a secondary drive-back vehicle.

One way to extend this limited range for a first mission would be for the pressurised rover to tow one or two detachable trailers containing consumables for life support, an inflatable shelter and power. These would be left at points along the outbound route corresponding to driveback circles set by available daylight hours, where they could serve as overnight camping stops for a crew driveback in an unpressurised TROV. The trailers could also serve the same function for a rescue crew coming from the habitat to aid the stranded sortie team. The trailers would be picked up during the return leg of the journey for reuse. Such portable life-support trailers could also have other uses in emergencies.

Navigation of the machine must not depend on a magnetic compass, since Mars has no (globally polarised) magnetic field. However, inertial gyrocompasses would be useable. Some scenarios involve time-of-flight trilateration using radio beacons either in surface towers or on satellites in orbit, as with Earth's Geographical Positioning System. NASA's JPL has plans to establish MARSNet, a network of communications microsatellites which could also double as navigation aids [6]. However, if satellites were not available, then solar-recharged beacons delivering simultaneous, individually coded radio pulses could be placed on towers around the base so that from any point
within the coverage region, the signals received from several could be distinguished. The differing times of arrival of the distinct signals would be easily converted into a point location. This has the advantage that the system elements would be accessible in the event of breakdown, but would require a good amount of equipment. To ensure line-of-sight with at least three beacons at any point within only 100km$^2$ would require at least 15 towers. This assumes the towers would be no more than 40km apart, enabling them to double as a communication relay system. A good deal of time and effort would be required to set these up, though this could be combined with other exploratory work using the rover, or even performed by robots. In either case, as backup the rover crew could use celestial navigation techniques, using a sun compass, sextant, almanac and chronometer to fix their position.

The most challenging requirement for the rover as conceived by the DRM and MD is for the vehicle to be automated. Consistent with the goal of applying multiple-use systems, the vehicle will be expected to perform surface operations, such as unloading and operating fuel and air processing facilities, before human astronauts arrive. This means that the vehicle would need to be delivered to the surface fully operational (i.e. not disassembled) and would need to be able to drive itself from its lander onto the surface. It would require enough sensors, navigation instruments, communication equipment and computational intelligence to enable it to perform its functions based on high-level commands only from Earth. Though challenging, these are not beyond currently available robot technology even if all the needed technologies have never been brought together on a single machine.

It is possible that the costs of development and construction could be met by selling data and images collected from the rover to commercial television networks. So the first humans emerging from a lander to set foot on Mars is likely to be greeted by the rover's cameras, sending the historic images back to a waiting world.

**Marsupial rover design and construction**

The Marsupial project aims to make available to the MSA a practical, affordable, 4WD off-road vehicle which can be used for

- simulating exploratory sorties of at least 100 kilometres away from a landing site which forms the core of a prototype Mars base at medium fidelity.
- raising public awareness of MSA activities and the value of exploring Mars by looking the part of a pressurised rover of the kind which might be flown on a future planetary mission, for the benefit of the media and during public exhibitions.

The vehicle is to be built around the chassis of a Series IIA Forward Control Landrover (Figure 1). This is a cab-over-engine version of the standard long wheelbase "troop carrier" and has been common as both a military truck and a safari bus. This base vehicle was purchased by the MSA in March, 2002 and is currently being renovated by the Marsupial team in Western Australia. It is recognised that some modification of the machine is required and that it may not be possible to obtain a perfect solution given the limited time, workforce and budget available. However, every effort must be made to produce a safe and practical vehicle representing a real Mars rover to at least moderate fidelity and the exterior finish and paintwork should be of a high standard so that the vehicle will enhance the reputation of the MSA and its sponsors when placed on public display, photographed or filmed by the media.

**FIGURE 1 - Rear and front views of the FC Landrover base vehicle.**
To avoid the expense and difficulty of towing the vehicle to test sites on a trailer, it is highly desirable to design the vehicle in such a way that it can be licensed to travel under its own power on public roads. This means that the body, engine, transmission, steering, brakes, wheels, lights, windscreen and wipers must be mechanically sound enough to pass a roadworthiness test in the Australian "experimental vehicle" class. Although meeting certification requirements may involve some design compromises (especially with respect to 2 above), the base vehicle is currently licensed and it is clear that fully restoring its roadworthiness would greatly expand the value of the vehicle to the MSA. Where appropriate, fitments such as tail lights or number plates that would interfere with experiments or spoil the appearance of the vehicle could be covered or made removable for when the vehicle is off the road.

