Preprint
UCRL-JC- 135329 Rev 1

WET MARS: Plentiful, Readily-Available Martian Water and Its Implications

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This article was submitted to the 2nd Annual International Conference of the Mars Society, Boulder, CO, August 12-15, 1999

September 14, 1999

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WET MARS:

Plentiful, Readily-Available Martian Water and Its Implications*

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ABSTRACT

Water and its major constituent, oxygen, in large specific quantities are essential for maintenance of human life. Providing them in adequate quantities is widely believed to be a major challenge for human exploration and settlement of Mars. The Martian regolith isn't known to bear either water or hydrogen, the ice-rich Martian polar regions are thermally inhospitable, and the measured water content of Mars' thin atmosphere represents a layer of liquid water of average thickness only ~1% that available on the Moon, or ~0.001 cm. Crucially, however, the atmospheric Martian water inventory is advected meteorologically to everyplace on Mars, so that the few cubic kilometers of liquid water-equivalent in the atmosphere are available anywherewhen, merely for the effort of condensing it.

Well-engineered apparatus deployed essentially anywhere on Mars can condense water from the atmosphere in daily quantities not much smaller than its own mass, rejecting into space from radiators deployed over the local terrain the water's heat-of-condensation and the heat from non-ideality of the equipment's operation. Thus, an optimized, photovoltaically-powered water-condensing system of ~0.3 tons mass could strip 40 tons of water each year from ~10^4 times this mass of thin, dry Martian air.

Given a 490 sec I_{sp} of H_2-O_2 propulsion systems exhausting into the 6 millibar Mars-surface atmosphere and the 5.0 km/s Martian gravity well, ~40 tons of water two-thirds converted into 5:1 O_2/H_2 cryogenic fuel could support exploration and loft a crew-of-four and their 8-ton ascent vehicle into Earth-return trajectory. The remaining H_2O and excess O_2 would suffice for half-open-cycle life support for a year's exploration-intensive stay on Mars.

A Mars Expedition thus needs to land only explorers, dehydrated food, habitation gear and unfueled exploration/Earth-return equipment – and a water/oxygen/fuel plant exploiting Martian atmospheric water. All of the oxygen, water and propellants necessary for life-support, extensive exploration and Earth-return can be provided readily by the host planet. Crewed exploration of Mars launched from LEO with only 2 Shuttle-loads of equipment and consumables – a commercial total cost-equivalent of ~$650 M – thereby becomes feasible.

The most challenging current problem with respect to human expeditions to Mars is escape from Earth's deep, 11.2 km/s gravity well, and is largely an economic issue. Living on Mars, exploring it extensively and returning to Earth, each hitherto major technical issues, are actually much less difficult, thanks in no small part to the effective 'wetness' of Mars. Similar considerations apply to other water-rich locations in the Solar system, e.g. Europa.

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[*] Prepared for publication in the proceedings of the 2nd annual international conference of the Mars Society, Boulder CO, 12-15 August 1999. Work performed under the auspices of the U.S. Department of Energy at LLNL under Contract No. W-7405-Eng-48. Opinions are the authors only.

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Introduction And Summary. Water is the *sine qua non* of human life. Not only is it essential *per se* for use in preventing eventually-fatal dehydration of our tissues, but its major constituent, oxygen, is essential in molecular form as the ultimate electron-sink in the chemical reactions which power all human metabolic processes. We die without molecular oxygen gas for respiration in a matter of minutes, without liquid water for tissue-rehydration in a handful of days. To stay alive, then, we must immerse ourselves in environments which aren't completely devoid of water, just as our distant ancestors required enormously water-rich ones.

Off-Earth human exploration and settlement appears especially challenging, then, for liquid water is known to be present in very few locations of near-term interest for exploration of the inner Solar system – actually, precisely none. The general mind-set has been that Mars is exemplary of such water-starved, innately inhospitable locales, for the very modest quantities of water which exist on its surface – by terrestrial standards, at least – seem to be tightly locked-up in polar caps of forbiddingly low temperature. Even the vacuum-enshrouded Moon, from our current, relatively poorly-informed perspective, might seem more attractive to water-addicted lifeforms such as our own, for its generally fine-powdery surface is known (from Apollo studies) to have several ppm of solar wind hydrogen implanted in it, which can be released by moderate-temperature roasting of this 'soil.' The corresponding amount of water-equivalent hydrogen in the top 10-20 meters of continually meteorically-churned lunar regolith is a liquid sheet of about 0.1 cm thickness, or 1000 metric tons of water per square kilometer of *mare* surface – everywhere! The dusty, wind-swept Martian surface seems desert-like in comparison.

The purpose of this paper is to invite general attention to the facts ***that Mars is actually reasonably water-rich, that the entire surface of Mars is truly covered with a very low-density albeit deep ocean of water – and that human exploration and settlement of Mars are therefore much less technically challenging – and far less economically demanding – than has been generally believed.*** This general point applies in a comparably compelling manner to other water-rich locations in the Solar system, e.g., the outer Galilean moons of Jupiter.

In particular, as specialists have long understood, the thin (~6 millibar surface-pressure) Martian atmosphere has the same *specific* water content as is found in the Earth's air over Antarctica – about 1 milliTorr vapor pressure, in the Martian case – and the pertinent transport properties of the Martian atmosphere are particularly conducive to condensation of this atmospheric moisture with modest specific quantities of equipment. Deployment and operation of remarkably small amounts of optimized equipment may readily extract enough liquid water to not only provide the feedstreams of oxygen and water to life-support systems for human explorers or settlers, but can also provide the few-fold greater quantities of liquid hydrogen and liquid oxygen needed to support vigorous rocket- and ground-vehicle-supported exploration of Mars, *as well as* supply the far-larger quantities of cryogenic propellants required for rocket-powered return-to-Earth from the Martian surface.

Martian explorers and settlers thus need bring to Mars little more than themselves, life-support and habitation equipments, dehydrated food (sufficient until greenhouse operation provides adequate foodstuffs), a Water Plant (with internal power-supply) and exploration and Earth-return vehicles. Water extracted from the Martian atmosphere – and products readily derived thereform – will fill in the rest of the traditional expedition's mass-budget – and this mass budget-fraction *characteristically* is the dominant one, as Table I and Figure 3 indicate. ***Exploration and settlement of Mars thereby may be several-fold easier, in terms of required mass leaving the Earth in trans-Mars trajectory, than has been estimated hitherto – and thus may be made to commence significantly sooner. Specifically, as little as 2 Shuttle-loads (or commercial space-launch-equivalents) of equipment and supplies positioned in LEO may suffice to launch a full-fledged manned mission to Mars with a crew of 4.***

In the following sections, we first review salient properties of the Martian atmosphere, including aspects of its meteorological repertoire, then consider the form-and-function of equipment mass-optimized to extract water from it, note the quantities of water of interest to support the full spectrum of activities of early exploration teams, suggest the steps to be taken toward the reasonably near-term implementation and demonstration of these prospects, and conclude by noting the rather striking implications of these results for initial Mars exploration mission-architectures.

Pertinent Properties Of The Martian Atmosphere. Our present knowledge of the pertinent features of the Martian atmosphere is derived from the Viking Lander 1 and 2 data-sets, supplemented by the Pathfinder results of 1997. The Viking data-set is of primary interest, as it represents essentially all that we know of a quantitative nature about Martian atmospheric seasonality – and because it sampled atmospheric properties at two quite different locations on Mars; at that, it's quite imperfect, as surface-level water vapor concentrations were measured only indirectly and only two sites on Mars, a planet whose meteorology apparently is not much less rich than that of the Earth, were studied for only over a single full year's variations, i.e., over an interval of 650 sols.

