IN-SITU RESOURCE UTILISATION THROUGH WATER EXTRACTION FROM HYDRATED MINERALS – RELEVANCE TO MARS MISSIONS AND AN AUSTRALIAN ANALOGUE

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ABSTRACT

Obtaining adequate supplies of water is a major challenge for Martian *In Situ* Resource Utilisation (ISRU). One proposed method is the extraction of water from hydrated minerals common in the Martian regolith, such as sulphates and clays. The amount of regolith needed to be processed is comparatively small assuming water contents of 5-20%, and are well within the capabilities of small excavators. The Opportunity rover has found extensive deposits of hydrated calcium and magnesium sulphates at Terra Meridiani on Mars, along with clays. The regolith of the Moon Plain area outside Cooper Pedy in South Australia a potential mineralogical analogue: it is the largest known terrestrial occurrence of magnesium sulphates (mainly epsomite), and is also rich in gypsum and clay. It is potentially an ideal location for full scale ISRU trials of water extraction from hydrated minerals. The proposed plant would excavate, mill and process the regolith using heat to extract the water. Waste would be dumped on site and the water stored. The small scale plant needed by initial Mars expeditions would allow the field trials unit to be similar in scale to that which would be deployed on the surface of Mars. The proposed plant would excavate, mill and process the regolith using heat to extract the water. Waste would be dumped on site and the water stored. The small scale plant needed by initial Mars expeditions would allow the field trials unit to be similar in scale to that which would be deployed on the surface of Mars. We propose a collaborative project coordinated by Mars Society Australia (MSA), and a partner or partners to fund, develop and trial such equipment. Liaison and coordination of the two components in Australia would be facilitated by MSA, who would also undertake and supervise the field operations. The project would make a significant contribution to ISRU research and is likely to generate significant public interest.

INTRODUCTION

The consumable requirements of a crewed Mars mission impose a major logistic constraint on expedition planning. Mass-wise, the largest consumable has always been propellant, followed by water and then breathing oxygen. Using ISRU to reduce the logistic burden of consumables has been a major focus of expedition planning since the early 1970's [1]. Most of these studies have focussed on manufacturing propellant *in situ* on Mars. The atmosphere has been considered the prime resource in many previous studies because it is homogeneous in composition and distributed across the whole planet. Proposals exist for both complete dependence on local resources, and use of imported terrestrial hydrogen in the manufacture of propellant [2].

The ability to extract water (H_2O) from Mars rather than relying on hydrogen from Earth has the potential to reduce the amount of supplies that need to be imported and greatly increase the self sustainability of Mars surface operations. Water is known to be present on Mars in many forms, including ground and polar ice, and in atmospheric water vapour. This paper focuses on water in hydrated minerals, where water is incorporated into the crystal lattice, for example in hydrated magnesium sulphate or epsomite (MgSO4.7H2O), popularly known as Epsom salts.

Widespread occurrence of hydrated sulphate minerals, most famously those discovered by the *Opportunity* rover at Terra Meridiani, offers a possible resource at sites that are ideal for early human Mars missions, with flat terrain, low latitude and at low altitude. Hydrated magnesium sulphates are a common component of these deposits, and contain up to 51% water in their structure. Development of viable water extraction technology from hydrated sulphate minerals is relatively straight forward in principle, requiring that the sulphate material be heated to >150 degrees, as is the case in the commercial manufacture of Plaster of Paris where calcium sulphate (gypsum) is partly dehydrated though simple heating. The apparent abundance of water-rich hydrated magnesium sulphates in Martian sulphate deposits implies that comparatively small amounts of surface material (~2 tonnes or less) need to be processed every day to supply a Mars mission. In this paper we will:

- Review the logistic justification and technological requirements for water-based ISRU
- Review the amounts of material that would need to be processed
- Propose a research project to develop a plant to test the viability of water extraction from hydrated minerals, and
- Propose using the Moon Plain in South Australia as a field test site.

WATER AS AN ESSENTIAL RESOURCE FOR ISRU

The availability of water would reduce the logistics burden on mission planners. Not only could the water supply the needs of the crew, commonly taken at 30 L per day [3], it could also be a source of the hydrogen feedstock needed for the more energetic fuels, propellant oxidiser and breathing oxygen. If this technology is to be applied to preliminary human missions at dispersed sites round the planet, the mass and volume of equipment needed to extract, store and process water from the local resource must be less than that of the imported water or hydrogen and the associated plant. This limitation does not apply to bases occupied by a succession of crews where the initial mass cost of the water extraction plant and benefits of *in situ* water extraction can be recovered and compounded over a longer period.