The vehicle should be capable of travelling at least 600km (three times the diameter of exploration zones proposed during the Jarntimarra expedition [7]) without refuelling. When operating in extremely remote regions, it is important to ensure that sufficient fuel is carried to achieve the mission objectives, plus a contingency supply. The design calls for two 60-litre fuel tanks on the rear chassis, which are expected to exceed this requirement. The existing Landrover engine will be replaced with 6-cylinder Holden 186 engine, a standard conversion option for vehicles of this kind. With the standard gearbox, transmission, and 0.88m diameter wheels, the vehicle will be capable of approximately 90kph in high gear and 14kph in low gear.

It is envisaged that the vehicle will be operated in either of two configurations, depending on the simulation work being done. In the utility configuration (Figure 2a), the vehicle will approximate a contemporary 4-door truck with a short tray back, the tray being used to carry specialised equipment such as an a drilling rig or sample boxes. A portable toilet with holding tank of the kind found on pleasure boats will be provided in a ventilated, screened-off corner of the centre cabin. The holding tank would be cleared by ordinary liquid waste pumping on return to base. In the covered configuration (Figure 2b), a modular camping unit consisting of a pair of bunks, a folding table, a washbasin and sink, which would then be covered by a convex hull representing a pressurised cabin.

FIGURE 2 - Optional Rover Configurations
In both configurations, the vehicle must be capable of comfortably supporting at least 2 persons driving off-road for long distances in the desert environments of outback Australia. Since the vehicle will be used for simulated rescue operations, it is important that the vehicle be capable of transporting an extra two passengers without undue reconfiguration (e.g., using two fold-down seats in the rear of the forward cabin). In the covered configuration, the interior equipment must be capable of comfortably supporting a crew of two persons for four days (four persons for two days in the rescue scenario).

Although the planned medium fidelity simulations will not require a real pressurised cabin, to meet the requirement for comfort in desert environments, an air conditioner capable of maintaining the cabin at a comfortable room temperature (20-25°C) during hot weather must be included. It is expected that a standard Landrover heating system will supply enough heat for cold weather comfort. The use of fibre-reinforced epoxy resin with insulating foam formers for the body is expected to reduce thermal loss at the same time as presenting a cost-effective solution to making up the body shape, which is suggestive of an aircraft cabin (Figure 3).

Since reconnaissance, photography and prospecting are all important functions of such an exploratory vehicle, all-round visibility should be maximised by use of transparencies, at least in the forward cabin. However, since these would make the cabin uncomfortably bright at times, and during summer months would increase the heat load in the forward cabin, some compromises to this ideal will be needed, such as reflective tinting, removable sunshades, or even ersatz transparencies. Properly chosen tinting could be used to mimic the natural light of Mars, during daylight hours, enhancing the simulation.

Under some test scenarios the crew will be operating the vehicle wearing analogue spacesuits. It is therefore important that the systems be designed to accommodate this, for example, by ensuring that control buttons and large and widely-spaced enough to be worked while wearing light garden-style gloves. Provision should be made for stowage of two spacesuits and their associated equipment in lockers on the wall of mid cabin. This would include power-recharging circuits for the batteries of the life-support backpacks.

One necessary trade-off in a low-cost, medium fidelity simulation is that of full automation. Although self-driving petrol road vehicles have been a reality for several years [8, 9] such modifications are difficult, expensive and legally risky. Nevertheless, Project Marsupial has planned to include, and done significant design work toward, at least one feature of an automated rover: a manipulator arm which can be teleoperated by a mission specialist inside the vehicle. As of April 2002, sufficient funding to build
the proposed manipulator arm had not yet been secured, so the requirements for this are not included here.

FIGURE 3 - Artist's conception of the completed Marsupial Rover (courtesy of Jo Michalek, Graphic Solutions)

Current plans call for this device to be stowed in an equipment bay on the passenger side of the vehicle and operated from a console in the rear of the mid-section cabin. The robot arm could be funded as a special project by the Western Australian mining industry or by support from the US Mars Society. If provided, the manipulator would be used in a variety of tasks such as sampling, digging, drilling, inspection, maintenance and refuelling. Future work could more fully automate the arm, so that it could also be used remotely from a distant habitat, or - using a time-delayed link - from "Earth".

The vehicle must be equipped with basic safety equipment appropriate for vehicles travelling in remote desert environments, or else always be escorted by a support vehicle which carries such equipment.

- Water tanks - At least 100L capacity (10 litres/day x 4 persons x 2 days) + 20% reserve (interior)
- Enough non-perishable food for 4 persons x 2 days + 20% reserve (interior)
- 12V auxiliary power sufficient to provide for incandescent/fluorescent/spot interior lights, invertors, fans, air compressor and other equipment. This must be independent of the starting battery. (interior/exterior)
- A good first aid kit (interior)
- A high-frequency radio capable of contacting the 4WD network and Royal Flying Doctor Service
- Vehicle spares and a toolkit needed for repair of the vehicle and its systems (exterior).
Spare tyre, electric air compressor and jacking system that can be used in desert conditions (exterior)

A second spare tyre should be taken for long missions.