The primary data of present interest are summarized in Figure 1, which, at the "bottom line" (represented by the "New Houston" plot, which is the best-estimate of the globally-averaged value-vs.-time of the Martian atmospheric water content) indicates that the global annual average of water content of the Martian atmosphere is about $2\text{x}10^{-6}$ kg/m^3, corresponding to a bit more than 1 milliTorr vapor pressure. The right vertical axis of this Figure indicates the saturation temperature for the corresponding water vapor pressures/gas densities on the left vertical axis. As may be readily appreciated, the saturation temperature for the global annual-averaged water vapor pressure is about -74^o C, or 199 K, while an order-of-magnitude lower vapor pressure is seen at -88^o C, or 185 K, and another order-of-magnitude reduction is seen at -100^o C, or 173 K. In somewhat more familiar terms, the average relative humidity of the Martian wintertime atmosphere is about 5-10% – not much less than mid-continental wintertime terrestrial conditions.

Stripping water out of the "average" Martian atmosphere thus consists of cooling it to a temperature of no more than about 185 K, providing a convenient surface onto which this now-supersaturated Martian 'air' can deposit and/or grow ice crystals, and maintaining this condition sufficiently long (in the particular cooling geometry employed) for essentially all water molecules in the parcel of chilled air to "see" the ice-covered surface via diffusive-and-convective transport. This whole process really isn't very complicated – splotchy hoar frosts on the nearby Martian surface were imaged regularly during local wintertime shortly after dawn at the Viking Lander sites, i.e., the Martian surface cooled-by-radiation sufficiently most every winter night to condense visible quantities of water from the overlying atmosphere.

Mass-Optimized Water Extraction From The Martian Atmosphere. *The* issue of present interest is the design of equipment of minimum mass with which a unit quantity of water can be extracted from the Martian atmosphere per unit of time.

As we will also mention quantitatively below – but which is intuitively obvious to those who have considered these matters in any detail – the present and near-term specific (i.e., per-kg) cost of soft-landing equipment on the Martian surface is so great that it exceeds the specific cost on the Earth's surface of virtually every type of human artifact. Simply stated, the per-kg transportation cost from Earth-surface to Mars-surface is so huge that it exceeds the purchase-cost here on Earth of a kilogram of almost everything. It is therefore "good engineering practice" in the Mars-mission architecture and design processes to drive the mass of *any* equipment that needs to go to Mars to as low a value as ever possible; no matter how expensive it may then be to fabricate here on Earth, the *total* cost to create and then transport it to the Martian surface will thereby be minimized. This is the approach which we take toward the optimized design of equipment for extracting water from the Martian atmosphere.

Our basic design approach is to use counter-current air-flow through the water-extracting apparatus, and cool-as-required the coldest spot ($T \leq 180$ K) in the system radiatively. As noted above, water starts condensing from the most moist Martian air at ~200 K, and 95+% (global- and time-averaged) of the Martian atmospheric water is stripped out at 180 K. This water-condenser's incoming and exhaust air-flows are cross-coupled thermally with heat-pipes terminating on each side on super-high surface-to-volume metal-to-gas finned/spiked surfaces. Photovoltaically-energized electric motor-driven fans make up condenser-internal aero-drag losses (with ~1.5 kWe of H_2/O_2 fuel cell-derived power being employed during nighttimes and milder dust storms). See Figure 2.

The core technical issue in overall system design is trading off condenser drag-loss vs. condenser mass vs. condenser air-blower electrical power (i.e., photovoltaic array or PVA, power-conditioning and fuel-cell masses) vs. condenser irreversible ΔT (the temperature differential between the exhausted air relative to the incoming air arising from finite air flow-speeds and imperfect heat-exchange), in order to minimize total system mass (including that of the system's radiator, which sizes and masses nearly linearly in proportion to ΔT – exactly linearly, after the 'base' $2.5\text{x}10^8$ J/day, or ~2.5 kW – of heat-of-condensation of 100 kg of water/day, or ~1 gm/sec, is subtracted off the bottom of the system's thermal radiation budget). The only major constraint on the radiator is that its working-surface be shaded, *if* it's going to be operated in daytime, as well as nighttime;

it *may* thus be split into AM and PM sections (*if* it's deployed in east-west symmetry; splitting is less necessary if deployed in north-south symmetry at a higher-latitude location in either Northern or Southern Hemisphere). A minor constraint on the radiator's design is that it's operating in 6 mbar 'air', so that it needs some 'standard' thermal decoupling from the local atmosphere, e.g., a transparent film-bounded layer or two of trapped still air, which involves some (modest) associated mass-expenditure.

Our scoping estimate is that the ~10^9 gm/day of Mars-air – processed through the ~10^2 m^2 condenser system inlet-aperture at 10 m/sec mean speed – will require of the order of 10^9 J/day (or ~10 kW, CW) of heat stripped from it, net; this corresponds to a flow-stream irreversible ΔT of 1 J/gm-equivalent, or 44 J/mole (of CO_2), or ~10 cal/mole, or a ~1.5 K ΔT, split into two roughly-equal portions, in the metal-to-air interfaces on each side of the counter-current flow (with the interposed heat-piping being taken to be a thermal superconductor, a quite good approximation). This is ~5% of the total temperature change which the processed air typically (i.e., in the diurnal-average) will be cycled through, so that the mean-reversibility of the condenser system is taken to be 95%. (We expect that this inlet-air flow-speed will suffice for centrifugal separation of all but the smallest dust particles from the inlet air-stream, given the low density of the air-flow; electrostatic precipitation will then serve to "polish" the inlet flow with respect to very small dust particles, so that minimal solids-removal processing (e.g., by a regenerable, multi-stage filter and ion-exchanger) of the extracted water will be required prior to its storage or electrolysis. We therefore expect that this system may be made to work effectively in all Martian dust storms of sufficiently low opticaldensity that PVA-derived electrical power will be available.)

If the Martian air-mass exits the 100 m^2-aperture condenser with the reference entry-speed of 10 m/sec, this represents only 850 W of kinetic energy, a modest fraction of the total power budget of the system, as will be seen below, so that use of pressure-recovery features probably isn't indicated. A simple electrically-powered blower-system provides the necessary ventilation of the condenser. An electrical-watt-to-flow-watt efficiency of ~0.71 is realistic for powered, optimized airfoils operating in the high Reynolds number conditions characteristic of the Martian surface atmosphere. Electrical power input to the condenser's air-moving system thus is ~1.2 kWe, assuming use of a 95% efficient fan-motor.

The system's radiator, working at 175 K at an emissivity of 0.85 (i.e., with a radiator system-internal mean ΔT of 5 K), sheds (into 2π steradians) about 50 W/m^2, so that 250 m^2 of open-sky-equivalent radiating surface is required to shed 12.5 kW; the radiator's area thus is comparable to the sum of the entry and exhaust port-areas of the condenser. (The Martian atmosphere is radiatively *reasonably* thin in the thermal IR – the current Martian 'atmospheric greenhouse' ΔT is only ~7 K, compared to ~35 K for Terra – so the radiator performs *almost* like it's radiating directly into space, except that only one side of it is available to shed heat, and the ambient air-&-soil must be kept out of effective thermal contact with the radiator's cold surface). As noted above, the radiator's operating surface also must be shaded from direct or indirect illumination by either the Sun or the Martian surface, e.g., it will be north-facing in northerly latitudes, with suitably thermally-decoupled baffles-&-shades positioned to keep it 'looking' only into non-Sun-bearing space; the Martian equatorial inclination to its orbital plane of 24^{o} (very similar to Terra's 23.5^{o}) is usefully large in this respect.