Prior to the discovery of high latitude ice deposits by the Mars Odyssey spacecraft [9, 10] and the Meridiani sulphate-rich sediments of Meridiani by the Opportunity rover [11, 12] there was considerable uncertainty regarding the amount of water available on Mars for ISRU. This has precluded integration of water ISRU on early mission designs, with the exception of atmospheric water extraction in some studies [4]. Atmospheric water extraction is quite demanding with respect to volume and energy because of the large amount of Martian atmosphere that would have to be processed. A number other of possible local water resources exist and extraction concepts have been developed for a number of these. They include: surface [5] and ground ice [6], deep artesian or sub-artesian aquifers [7] and hydrated minerals [8]. The problem with using all of these sources has been either the need to guarantee the presence of the resource before the arrival of the crewed mission (an issue for the use of aquifers, subsurface ice, or hydrated minerals) or the resource occurs at high latitudes (as is the case with surface ice) which, for operational reasons, are unlikely to be landing sites for early missions.

The discovery of widespread hydrogen on Mars [9, 10] has led to a major reassessment of the availability of water in the top metre of the Martian regolith. From the poles down to latitudes of 60 degrees the regolith is inferred to contain at least 40% water by mass. At low latitudes the hydrogen signal in the neutron spectrometers aboard Mars Odyssey reveals wide areas with ~10% water by mass. The presence of 15-35% abundant hydrated sulphates such as gypsum ($CaSO_4.2H_2O$) and kieserite ($MgSO_4.H_2O$) at Meridiani [11, 12] equates to 9% water. An unknown amount of water is also likely to be contained in the 20-30% of layer silicates (e.g. clays) present in the bedrock. Thus regolith water contents across large areas of the Martian surface are now estimated to be an order of magnitude larger than the 1% assumed by earlier studies [8]. The most documented occurrence are the hydrated sulphate deposits at Terra Meridiani where orbital remote sensing has been backed up by ground truth data from the *Opportunity* rover.

As a result of these discoveries several recent studies have included extraction of local water resources as a key element of Mars expeditions [13, 14]. This would reduce the mass transported and greatly reduce the mission complexity. All ISRU water requirements would be extracted robotically prior to the launch of the first crew, with optional of manual operated top-up, if required.

MISSION WATER REQUIREMENTS

Water is a key resource for several uses in human Mars missions. These include:

- As a source of hydrogen and oxygen for spacecraft propellant for the return trip, with the hydrogen being used either directly or as a hydrogen-bearing compound such as methane or ethylene.
- As a source of hydrogen and oxygen for surface applications such as fuel cells or internal combustion engines, as with spacecraft the hydrogen can be used either as the element or as a hydrogen-bearing compound such as methane or ethylene.
- As water for crew use, including washing, drinking, and atmospheric humidification.
- As a source of oxygen for breathing.
- For Mars stations as water for food production.

This paper will focus on water use on the first Mars missions, as a supply of oxygen and hydrogen compounds for spacecraft propellants, and of oxygen and water for crew use. Food production requirements will not be considered, as we see this as a requirement for permanent stations.

The amount of water required during a human Mars mission will vary markedly with the chosen mission architecture, crew size, and life support system assumptions. In this paper we consider the requirements for three classes of mission:

- Missions with Mars direct architectures, where all the propellant for the return journey is manufactured on the surface. A crew of four is considered, as in the original "Mars Direct" proposal [15].
- Missions with semi-direct architecture and a crew of four, as in the MSA mission [16].

- Missions with semi-direct architecture and a crew of six, as in version 3.0 of NASA Design Reference Mission for Mars [17]

Each of these missions assumed that all hydrogen for propellant and water was obtained using imported hydrogen. Specific hydrogen masses in tonnes are converted into water equivalent for each mission class and shown in Table 1.

In both direct and semi-direct architectures all consumables needed by the mission must be available when the crew departs for Mars. Assuming a 240 day transit time to Mars for the initial unmanned logistics mission and a 30 day set-up period allows calculation of the daily extraction rates over a 510 day period for the water plant, as shown in Table 2. The big reduction in the amount of hydrogen (and thus water required) for the MSA mission compared to Mars Direct is due largely because of the need to provide propellant for the ascent stage only, rather than the entire Earth-return spacecraft. The NASA DRM, which uses a similar Mars-semi-direct architecture to the MSA mission, requires much more propellant for its ascent stage because of its larger crew (6 as against 4).