- A 1:250 000 scale topographic map and compass (not useable within simulation).
- Arial photographs and/or satellite imagery of traverse area.
- A fuel stove, flashlight and matches (interior).
- An easily accessible portable fire extinguisher (interior).
- The vehicle should be licensed to travel on Australian public roads

Though the project is currently supported from the MSRI seed funding and cash and in-kind contributions from Graphics Solutions P/L, more funding will be required to allow the project to successfully complete the rover to MSA standards. For this reason, the Project Director has separated the project into stages, with each stage being commenced only when enough money has been raised to complete it. As of May, 2002, Stage 1 is about 20% complete and work is proceeding.

Stage 1 Chassis refurbishment and design. This work is conducted by Marsupial project volunteers from MSA. The base vehicle is acquired, assessed, refurbished and, were necessary, modified to make it a safe, roadworthy and reliable 4WD vehicle around which the rover will be formed. The overall design process for all stages is commenced. The suspension, brakes, engine, gearbox, transmission and control linkages are disassembled and inspected. Where necessary worn parts are repaired or replaced. The existing engine, old and underpowered for a vehicle of this sort, is replaced by a suitable 6-cylinder petrol engine. The heater/air-conditioner is installed. A customised exhaust system is fitted. Power steering is installed. Customised fuel and water tanks are fitted. The tyres are replaced, while the spare is relocated for the new configuration. The electrical system is completely rewired. A temporary console is fitted for the basic instruments. Removable trafficators, stoplights, license plates and mirrors are provided. Front seats with seatbelts are fitted. The chassis is generally restored to roadworthy condition.

Stage 2 Fabrication of body. Design work on the body commenced during Stage 1 is finalised and detailed construction prints are extracted to simplify the fabrication process as much as possible. A plastic-forming contractor is hired to produce the basic hull, then fitted to the chassis and customised by the Marsupial team. The rear convexity for the covered configuration is manufactured and fitted at the same time. The forward canopy is built up around standard shatterproof windscreen for licensing purposes. Non-slip flooring with engine access panels is installed. Side door and fold-down stepladder are constructed and installed. Rear cabin and exterior doors are fitted. Radio antenna wiring is installed. Because it is mostly done by full-time contractors, this stage is likely to be both faster and considerably more expensive than Stage 1.

Stage 3 Interior Fitout. Remaining interior fitout is completed. This consists of mid-cabin utilities such as the spacesuit lockers, sink and microwave oven, fold-down webbing seats for rear passengers, interior lighting units, console for remote manipulator arm. The rear section module, for use only with in the covered option, comprises twin aluminium frame bunks, a folding table, overhead lockers and a private screened cubicle containing a portable cassette toilet. Essentially, the vehicle is to be fitted out as a fully self-contained camper van for outback travel. Part of this work is expected to be completed by recreational vehicle contractors, part by volunteer workers. The vehicle may be useable for some utility-configured experiments or promotional work before Stage 3 is fully complete.
Planned surface simulation operations

Although the Marsupial Project is self-contained and could be test-operated in the desert relatively independently of other projects, it is expected to form part of the joint Operation Red Centre, i.e. in concert with the Mars-Oz habitat, MarsSkin MCP spacesuits and SAFMARS communications experiments. As with these other MSA projects, the rover will try out certain design and operational elements that are not part of the North American or European Mars Society efforts. These include carrying and deploying a drilling rig in tray-back utility configuration and a dust-storm simulation. In future, however, the Marsupial Rover could also be used in cooperative exercises with other Mars Society rover projects, such as those of the Michigan and Toronto groups. One idea is that Project Marsupial engineers to build a robot arm for the Michigan rover similar to that on the Marsupial rover, so that teleoperation experiments could be conducted over international distances.

To be of maximum value to the designers of future flight hardware, the test operations must be organised as ergonomic (human-factors) experiments which try out equipment designs, operational procedures and training methods under protocols as faithful as possible to expected reality. The author favours methods outlined by Champanis [10]. Some experience from the Flashline-MARS 2001 field season, which used NASA EVA protocols, can be drawn upon here. The results must then be published in a form that is detailed enough - and credible enough - to rule out designs, procedures and training methods that lead to trouble and encourage development of those that work well. These documents, which should take the form of MSA technical reports, addenda to the Design Reference Mission, and papers in scholarly journals and conferences, will be circulated freely in the spirit of international exchange of scientific knowledge.