If it's deemed too tedious to shield the radiator from the Sun-&-surface, the condenser may be operated only when the Sun is below the local horizon, and then may heatpipe-couple to a simple radiator lying on the local surface, looking into the entire 2π of the dark sky. In this case, the entire [condenser+radiator+fuel cell] subsystem must be oversized by two-fold, relative to the operating-all-the-time baseline system, and the photovoltaic array (PVA) simply 'pumps up' the store of cryogenic H_2 and O_2 during daytime, for nocturnal use by a ~3 kWe fuel-cell (which also provides ~1.5 kWe to the Base during nighttime intervals). This variant is considered likely to be off the mass-optimum, however; it's of interest if total system simplicity – and (perceived) technical risk – is at a premium.

Periodically – e.g., diurnally – the system will (hermetically) close its entry-and-exit hatches and electrically heat its "cold-spot" to ~275 K, so as to liquefy the condensed H_2O and gravity-drain it into a sump for pump-transport to electrolysis-&-cryogen storage, to water storage, etc. (The molten-H_2O vapor pressure at 2-3^{o} C will add only ~6 mbar to the condenser-internal pressure, so that a high-strength shell around the condenser and its hatches is quite unnecessary to contain the internal gases during the system's "defrost cycle," during which interval the dust-scavenging surfaces at the condenser inlet are also mechanically brushed-&-air-blown clean.) The system then radiatively re-cools to working temperatures (in order to scavenge internal liquid water and water-vapor), its hatches re-open and atmospheric water-condensing resumes; the daily defrost-&-regeneration cycle has been completed.

The actual condenser system likely will be implemented with many identical small modules working in parallel, for reasons of economy in Earth-side prototyping and testing, of simplicity of packaging-for-transit, of ease-of-erection and of system-level reliability-in-operation – although this is likely to be somewhat off-mass optimum. Thus, the condenser *per se*, the radiator and the PVA functions may well be fully-integrated in each module, so that there will be precisely <u>no</u> single-point failure-sites in the total system – and so that the system's capacity can be readily "cut-to-length" to meet varying mission requirements.

Insolation at Mars *diurnally-averages* about 150 W/m^2, or about 15 W/m^2 electrical converted with a-Si – or 30 W/m^2 converted with high-efficiency, thinned Si – photovoltaic arrays (PVAs). Electrolyzing the (time-averaged) 1 gm/sec of water condensed from the Martian atmosphere will require ~15 kW electrical power (time-averaged), or the output of 500-1000 m^2 of such PVA. The best-current a-Si offers about 1 W/gm at 1 AU AM0, and the comparable value for high-efficiency 4-mil Si is ~0.5 W/gm, so that a 15 kW average-power (i.e., 50 kWe initial peak-power) requirement entails ~115 kg of a-Si PVA, or ~230 kg of PVA implemented with thin-crystalline Si, at Mars AM1; a-Si PVA usage is therefore preferred. An option which we consider interesting but haven't examined in detail features double-use of one-and-the-same large-area deployed surface: as a PVA during daytime and as a radiator-surface at night. If this is done, ~500 m^2 of effective surface area is required if we condense-and-radiate only at night, which is comparable to the 500-1000 m^2 of PVA needed during daytime. If we were to employ a 1000 m^2 area, the 2.5X larger radiator surface area would permit us to operate with a condenser-internal irreversible ΔT which is 2.5X greater, i.e., ~4 K, realizing a corresponding savings in condenser system mass. However, such double-use doesn't come free; we would have to provide adequate thermal decoupling of both top and bottom surfaces of the entire radiator-PVA area during nighttime. Thus, unless suitable {atmosphere+soil} insulation of quite modest areal density – <0.05 gm/cm^2 – is available, we might be better off with employing a crystalline-Si PVA and working with the smaller 1.5 K ΔT in the condenser's air-flow – if we were to pursue this double-use option at all. All these are instances of second-level design issues which may be resolved only by comparison of the details of several alternate point-designs, which we have not yet done.

These, then are the essential considerations upon which our baseline-design Water Plant mass-estimate of 300 kg (0.3 tonne) is based. We allocate 115 kg to the PVA, 85 kg to the condenser *per se*, 50 kg additional to the radiator(-function), 10 kg each to system fluidics (fans, piping, meters, valves and pumps) and to a 45 kWe electrolytic cell, 5 kg each to power conditioning, 3 kWe fuel-cell, cryogen liquefaction, and control system, and 10 kg to a flex-wall-implemented, bladder-type water storage module of 0.5 tonne capacity. The cryogens, LH_2 and LO_2, are stored in the same multi-layered, flex-walled bladder-tanks as are employed for primary propellant-storage for the mission propulsion-plant, which have cylindrical symmetry with multi-coaxial-walls with intra-positioned lofted-fiber insulation interleaved with standard aluminized-plastic multi-layer insulation (MLI), and operate with ullage pressurization only modestly (ΔP~0.3 bars) above ambient pressure. Roughly 70% of this total tankage is not required for the return-to-Earth mission, and thus is left at the Mars Base. See Table I.

Obviously, we contemplate the pervasive use of the highest strength-to-weight structural materials (e.g., polyaramid fabrics and carbon fiber-composites) and highly mass-economized (e.g., thin-walled) fins, heat-pipes, etc., all employed in optimal designs, in which mass of carefully-selected properties is employed only in amounts actually required for transport performance or to bear structural loads. We exploit the facts that Martian winds, though of very high peak speed (~200 km/hour), have only the peak momentum flux density of a brisk Terran breeze, and that there is no Martian rain. At that, our baseline design for all expedition hardware, specifically including the Water Plant, requires the use of <u>nothing</u> which isn't commercially sourced – COTS, or commercial off-the-shelf – at the present time. (Nonetheless, we aren't inclined to argue extensively with those who might choose to design in a less mass-economized manner, and thus to realize a Water Plant with even 2-3 times the mass of our baseline one; the mission-architectural gains realized from a Water Plant of 40 tonnes-of-H_2O/year output capacity are so great that it doesn't matter greatly whether the Plant's mass is 0.3 tonne or 1 tonne – so long as it's quite small compared to 40 tonnes.)

In concluding this section, we feel obliged to note briefly a lower-likelihood but high-payoff alternative to the approach which we've just outlined. It proposes to exploit the meteorological prospect of reliably-appearing nocturnal fogs on the Martian surface, which naturally raises the corresponding technical prospect of erecting large-area, Cottrell-type electrostatic precipitators through which the ambient 2-4 m/sec Martian nocturnal breeze would blow the ice/water-droplet-laden Martian atmosphere. The fog would be condensed on the precipitator plates, and the whole precipitator assembly would button itself up in a gas-tight manner at local dawn; later in the day, it would electrically heat the precipitator plates to melt the deposited ice-film and transport the resulting liquid-water into a sump. It seems entirely possible that such a system, with an aperture of ~1000 m^2 – 10 X that of our baseline design-value of 100 m^2, one factor-of-3 due to the average wind speed being lower than our forced-convection speed and the other due to only 33% duty-cycle, i.e., during the coldest third of the local diurnal cycle – might be quite mass-competitive overall with the baseline system just outlined.

If such a system were implemented in a very highly mass-economized, Venetian-blind-like format, it might be feasible to deploy it by simply unrolling its base across the local landscape, and then erecting it from this base, all perpendicular to the prevailing diurnal breeze direction. Although the electrical power required to operate such a system would be far smaller than that for the baseline system, a good-sized PVA would still be required in order to convert the large majority of the electrostatically-stripped Martian atmospheric water to cryo-propellants/fuels and to O_2 for the life-support system of the Mars Base. Thus, if nocturnal fogs appear reliably at the expedition's landing-site, then God graciously condenses the water from Martian atmospheric water vapor most every night, and harvesting it from the air by the figurative waving of electrostatic wands is all that Man need do for his mundane purposes.

Early Expedition Water Budgets And Sizing Of Water-Supply Equipment. We employ basic results from our previous work on the Space Exploration Initiative – i.e., the *Great Exploration* Program proposal – for reference mass-budget numbers for a first manned expedition to Mars. See Figure 3.