Table 1
Masses of hydrogen and water (tonnes) required for specific Mars mission proposals

	Mars Direct	**MSA**	**NASA DRM 3.0**
Imported hydrogen	6	1.6	5.42
Water equivalent	54	14.4	48.78

Table 2

Water extraction rates required to support different Mars mission proposals

	Mars Direct	**MSA**	**NASA DRM 3.0**
Total water required (tonnes)	54	14.4	48.78
Daily rate (kg) (over 510 days)	106	29	97

Assuming a standard density for Martian regolith of 3.3 [11] we can calculate the mass and volume of the sulphate-bearing unit that needs to be processed for different water contents to meet these requirements on a daily (Table 3) and total mission (Table 4) basis.

Table 3

Daily mass sulphate-bearing regolith processed

Mass water (kg)	**Mass sulphate-bearing regolith required**					
	20% recovered water		**10% recovered water**		**5% recovered water**	
	Mass (kg)	**Volume (m^3)**	**Mass (kg)**	**Volume (m^3)**	**Mass (kg)**	**Volume (m^3)**
106[1]	530	0.161	1060	0.322	2120	0.643
97[2]	485	0.147	970	0.294	1940	0.588
29[3]	145	0.044	290	0.088	580	0.176

Notes: 1 NASA DRM 3.0; 2 3 Mars Direct; 3 MARS-OZ, from Table 2.

Table 4

Total amounts sulphate-bearing sediment processed

Mass water (t)	**Sulphate-bearing material required**								
	20% recovered water			**10% recovered water**			**5% recovered water**		
	Mass (t)	**Vol. (m^3)**	**Area[4] (m^2)**	**Mass (t)**	**Vol. (m^3)**	**Area[4] (m^2)**	**Mass (t)**	**Vol. (m^3)**	**Area[4] (m^2)**
54.0[1]	270	81.8	81.8	540	163.6	163.6	1080	327.2	327.3
48.8[2]	244	74.0	74.0	488	148	148	976	296	296
14.4[3]	72.0	21.8	21.8	144	43.6	43.6	288	87.2	87.2

Notes: 1 NASA DRM 3.0; 2 3 Mars Direct; 3 MARS-OZ (all from Table 2); 4 assuming excavated depth 1 m.

A number of different technologies have been proposed for extraction of water from the Martian surface [8, 15]. These include direct heating of the surface by solar concentrators or microwaves, the excavation of regolith and heating (by microwaves, resistance heaters, or solar concentrators within a suitable retort.

MOON PLAIN AS A MARS ANALOGUE

Laboratory tests of Mars surface simulants and field trials of full scale equipment are essential stages in the development of this ISRU technology. Key to the project is a suitable analogue site. A suitable site must:

- Arid, to minimise the presence of precipitation moisture;
- Be above the water table and its capillary fringe to exclude the presence of ground water;
- Consist of suitable minerals (epsomite, gypsum, and smectitic clays all in abundances above 10%);
- Occur in an appropriate physiographic setting (near surface, low relief and easily trafficable);
- Have appropriate material properties (porous and easily excavated); and,
- Be accessible but secure, allowing easy setting up of the plant and minimal risk of uncontrolled interaction with the public.

Such locations are rare on Earth. On Earth magnesium sulphate minerals are a relatively rare mineral, occurring mainly as minor coatings or growths in mines and caves, extremely arid environments or in final stages of brine evaporation pans (“bitterns”). One of the largest, most extensive, and highest grade occurrences occurs on the Moon Plain, north east of Coober Pedy, in central Australia (Figure 1). This area is extremely arid, abundant epsomite, along with other hydrated magnesium and calcium sulphates, occurs in the soil profile which may contain up to 20% water by mass (see below). The whole area is under either pastoral or mining lease which can be made secure from casual visitation. We recommend use of the Moon Plain as an ideal site field research into extracting water from hydrated minerals in the regolith.

Setting

Cooper Pedy (134° 45’ E, 29° 00’ S) is situated in the remote mid-north of South Australia, 850 km north of Adelaide and 700km south of Alice Springs on the Stuart Highway (route 87). The town is a major opal mining centre and offers a wide range of services in support. There is a scheduled air service and hospital. Cooper Pedy is an ideal centre to support proposed operations on Moon Plain, which lies less than two hours drive out of town along an all-weather gravel road. The surrounding plains, however, can become impassable for several days or weeks after rare heavy rain because of the high swelling clay content in the regolith. Moon Plain was assessed as a possible Mars analogue site during the JNT-1 expedition in 2001 [18]. The significance of the epsomite deposit was not appreciated until after recent reports from Mars missions, however.