Second and Third Team Training. Up to four days of vehicle driver/operator training will be given by the designer/builders (forming the first team) to the second and third 2-person teams. As well as preparing teams for the following test operations, this will be an opportunity to assess the usability of the vehicle by observing which aspects of vehicle operation are easy for the trainee crew and which are troublesome. Following the air force tradition of putting teams into competition, these will then rotate as Rover Crew, Environment/Data Collection Crew and Support/Other Duties. In scenarios which pit the Rover Crew against system malfunctions and the Mars environment, the Environment/Data Collection Crew will try to defeat the Rover Crew, by pitching challenging yet solvable problems for them to overcome. Each crew will spend one third of their rotations either in a Support/Other Duties role (fetching fuel, repairing equipment, setting up test or measurement equipment, etc.), doing other work at the base, or resting.

Refuelling Simulation. An oxygen-methane power plant on rovers would necessitate a refuelling operation which transferred pressurised gas from the fuel generator tanks into the rover's tanks. Although it is likely that such an operation would be automated, so as to allow the vehicles to operate in autonomous robotic mode, it might become necessary for a number of reasons to refuel manually. The vehicle is moved from the habitat's garage to the fuel generator. Both of the crew don spacesuits. One leaves the rover and carries out the work while the other monitors the refuelling operation from the cockpit. Different scenarios can be tried out, from the routine filling to valve jams to gas explosion accidents.

FIGURE 4 - Computer generated image showing location of proposed robotic arm (courtesy of Jo Michalek, Graphic Solutions.)
**Rescue Simulation.** This tests communications, navigation and entry/exit equipment and procedures under time pressure. One of a crew pair, working on the surface, suffers an incapacitating accident, such as a broken ankle. The able crew member alerts the habitat nowcaster. The rover crew, working at a random location, is alerted by the nowcaster. As quickly as possible, the rover crew locates the injured team, picks them up, returns them to the habitat, and transfers the injured crew member into the habitat. This can be tried out with the rover in either the utility or covered configuration.

**Sample Tour.** With the rover in utility configuration, the rover crew leaves the garage and navigates around a trajectory of pre-mapped waypoints, collecting samples. The Environment crew may place geological/fossil "treasures" for the crew to find. With the manipulator arm, one crew member operates the arm while the other supervises the operation outside (Figure 4). Without the remote manipulator arm, the rover crew will have to EVA and dig, drill or shovel regolith to fill sample containers. May be combined with an areology exercise.

**Drilling Trip.** With the rover in utility configuration, the rover crew navigates from the habitat's garage to a nominated location, and EVAs to deploy a small drilling rig. A core sample from a depth of about 10 meters is taken, stored in a sample carrier in the tray back. The drilling rig is packed up, and the rover returns to the habitat.

**Random Breakdown.** While the Rover Crew is conducting a routine sampling mission, the Environment Crew simulates a random breakdown. The Environment Crew can either role-play the failure or (non-destructively) physically sabotage the vehicle. Breakdowns may be simple enough to be fixed on the spot (eg. broken wheel) or complex enough to demand abandoning the rover and driving back. (eg. total electrical power failure).

**Long Mission.** The rover crew departs from the garage and follows a pre-mapped path which takes it to the maximum safe distance from the habitat for at least four days. The vehicle is in the covered configuration. During this time the crew is not to leave the vehicle except in emergencies. This tests the navigation and communications capabilities.
as well as the liveability of the rover accommodations, while operating far from support. It also tests the usability (even driveability) of the vehicle at night. The mission could perform some useful simulated activity, such as placing a ring of radio navigation beacons around the 40km horizon.

Dust Storm. According to Zubrin, the risks of dust storms on Mars have been exaggerated, since the low-density atmosphere effectively reduces the dynamic pressure exerted by the wind. Seen this way, a 100 km/hr wind on Mars would be approximately equivalent to a 10 km/hr wind on Earth [1, p.129]. However, Zubrin neglects to mention that in 0.38G a significant amount of potentially abrasive and visibility-reducing regolith fines would be still be likely to be transported by such a wind. Furthermore static electric discharges may be a serious problem. To examine this notion, the Environment crew follows the rover away from the habitat in a support vehicle which carries a motorised fan. This is used to gently blow a large amount of fines over the rover during a routine operation, possibly including an EVA. Effects of suspended fines on spacesuits, vehicle exposed surfaces, joints and seals, visibility and radio communications interference will be studied. This is a tough test of equipment and personnel, and may well test the patience and endurance of simulation crews. It will also require cleaning and maintenance of the equipment afterwards. For these reasons, this simulation should be conducted last in the field season.

REFERENCES

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