These indicate the above-assumed requirement for of the order of 0.1 tonne – 100 kg – of water per day, or 1 gm/second, in the time-average, over the duration of the 400-day stay of the expedition crew on the Martian surface, or 40 tonnes of water total. This rate of water-production will suffice for all life-support system needs, all energy requirements for vigorous, long-distance surface Rover- and rocket-performed exploration of the Martian surface – see Figure 4 – and for all fueling requirements for the ascent stage of the crew's return-to-Earth vehicle. It represents over 90% of the total mass which leaves LEO in a conventional Mars exploration mission whose mission-architecture specifies powered descent of Earth-derived life-support water and oxygen and Earth-return propellants down to the Martian surface – and 70% of the total leaving-LEO mass of a more advanced mission-architecture which aerobrake-lands the expedition onto the Martian surface. See the three basic mission architecture comparisons in Table I.

The first-level breakdown of the baseline mission mass-budget is as follows: each of the crew-of-four needs about 1.2 kg/day of (~0.8 kg respiration consumption + ~0.4 kg leakage make-up) oxygen for 725 days after Mars-touchdown (400 days on Mars and 325 days of Mars-to-Earth return journey in a Hohlmann minimum-energy transit-trajectory) and 0.5 kg day of water (for system+pressure-suits leakage make-up, assuming nearly-full water-recycling, including partial metabolic water recovery, but with no carbon or nitrogen recycling). The ascent-stage propulsion-plant is taken to be RL-10-based, and exhausts a 5:1 (by mass) O_2/H_2 propellant-mix with a near-vacuum I_{sp} of 490 seconds (expansion ratio of 200:1); it'll require about 21 tonnes of this propellant mix to inject an 8-tonne return-to-Earth module into a trans-Earth trajectory from the Martian surface. Martian surface exploration is assumed to require another 5 tonnes of this propellant-mix to fuel the 0.5 tonne (dry-mass+Rover+crew-of-two) Hop-About for ~5 rocket-liftoff/ballistic flight/aerobrake-landing forays to sites roughly equally-spaced all over the Martian surface. These requirements aggregate to a total post-Mars touchdown mission demand of 24.5 tonnes of O_2, 4.2 tonnes of H_2 and 1.4 tonnes of H_20 *per se*; this is equivalent to about 39 tonnes of water, with 10.3 tonnes of O_2 to spare (e.g., for use in Base, pressure-suit and Rover crew-module leakage make-up, at a mean rate of ~25 kg/day). It's therefore appropriate to scale the Water Plant to produce 40 tonnes of water during the 400 day stay-duration, i.e., to average a daily production of 100 kg, or ~1 gm/second – all as foreseen above.

Implications For Manned Mars Exploration. The present work represents another step down the path charted by Zubrin – with his proposal for a landed methane-generating plant carrying its own liquefied hydrogen feedstock – of innovatively exploiting indigenous Martian resources to drive down the mission-mass cost – and thus the total mission dollar cost – of mounting even the first human expeditions to Mars. Ours is a more ambitious, "philosopher's stone" gambit, which aims at generating essentially all the consumables *ever needed thereafter* by the as-landed expedition from readily available local feedstreams – Martian air and ambient sunlight – with a single Water Plant consisting of a handful of readily-available or -fabricated components: *water-condenser, radiator, water-electrolytic cell, H_2/O_2 liquefaction unit, cryogen and water storage-tanks and a photovoltaic array.* (We emphasize use of PVA power sources over alternate, e.g., nuclear, ones purely for their current "commercial off-the-shelf" availability characteristics.)

The beauty of the present gambit is that it substitutes equipment having about 1% of the mass of the materials generated for the far greater mass of the materials themselves. This attractiveness is accentuated by the fact that *the thereby-substituted-for mass comprises about 70% of the total leaving-LEO mass-budget of a large set of innovative, aerobrake-intensive architectures for the Mars exploration mission – and 90% of the leaving-LEO mass of conventional initial exploration architectures involving powered descent to the Martian surface.* The immediate implication of this is that the lifting-to-LEO challenge for mounting even the first Mars Expedition – one which benefits not-at-all from legacies from previous expeditions – can be reduced from a few dozen Shuttle-equivalent payloads to 2 such cargoes, i.e., <50 tonnes total mission-mass, staged within a single year. A set of comparable mission mass-budgets for the three basic types of mission-architecture – conventional powered descent to the Martian surface, conventional aerobraked descent and aerobraked descent with Water Plant – is shown in Table I. Figure 2 graphically depicts these basic differences, in a toe-to-toe comparison of two aerobrake-descent Mars manned mission architectures, one with and the other without a Water Plant.

The incremental cost of the lifts-to-LEO required to mount an initial manned expedition to Mars is reduced by Water Plant usage to ~$100 M, at NASA's quoted marginal cost of a Shuttle launch of ~$50 M – or a cost of ~$1.1 B, at OMB's estimated full average operational cost of $550 M for a Shuttle-flight. (Lifting 41 tonnes of payload into LEO via commercial space-launch services would entail a present-day cost of ~$450 M, at a cost of $5,000/pound.) The cost of the 10 tonnes of mission hardware, estimated-in-bulk using the usual rule-of-thumb of $10/gm, would be roughly $100 M. RDT&E costs should be (at most) comparable to the purchase-cost of the mission hardware, due to the basic COTS character of the materials and equipments chosen, so that total attributable mission costs should aggregate to $300 M - $1.3 B, depending on whose Shuttle-mission cost estimates you prefer to believe – and assuming that 2 Shuttle launches are employed. Alternatively, the cost of preparing and executing the baseline mission in a purely commercial mode would be ~$650 M – $450 M for the space-launch services procured to lift-to-LEO $100 M of hardware and consumables, after ground-side RDT&E of $100 M.

The realistic prospect of a Mars Expedition realized at a cost of significantly less than a single year's *Station* construction budget of ~$2.5 B is surely one that most reasonable political leaders couldn't long resist – even in an era when the two major political parties effectively differ on civil-space policy only by how much the NASA budget should be cut each year. Moreover, and quite importantly, sponsorship of the first human expedition to Mars thereby is brought well within the means of a single exceptionally wealthy individual – this in an era when no one yet lives forever, and means of "taking it with you" have yet to be perfected.

Full, innovative exploitation of Martian water thus *might* be a make-or-break issue for manned Mars exploration *this* side of the indefinite future.

Expedited Exploration Of The Mid- Solar System: The Jovian and Saturnian Systems. Aggressive exploitation of indigenous water resources for realization of life-support and cryogenic propulsive liquids may be the key to relatively near-term manned exploration of the Solar system, particularly its "middle" portions, e.g., out to the Jovian and Saturnian ice-bearing moons. The basic point, of course, is that leaving-LEO mass-budgets for effectively one-way missions – ones which fully exploit water at their destination-point for life support there and for return-to-Earth propellants – are *exponentially* smaller than for round-trip ones. Now it is currently unfashionable to send even volunteers on one-way, i.e., settlement-committed, Government-sponsored space missions, in the manner in which the East Coast of the United States was initially settled. Thus, it is necessary at present to consider mission architectures which return expedition crews to Earth after comparatively brief stays at their outbound destinations. The corresponding Gordian knot may be slashed by equipping expeditions to places such as Ganymede and Europa (and ice-bearing asteroids, and icy Saturian moons, and . . . .) with equipment quite similar to the Mars Water Plant which we discussed above, so that they can re-equip themselves for the return segment of the trip – as well as support their local living and exploration activities – entirely with products derived from local water at their destinations.