Geology

Information on the Moon Plain epsomite deposit is limited, with only one published reference [19]. There is also an extensive body of unpublished data and interpretation [20] associated with a mineral exploration program that assessed the resource potential of the area. The occurrences occur over an area of 5100 km^2 and contain up to 22.5% epsomite in the upper 3.5 m of the weathering profile. The highest grade part of the deposit occurs between Oolgelima and Giddi Giddinna Creeks, to the east of the Stuart Range and lookout known as The Breakaways (Figure 2). The deposit forms in a weathering profile developed on the transitional unit between the Cadna-owie Formation and the Bulldog Shale, both of Cretaceous age. The weathering profile is overlain by a thin, silty clay unit, the Benitos Clay [20] of probable aeolian origin, and is mantled by gibbers (Figures 3, 4).

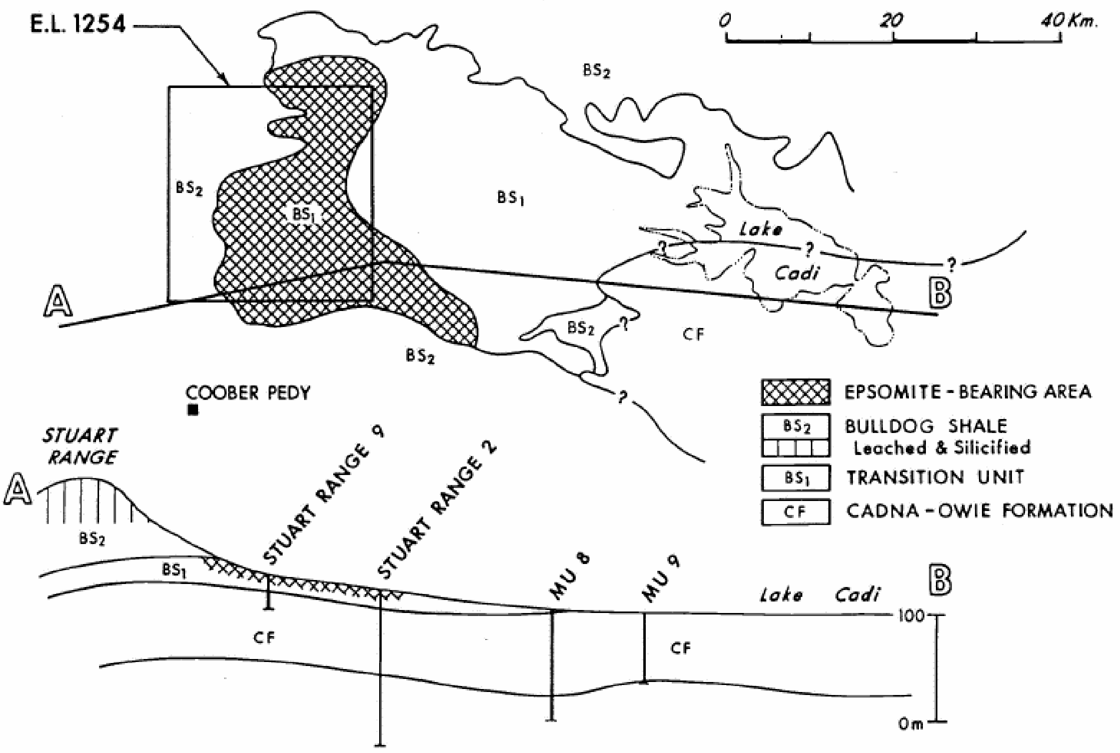

Figure 1. Location map and geological cross section of the epsomite deposit. Modified from [20].

The highest grades occur in three deposits spread over 46.68 km^2 and contains 94.4 million tonnes of *in situ* material averaging 7.4% Mg_2SO_4. The epsomite occurs at depths of 0-2 m beneath the surface and averages 1.35 m thick.

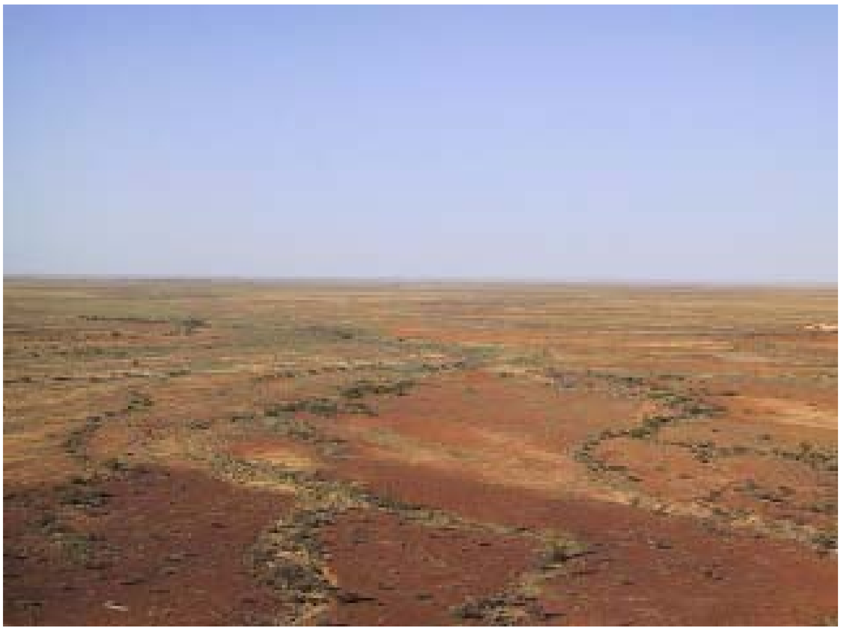

Figure 2. View from The Breakaways over the Moon Plain. Photo G. Mann.