It might appear difficult to photovoltaically energize the equivalent of a Mars Water Plant for a location as distant from the Sun as Europa, let alone Titan, simply because the intensity of sunlight is 1-4% of that on Earth at the Saturnian and Jovian orbits, respectively, and use of photovoltaic arrays for generation of the required electric power thus would appear to be impractical. Actually, this isn't the case, since direct band-gap semiconductors, e.g., GaAs, are more than two orders-of-magnitude more mass-efficient than indirect band-gap ones, such as Si, in photovoltaic conversion, i.e., ≤1 micron thicknesses of GaAs are optically thick to most of the solar spectrum whereas >100 microns is required for equivalent solar-spectrum photoopacity of Si. Very thin sheets of direct band-gap semiconductor, strengthened appropriately with an underside polyaramid layer, thus may be expected to provide practical, ≥1 W/gm specific photoelectic electric power production as far out as Saturn's orbit, i.e., in 14 W/m^2 sunlight.

A manned mission to Europa is challenged by the nominal 6.3 km/sec trans-Europan insertion Δv from LEO, which has added to it the 6.8 km/s of Δv required to brake to a soft-landing on the near-vacuum surface of Europa upon entering the Jovian system on a Hohmann transfer trajectory. Even the use of RL-10-based propulsion systems, with their restartability and their 4.9 km/s exhaust speeds, seemingly implies mass-ratios of 14.5 for such *one-way* missions. Actually, a Minovitch (gravity-assisted) Earth-Venus-Jupiter trajectory can reduce the outbound insertion Δv to 4.4 km/s without a significant increase in outbound trip-time and a Jovian-system capture-burn at Io's depth in the Jovian gravity-well, followed by more Minovitch maneuvering among the Galilean moons before a powered touchdown on Europa can trim the total circum-Jove maneuvering Δv to 5.1 km/s, so that the total outbound mission Δv can be thereby reduced to no more than 9.5 km/s. This, in turn, implies a Rocket Equation multiplier of 6.95 on the leaving-LEO mission-payload mass of ~25 tonnes (corresponding to a total mission-time of about 7 years, including a year on the Europan surface), so that the reference Europan expedition's total leaving-LEO mass is only 173 tonnes; the numbers for a crew-of-four expedition to Callisto or Ganymede are essentially the same. (Of course, the same expedition might care to average down its outbound-and-return "travel overheads," and touchdown successively on more than one icy Galilean moon, "while in the neighhood," refueling at each stop.)

The corresponding leaving-LEO Δv on a Minovitch trajectory to Titan is only 4.7 km/s(!), reasonably assuming use of aerobraking for a Titan touchdown (although use of highly mass-economized photovoltaic arrays on the Titanian surface, where wind momentum flux densities might be quite large, cannot be assured until confirming meteorological data, e.g., from the Huygens probe of Cassini, is in-hand). Soft-landing on a vacuum-shrouded, ice-bearing Saturnian moon naturally would be significantly more expensive in Δv, *unless* the first stop in the Saturnian system were made at Titan, thereby sinking the interplanetary Δv; in this case, refueling could be done first at Titan and then the tanks could be "topped off" as indicated at successive stops on other icy-albeit-vacuum-shrouded Saturnian moons, prior to Earth-return from the final one of them. The corresponding Rocket Equation multiplier for the Titan expedition is (only!) 2.6 on a characteristic Saturnian mission-payload mass of ~40 tonnes, so that the leaving-LEO mass for a manned expedition to the surface of Titan is (only) 104 tonnes! The total mission time would be about 14 years, assuming 1.5 years were spent on the surface of Titan (as well as skipping among the icy Saturnian moons). In both the Europa and Titan expedition cases, the total impulse required for the lift-off of the surface and insertion into a trans-Earth trajectory isn't larger than the total outbound impulse, so that propellant tankage reuse is entirely feasible: the expedition's transit-vehicle touchs down at the icy destination with dry cryopellant (and water, and oxygen) tanks and lifts off with (in the case of cryopropellants, partly-) full ones reloaded with local water products. These Jovian and Saturnian system exploration data are summarized in Table II, along with those of the baseline case for Mars.

These relatively very modest leaving-LEO masses for *round-trip* manned expeditions to Solar system destinations hitherto considered to be unattainably distant relative to contemporary human technology should motivate serious thought about mounting such expeditions during the next few minimum-energy "launch windows". That most all of the leaving-LEO mass in all of these cases is comprised of water products – LH_2 and LO_2 – and thus of material which may be Earth-orbited in convenient-sized parcels with high-acceleration, potentially low-cost means, should be especially thought-provoking.

Moving Out From Here. What's a reasonable path to follow along the lines just sketched, leading from the present to a first crew return from the Red Planet – or to launching of an manned expedition to the Jovian or Saturnian systems?

It might be reasonable to first design, then to prototype in sub-scale, and then to build in full-scale such a Water Plant for Earth-side evaluation. Such evaluation presumably would culminate in an environmental chamber which duplicates the key features of the Martian surface, atmosphere and sky – and likely would involve a Water Plant implemented in something like 1% of full scale, i.e,. a 1-meter scale-size, producing 1 liter/day of water. Once the basic design had thereby been qualified and a full-scale one had been deployed satisfactorily in Earth-surface simulation from an as-landed package, it would be appropriate to send the full-scale system to Mars for real field trials. Even the first such trial could lay the Martian logistics foundation for a follow-on manned expedition in the next launch-window 25 months thereafter, if it were adequately successful.

It's readily feasible to send a full-scale Water Plant of the type sketched above to the Martian surface on *a single Atlas-Centaur-class launch* inserting an aerobraked descent package into trans-Mars orbit, to deploy it and put it into operation robotically once it's landed, and then to operate it until its water and cryogenic propellant tanks all are full. A manned expedition, perhaps carrying a back-up Water Plant as well as a Mars Greenhouse, could thereafter leave for Mars in a far smaller – and corresponding less expensive – total mission-package than any currently contemplated.

A program of this type seemingly would fit aptly within a NASA *Discovery* programmatic time-and-dollar envelope – <u>if</u> it were planned and executed in a thoroughly competent and reasonably innovative manner (e.g., involving collaborations between major technical universities and aerospace primes). As such, it would constitute a notably low-cost, short execution-time technology-demonstrator and mission-enabler of remarkably large proportions for the first manned expedition to Mars.

Eventually, sustained-and-concatenated exercising of human ingenuity *will* reduce the cost of a first human expedition to Mars – and to the icy Jovian and Saturnian Moons – to levels such that even non-governmental resources will suffice readily to sponsor it. We offer the Martian Water Plant sketched in the foregoing as a stone for use in raising this great edifice of technology-and-intellect, moreover in *our* time.

Acknowledgments. We thank our many colleagues who have discussed with us over the past third-century various aspects of the manned exploration and settlement of Mars; we regret not being able to acknowledge them individually. No claim is made for originality, either of the basic concepts or the specific technological approaches, discussed in the foregoing, any number of which may have been anticipated by others unknown to us.

TABLE I. COMPARABLE MASS BUDGETS FOR THREE MANNED MARS MISSIONS

Conventional Powered Descent Equivalent Leaving-LEO Mission Mass-Budget

Material/Sub-system	Tonnes
Entire mission food (4200 crew-days @ 0.8 kg/c-d)	3.4
Entire mission water make-up (4200 crew-days x 0.5 kg/c-d)	2.1
Entire mission O_2 (4200 crew-days x 1.2 kg/c-d)	5.0
Transit module (flex-walled; incl. 3X life-support system)	1.3
Mars Base (flex-walled; incl. 3X life-support system)	5.9
Propulsion (RL-10 + 2% flex-wall cryogen tankage)	2.9
Mars Rover & Hop-About	0.5
Earth reentry aerobrake (incl. reaction orient. cntrl.)	0.6
Earth parachute	0.2
Structure	2.9
Crew, pressure-suits & personal effects (4 x 250 kg)	1.0
Mars-surface propellants for Hop-About	5.0
Mars-surface lift-off/trans-Earth injection propellants	20.7
Miscellaneous	1.0
Payload subtotal	52.5
Propellant (4.0 km/sec trans-Mars injection+6.0 km/sec Mars orbital insertion and powered descent to Mars surface Δv; I_{sp}=490 sec)	369.1
Leaving-LEO Mission total	421.6

Conventional Aerobraked Descent Equivalent Leaving-LEO Mission Mass-Budget

Material/Sub-system	Tonnes
Entire mission food (4200 crew-days @ 0.8 kg/c-d)	3.4
Entire mission water make-up (4200 crew-days x 0.5 kg/c-d)	2.1
Entire mission O_2 (4200 crew-days x 1.2 kg/c-d)	5.0
Transit module (flex-walled; incl. 3X life-support system)	1.3
Mars Base (flex-walled; incl. 3X life-support system)	5.9
Propulsion (RL-10 + 2% flex-wall cryogen tankage)	2.9
Mars Rover & Hop-About	0.5
Mars-&-Earth reentry aerobrake (incl. reaction orient. cntrl.)	2.6
Mars-&-Earth parachute	0.8
Structure	2.9
Crew, pressure-suits & personal effects (4 x 250 kg)	1.0
Mars-surface propellants for Hop-About	5.0
Mars-surface lift-off/trans-Earth injection propellants	20.7
Miscellaneous	1.0
Payload subtotal	55.1
Propellant (4.0 km/sec trans-Mars injection Δv; I_{sp}=490 sec)	71.7
Leaving-LEO Mission total	126.8

TABLE I. COMPARABLE MASS BUDGETS FOR THREE MANNED MARS MISSIONS, cont'd.

Baseline (Water Plant/Aerobraked Descent) Leaving-LEO Mission Mass-Budget

Material/Sub-system	Tonnes
Entire mission food (4200 crew-days @ 0.8 kg/c-d)	3.4
Earth-to-Mars water make-up (1200 crew-days x 0.5 kg/c-d)	0.6
Earth-to-Mars O_2 (1200 crew-days x 1.2 kg/c-d)	1.4
Transit module (flex-walled; incl. 3X life-support system)	1.3
Mars Base (flex-walled; incl. 3X life-support system)	5.9
Propulsion (RL-10 + 2% flex-wall cryogen tankage)	1.2
Mars Rover & Hop-About	0.5
Water Plant (incl. Mars Base power unit)	0.3
Mars-&-Earth reentry aerobrake (incl. reaction orient. cntrl.)	0.6
Earth parachute	0.2
Structure	0.7
Crew, pressure-suits & personal effects (4 x 250 kg)	1.0
Miscellaneous	1.0
Payload subtotal	18.1
Propellant (4.0 km/sec trans-Mars injection Δv; I_{sp}=490 sec)	23.6
Leaving-LEO Mission total	41.7

Leaving Mars-Surface Mass-Budget (All 3 Cases)

Material/Sub-system	Tonnes
Mars-to-Earth food (1300 crew-days @ 0.8 kg/c-d)	1.0
Mars-to-Earth water make-up (1300 crew-days x 0.5 kg/c-d)	0.6
Mars-to-Earth O_2 (1300 crew-days x 1.2 kg/c-d)	1.6
Transit module (flex-walled; incl. 3X life-support system)	1.3
Propulsion (2xRL-10 + 2% flex-wall cryogen tankage)	0.9
Atmospheric reentry aerobrake (incl. reaction orient. cntrl.)	0.6
Parachute	0.2
Structure	0.3
Crew, pressure-suits & personal effects (4 x 250 kg)	1.0
Martian sample-set	0.5
Miscellaneous	0.3
Payload subtotal	8.3
Propellant (6.0 km/sec trans-Earth injection Δv; I_{sp}=490 sec)	20.7
Leaving-Mars surface total	29.0

TABLE II. MISSION PARAMETERS FOR MANNED EXPEDITIONS "WATERING" AT THE DESTINATIONS

Destination	**MARS**	**EUROPA**	**TITAN**
Leaving-LEO Δv, km/s **(Venus fly-by, for Europa and Titan)**	4.0	4.4	4.7
Destination maneuvering Δv, km/s **(Aerobraking at Mars, Titan)**	0	5.1	0
Total outbound Δv, km/s	4.0	9.5	4.7
Rocket Equation mass-multiplier **(RL-10 5:1 LO_2:LH_2; $v_{exhaust}$ = 4.9 km/s)**	2.26	6.95	2.61
Leaving-LEO mission payload mass, T	18	25	40
Leaving-LEO total mission mass, T	41	174	104
Outbound trip-time, years	0.9	3.0	6.2
Stay-time at destination, years	1.1	1.0	1.6
Leaving-destination Δv, km/s	6.0	5.1	4.8
Return trip-time, years	0.8	3.0	6.2
Total mission-time, years	2.8	7.0	14.0

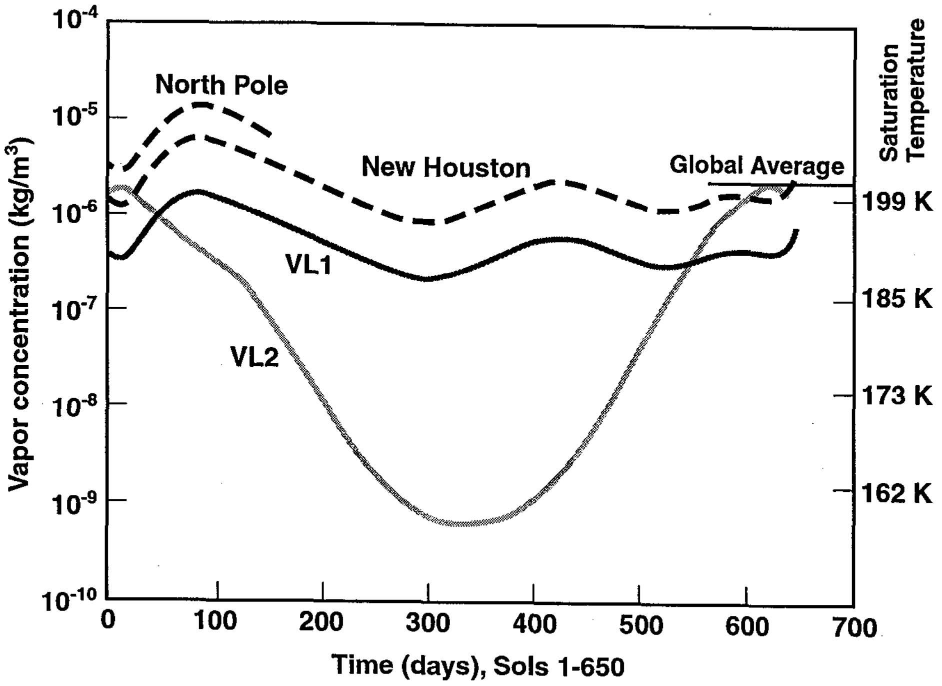
FIGURE CAPTIONS

Figure 1. Water content of the Martian surface-level atmosphere versus time in Martian days (Sols) measured indirectly by the Viking Lander 1 (VL1) and Viking Lander 2 (VL2). The VL1 data-set is significant more consistent with other measurements of Martian atmospheric water content, and thus is used as the basis for the calculated seasonal variation of the inferred globally-averaged atmospheric water content, which is labeled 'New Houston.' The globally- and seasonally-averaged single-value is labeled 'Global Average.' [After Grover and Bruckner, "Water Vapor Extraction from the Martian Atmosphere by Adsorption in Molecular Sieves," AIAA Paper 98-3302 (1998).] The vertical right axis indicates the temperature at which the water vapor content on the left vertical axis is the saturation vapor pressure, i.e.,. below which temperature water vapor will condense from the air.

Figure 2. A diagrammatic representation of the major components of the Water Plant.