Figure 3. Surface cover of gibber lag and silty clay (Benitos Clay) over epsomite deposit. From [20].

The bedrock is composed of black pyritic-bearing smectitic shales containing thin bands of dolomitic limestone. Oxidation of pyrite during weathering produces acid sulphate soil waters that dissolve Mg and Ca out of the dolomitic limestones. Evaporation in an arid regime (Coober Pedy has only 159 mm average annual rainfall [21]) leads to precipitation of gypsum and epsomite in the weathering profile. February and March are the driest months.

The weathering profile is shallow (Figure 4). Fractures in the fissile weathered shale contain gypsum, bloedite ($Na_2Mg(SO_4)_2 \cdot 4H_2O$), iron sulphates, and epsomite. The powdery soils contain abundant montmorillonite ($(Al,Mg)_8(Si_4O_{10})_3(OH)_{10}.12H_2O$), fine quartz sand, and minor non-swelling clays, in addition to the sulphates. Pebbles derived from dropstones within the bedrock and eroded from the receding breakaways of the Stuart Range armour the surface, forming a gibber plain. At the soil surface the epsomite is partly converted to hexahydrite ($Mg(SO_4) \cdot 6H_2O$).

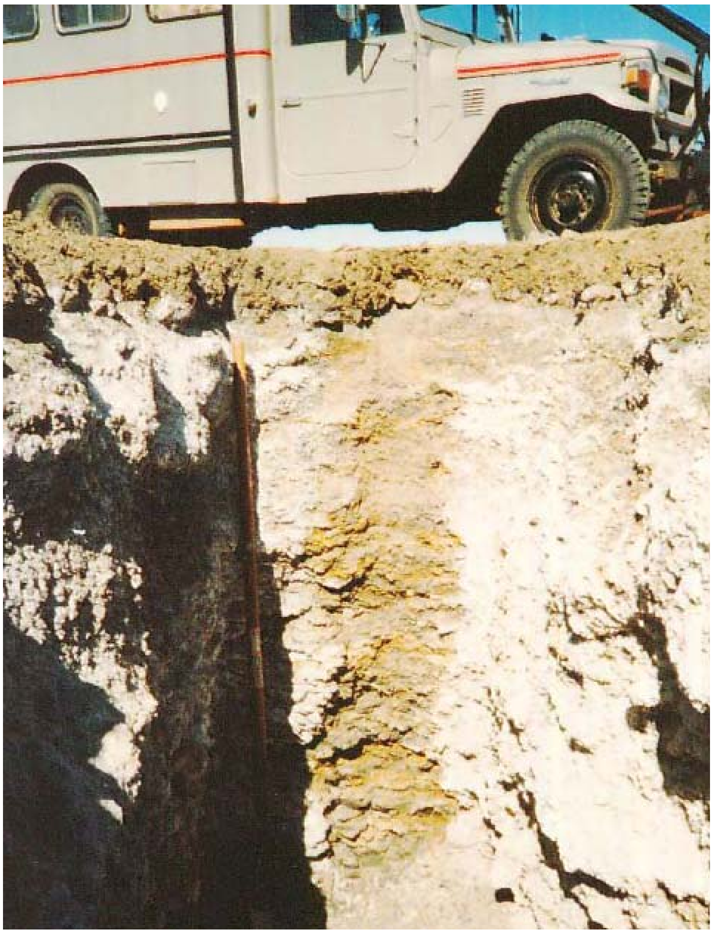

Figure 4. Backhoe pit into high grade portion of the deposit showing white sulphate efflorescence on weathered shale neath thin cover of gravel lag and aeolian silty clay (Benitos Clay). Modified from [20].

PROPOSED RESEARCH PROGRAM

We propose the construction of a plant capable of extracting water from the regolith at Moon Plain to demonstrate the feasibility of such a process. Given the relatively small amounts of water that needs to be extracted the test plant could be of a similar scale to what would needed on Mars. It need not be operated for the full period (780 days) that would be the minimum expected on Mars, but for an arbitrarily determined period, for example 30 days, or until a specified amount of water (e.g. 1000 L) has been collected.