Figure 3. The time-evolution of the mass budgets of two manned expeditions to Mars consisting of a crew-of-four, which stays on Mars the 400-day fraction of the synodic period corresponding to minimum-energy trajectories from Earth-to-Mars and then from Mars-to-Earth. [After Hyde, Ishikawa & Wood, "The *GREAT EXPLORATION* Plan For The Human Space Exploration Initiative," UCLLNL PHYS-BRIEF 90-402 (1990).] The "No Martian Water Usage" mission-architecture is a 'neo-classical' one which aerobrakes the Mars landing-package but brings all mission-required consumables from the Earth, and is the second of the three cases of Table I. The "Martian Water Exploitation" mission-architecture fully exploits Martian atmospheric water via a Water Plant of the type discussed in the text, and thus is the third, "baseline" case of Table I, and thereby realizes ≥ 3-fold savings in the leaving-LEO mass-budget, relative to the mission involving no Martian water exploitation. The "wet Mars" mission-architecture also readily extends to include a flex-walled Mars Greenhouse of 2 tonne/500 m^2-scale, the principal item in whose in-use mass-budget is Martian water, in ≥ 10 kg/m^2 -illuminated specific quantities; manned Mars expeditions of indefinitely great duration and self-sufficient Martian settlements are thereby enabled.

Figure 4. An artist's conception of the two primary types of Mars surface-exploration vehicles. A RL-10-based rocket propulsion unit – dubbed a 'Hop-About'– is used for launching into a ballistic trajectory – aerobraked at its terminus – a pair of expedition crew-members enclosed in a flex-walled cabin and a Mars Rover (a technological descendent of the Apollo Lunar Rover) from the expedition's Mars Base to any other site on the Red Planet. At any such secondary exploration site, the H_2/O_2 fuel-cell-powered Rover is roll-on/roll-off-deployed from its stowage-point on the Hop-About to carry the crew-pair and their light equipment around for local exploration, sample-gathering, etc.; the return-to-Base flight has the same characteristics as did the outbound one. [After Hyde, Ishikawa & Wood, "The *GREAT EXPLORATION* Plan For The Human Space Exploration Initiative," UCLLNL PHYS-BRIEF 90-402 (1990).] All of the consumables of the exploration transportation system – propulsive mass, H_2/O_2 fuel-cell feedstreams and all life-support fluids – are derived from Martian atmospheric water via the Water Plant discussed in the text, so that such intensive all-planet exploration, even on the first manned Mars mission, is cost-free with respect to all consumables.



10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
Vapor concentration (kg/m^3)
North Pole
New Houston
Global Average
VL1
VL2
Saturation Temperature
199 K
185 K
173 K
162 K
0
100
200
300
400
500
600
700
Time (days), Sols 1-650