Objectives

Primary Objective

The hypothesis to be tested by this research project is:

That an analogue plant for the practical extraction of water from hydrated minerals can be successfully field trialled

The success criteria for the plant will be:

Extraction of a minimum of 100 L of water per day over 1 week.

The project would provide baseline data on:

- Preferred heating methods;
- Optimal operating temperature;
- Time requirements for operation;
- Power requirements;
- Process rates
- Plant masses; and,
- Water extraction efficiencies

Data from this experiment will allow more meaningful assessment of the viability of extraction of mineral water for Mars missions including likely flight rated equipment masses and power and time requirements.

Follow-on objectives

Success of the main objectives could allow a range of follow-on investigations. These could include but are not restricted to:

- Assessment of whether analogue plant can be operated under direct human control in simulated space suits.
- Feasibility of operating the plant under remote control using various levels of autonomous and/or teleoperated systems.

Project Structure

The project will consist of three phases.

Phase 1

This consists of a preliminary visit to Coober Pedy. This visit will result in:

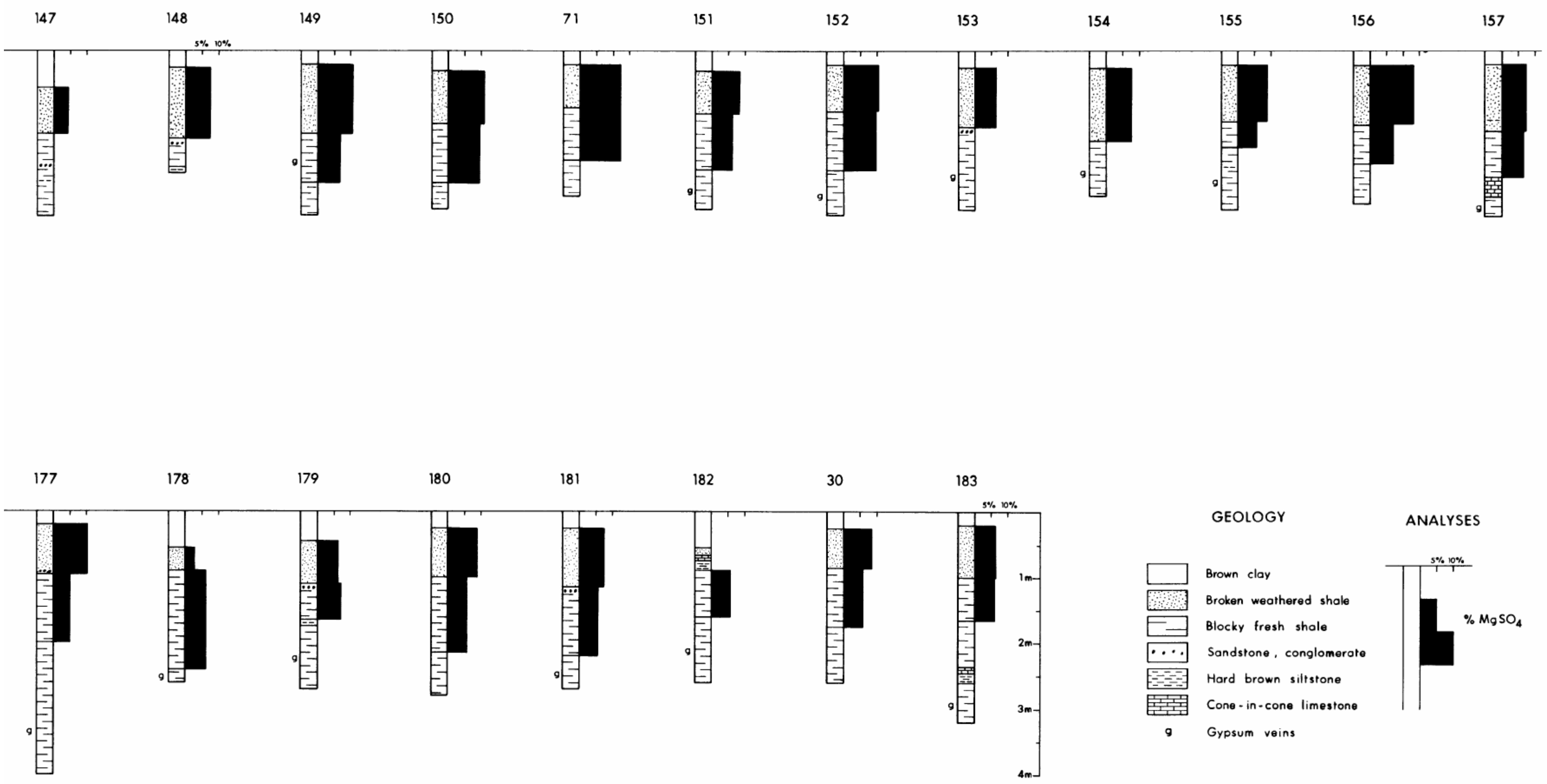

Figure 5. Cross section through part of the deposit, locality 2, traverse A (top) and B (bottom). Modified from ref. 20.

- Discussions with local land holders and government agencies in Cooper Pedy and Adelaide to determine the statutory and cultural framework for working in the area;
- Documentation of the regolith profile and mineralogy of the area;
- Collection of samples for preliminary analysis and testing; and,
- Selection the site for further work.

Phase 2

Development of an ISRU plant to process analogue materials. Aspects to be determined include:

- The optimum feed stock parameters required after crushing. This includes mass, particle size and constancy;
- The optimal processing rates;
- Method of heating (e.g. microwave, resistance heaters, solar);
- Water collection and storage technology; and,
- Energy requirements.

Phase 3

Development of an excavation and processing system capable of delivering raw materials to the ISRU plant. The plant would include:

- Excavation and transportation system;
- Storage and milling system;
- Oven;
- Water condenser and storage system; and
- Waste disposal system

Coordination

Each phase will be independently funded and managed by the contributing party or parties. MSA will fund coordination of the project out of an up front 10% levy on the budgets participating organisations. MSA will be responsible for coordinating all activities, including research, field operations, PR and outreach.

Outcomes

The project is expected to have the following outcomes:

- Geological documentation and explanation of the largest and highest grade epsomite deposit on Earth.
- Identification of the some of the major issues associated with operating a mineral-water extraction plant on Mars with respect to efficiencies, scale, power requirements, time factors, excavation, and processing;
- Demonstration of a full scale concept plant in a terrestrial analogue of sulphate rich areas on Mars;
- Develop a platform for further studies in the field of extraction of water of from hydrated minerals for ISRU;

- A platform for investigation of plant using simulated space suits;
- A platform that can be used for robotics research;
- An operational ISRU water supply system that can be incorporated in an analogue Mars station;
- Public interest, education, and outreach;
- Opportunities for Australian student participation in a space-related field engineering project; and,
- Publicity for the research and education activities of the participating organisations.

Deliverables

The project will have the following deliverables:

- Geoscientific paper on the Moon Plain epsomite deposit;
- Engineering papers on the design and operation of the processing plant; and,
- Research papers on the feasibility of hydrated mineral-based ISRU on Mars.

We expect that all these will be published in relevant peer journals. Additional papers will be presented at the Mars Society conferences in Australia and the United States and at various space science and engineering conferences as the opportunity arises. Further papers can be expected from follow on research involving operation under simulated EVA conditions and using robotics, should these projects eventuate.

CONCEPTUAL PLANT

The conceptual plant (Figure 6) would include:

- Excavator, such as a small “Bobcat”, to dig up the epsomite rich regolith;
- A small front-tipping truck to carry the regolith to the mill, this could possibly be combined with the excavator;
- Hopper with grizzly (screen to prevent over-sized rocks entering the system);
- Crusher, fed by conveyor from hopper;
- Oven to heat the milled regolith to optimal temperature and fed by conveyor from crusher;
- Water condenser, to collect water released from oven;
- Water tank; and
- Waste pile, fed by conveyor from over, this would be back filled into the excavation pit at the end of project.

Given a reasonable mix of 20% each of epsomite (51% water), gypsum (14% water), and montmorillonite (up to 26% water) and the remainder quartz in the Moon Plain regolith, it is probable that the regolith will contain up to 20% water by mass, allowing for a modest 2% contribution from the soil moisture present even in powder-dry soils. Assuming 100 L per day (Table 3, and a weathered shale density of 1.5 [ref. 20], the following masses and volumes of regolith would need to be processed at varying extractive (Table 5).

Careful site selection may be able locate areas where this material occurs at the surface, however excavation of up 0.5 m of overburden may be necessary.