FIGURE 1

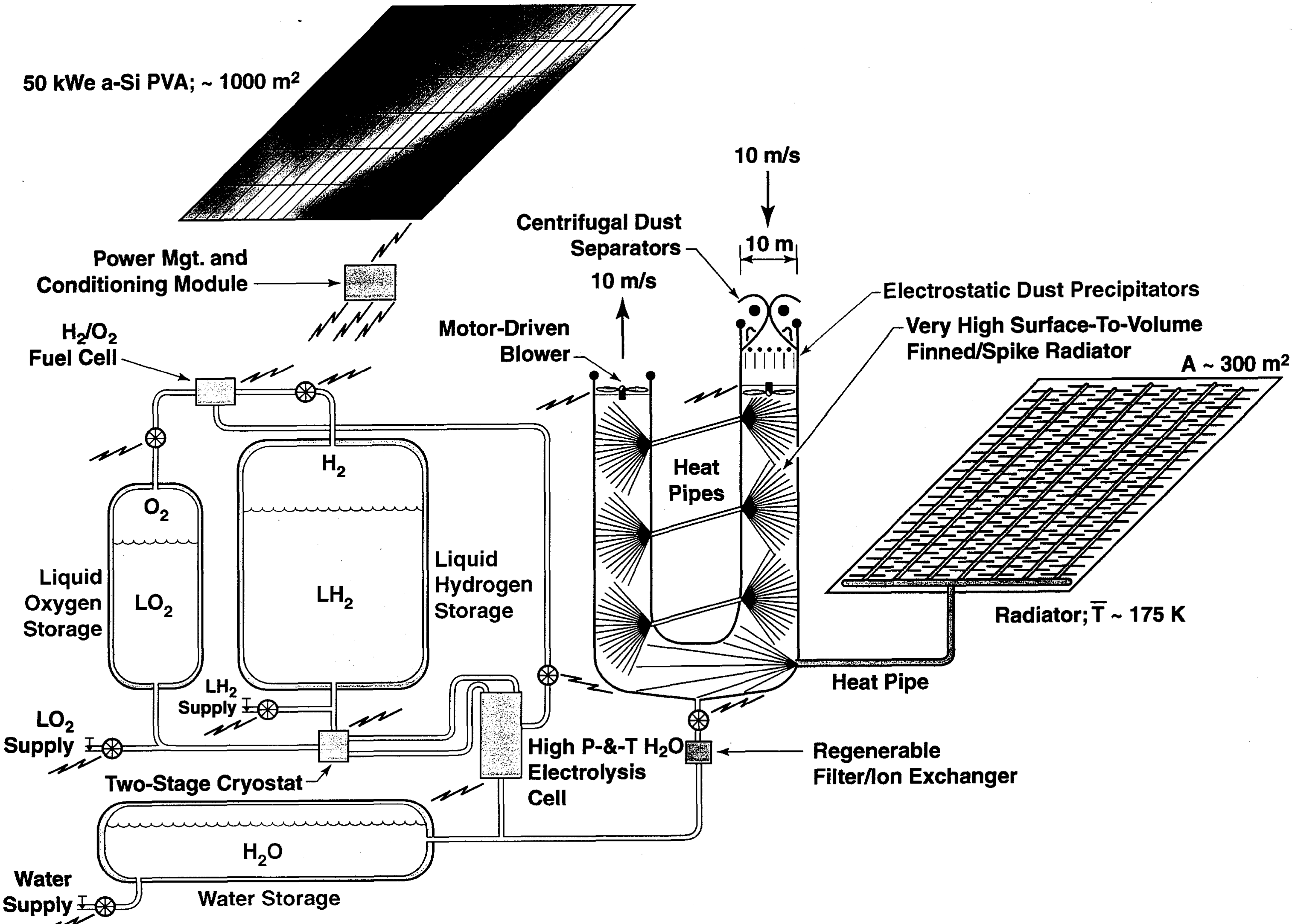


Figure 2

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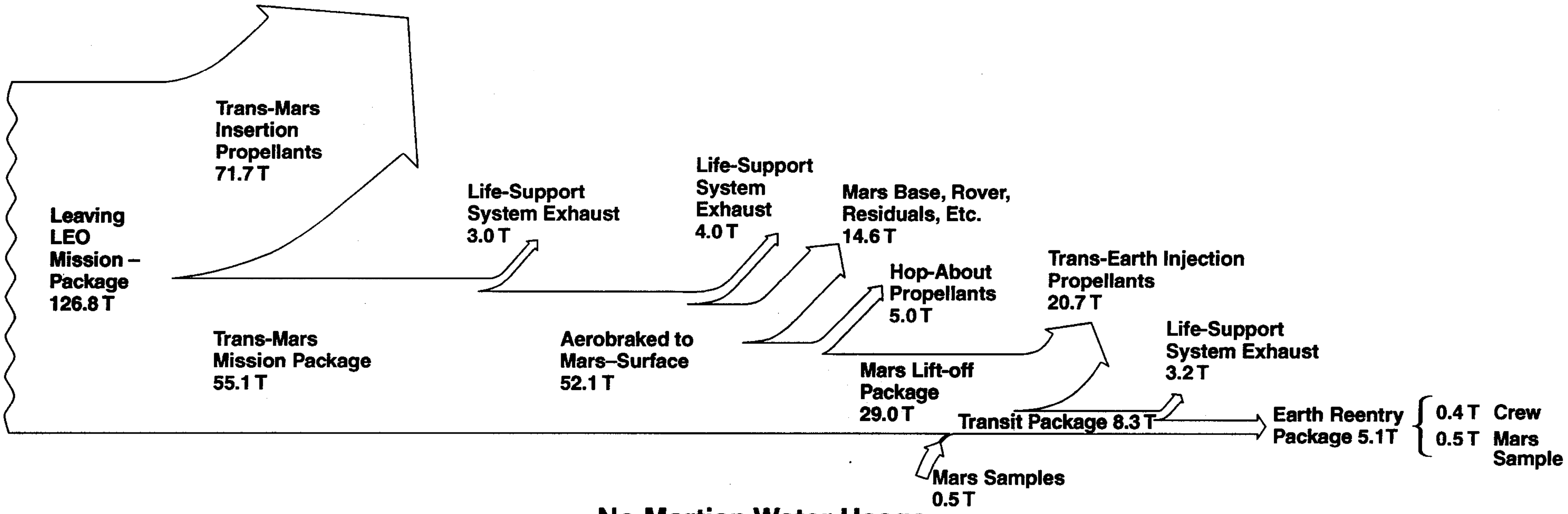
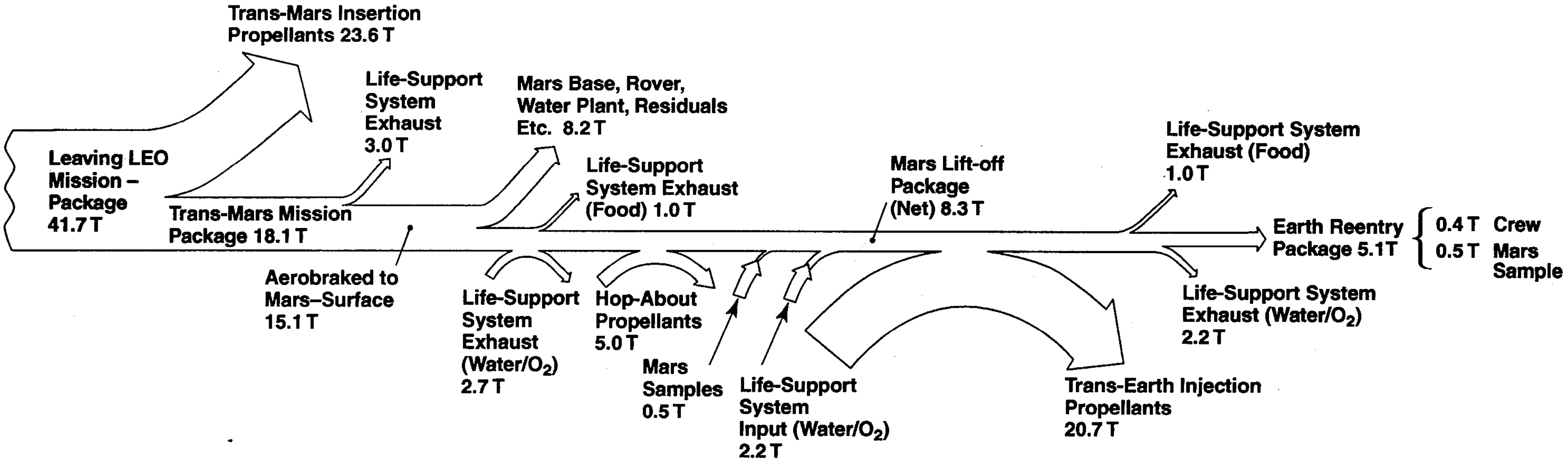


No Martian Water Usage



Martian Water Exploitation

Figure 3

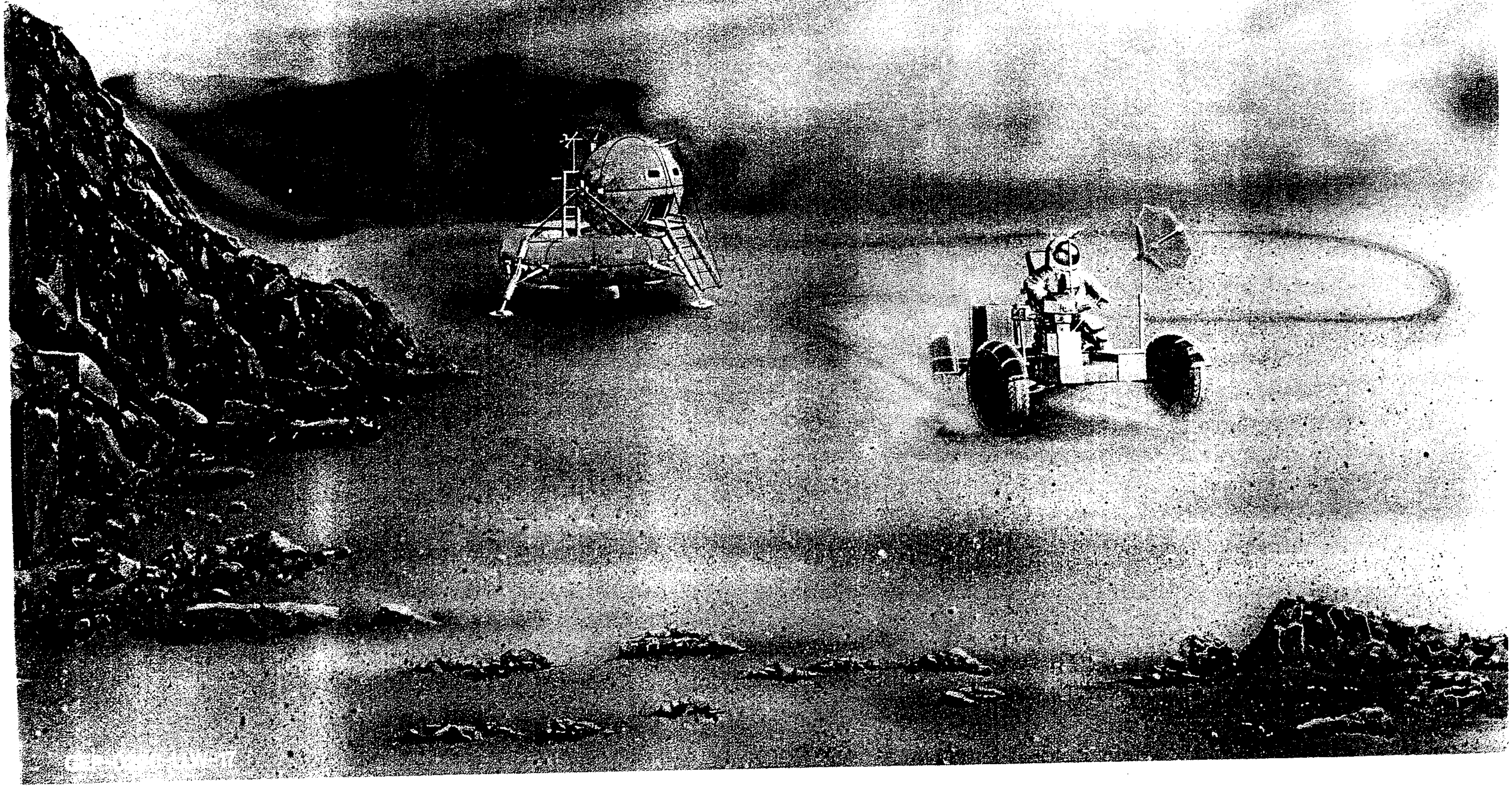


FIGURE 4