Table 5
Test plant processing requirements for 100 L water per day

Regolith required						
	20% recoverable water		**10% recoverable water**		**5% recoverable water**	
	Mass (t)	**Volume m^3**	**Mass (t)**	**Volume m^3**	**Mass (t)**	**Volume m^3**
	0.5	0.33	1.0	0.67	2.0	1.33
Over 7 days	3.5	3.31	7.0	4.69	14.0	9.31
Excavated m^2 (assuming 0.5 m thickness)	6.61		9.38		18.62	

CONCLUSIONS

ISRU is a key philosophy for minimising the logistic cost of crewed Mars missions. The ability to extract water from the Mars environment will be the cornerstone of ISRU that allows a high level of independence from terrestrial resupply. Recent confirmation of locally abundant hydrated minerals in the Martian surface materials makes water extraction a feasible option early in the Mars mission sequence, possibly even from the first mission. Development of plant capable of extracting water from the Martian regolith must therefore be a priority for ISRU research. We believe that the Moon Plain region of South Australia offers a significant and unique opportunity to field trial water extraction plants that process hydrated sulphate minerals. Furthermore, we consider that development of a full sized field test bed may be within the cost range of MSA and partners in Australian Universities, and of major benefit to collaborating institutions and Australian Mars analogue research and science in general.

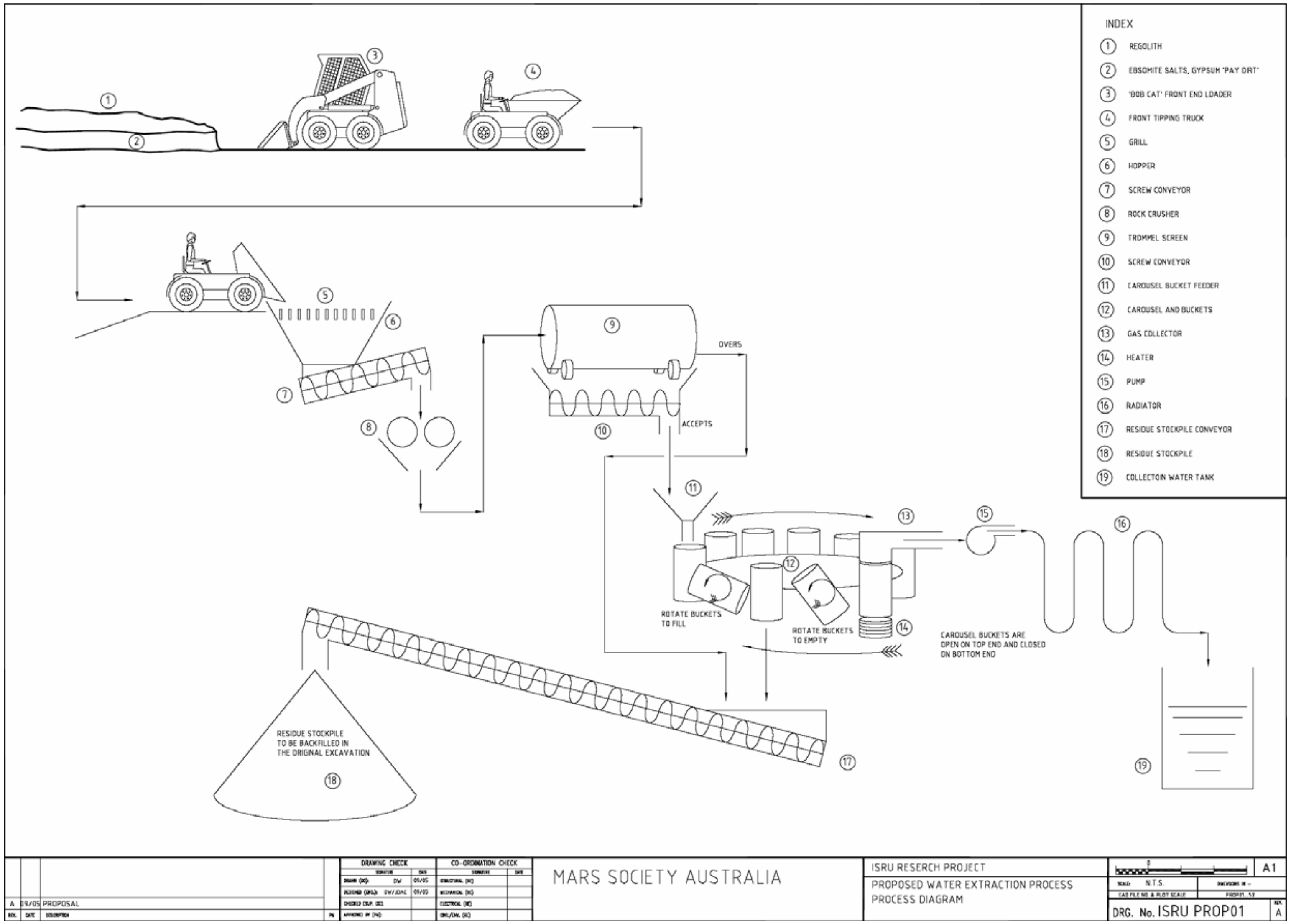

Figure 6. Conceptual plant layout

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