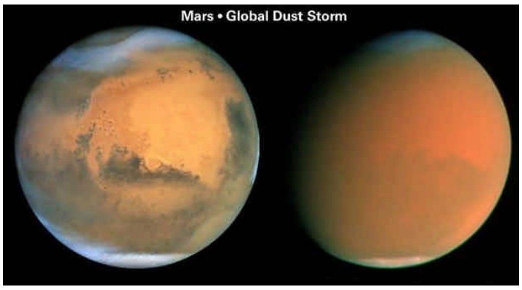
Future Power Systems for Space Exploration:



Executive summary

35 pages
February 2002
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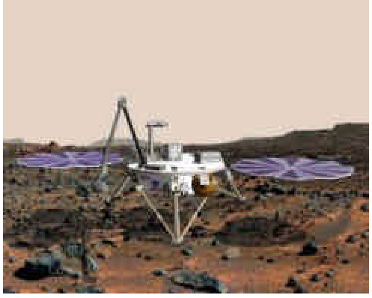


1 Introduction

This document summarises the findings and recommendations of a study into future power systems for space exploration, aimed specifically at a human mission to the Mars surface to take place in the 2020-2030 timeframe. The study was comprised of 5 parts:

- System requirements and constraints: Requirements for a European contribution to a future international human Mars mission were defined as a number of mission elements, described later. Using these requirements, an initial assessment of the difficulties of generating power on the surface of Mars, a review of possible power systems, and a preselection of those which might be most appropriate for the selected mission elements were made. The preselection focussed primarily on non-nuclear options for static mission elements, which were felt to be most challenging. Mobile mission elements, which were less well defined at this stage, were not reviewed in any great detail. However a decision was made to only consider non-nuclear power sources for mobile elements. *Technical Note 1* summarised this study part.
- Technology Inventory: A database of innovative non-nuclear technologies which could enhance Europe's industrial capabilities and the value of power systems within human Mars exploration scenarios was created. The database was created from a review of patents, journal papers, on-line databases, articles in popular literature and other sources. 16 key technologies were analysed and arranged in order of merit, using a ranking system derived for the study. A summary of nuclear power technologies was also made in this study part, summarised in *Technical Note 2*. However the integrated nature of nuclear energy systems meant that technologies could not be compared directly and ranked as in the non-nuclear section.
- Nuclear power systems: A review of nuclear fission reactor designs and subsystem technologies for space and planetary surface usage was undertaken. Brief mention of more advanced concepts such as fusion was made, although the emphasis was on fission reactors, with designs derived from previous studies. The results of a parametric analysis of the performance of two alternative reactor system concepts generating 50kW(electrical) on the Mars surface were presented. The analysis also included a safety assessment. *Technical Note 3* summarised this work.
- Architectural design of reference system: A more detailed analysis of power system options was made for the 5 selected ESA mission elements, based on updated requirements provided by another study. A preferred non-nuclear (photovoltaic) and nuclear options for static mission elements was presented, as well as a number of alternative, more speculative (e.g. wind power) solutions. A range of non-nuclear power options for mobile mission elements was also provided. An design analysis at system level for an In-Situ Resources Utilisation (ISRU) chemical plant for production of propellant and life support consumables was made. *Technical Note 4* summarised this study phase.
- Technology Development Programme: The final part of the study attempted to elaborate on how technology needs determined from solutions presented in *Technical Note 4* could be met in a European context. These were confirmed using the conclusions of the technology inventory summarised in *Technical Note 2*. Research and development goals in the short term (up to 5 years), medium term (5-15 years) and long term (15-30 years) were suggested, taking account of existing programmes of European technology development. Consideration of Aurora programme goals in particular was made. *Technical Note 5* summarised this section.

2 Mission elements

Mission element and corresponding power system requirements have been generated by the S51 study, and refined in discussion with the S54 (power systems) and S56 (robotics) studies. Missions elements are separated into those which remain in one place on the Mars surface (static elements), and those which are mobile. Requirements are summarised in the tables below:

2.1 Mobile mission element requirements

	Disseminated surface systems			**Mobile pressurised laboratory**	**Utility Truck**
	Drilling platform	***Mini inspection rover***	***Long range exploration rover***		
Purpose	Local investigation	Inspection & monitoring, facility construction, support	Long range autonomous exploration	Long range manned exploration and safe haven	(1) Move mission elements from landing site (2) Build nuclear reactor shield
Total mass (kg) ***(ex-lander)***	300	15-20	200	7500kg + 1500kg power cart	8000 unloaded 16000 loaded
Power (W)	500 (mean) – 2000 (max.)	7W + 7W emergency	25 (min – payload only) – 200 (max. drive)	19600 average (drive only), 98000 peak	48000, for either unloaded 10km/h, flat surface, or loaded, 2.4km/h, climbing 20° slope
Energy (Whr)	Not specified	45Wh/day. *Includes margin.*	Not specified	1550kWh (min) – 2800kWh (likely). *Note: no margin.*	1458kWh for 292km 1 way traverse, + 120kWh for emergency.
Volume constraint (mm)	150 x 150 x 300	60 x 40 x 30	Not specified	2 x 3000mmø spheres + 2mø x 2m long connecting tube	4300 x 2300 x 4500 for power unit, max.
Lifetime (ROM)	30-120 sols	Min. 200 sols + 4 week dormant	Min. 200 sols + 4 wk dormant	N/A	N/A
Lifetime (HEM)	Not specified	TBD	Several x 400 sols, with maintenance	600 sols total. 20 day mission.	Min. 26 Mars months, pref. 6 Mars years.

In addition to the data in the Table above, an autonomous research island has been specified, consisting of a fixed base station and a micro rover. Power requirements have not been generated for this element, however the rover volume constraint is 220x165x65mm, and mass is 3kg (base station 12kg). The micro rover may run from an umbilical, or be independent from the base station but require recharging from it.

Assumptions regarding the likely mission profiles were made in order to accurately trade-off power system options. These assumptions are detailed further in *Technical Note 4.*

2.2 Static mission element requirements

	ISRU plant	**Greenhouse**
Purpose	Production of propellant, life support consumables, fuel for surface activities (e.g. fuel cells).	Experimental bio-regenerative life-support facility.
Total mass ***(ex-lander)***	Estimated 4000 excluding hydrogen storage unit.	10000
Power (W)	31-38kWe during production phase, currently assumed to be 12 months. Energy during storage phase estimated as 4.5kWe.	15kWe (peak) for operational phase, and 2.5kWe during dormant phase (6 month Mars transit, 6 month wait for crew arrival). Emergency power 1 kWe for 10 hours.
Energy (Whr)	270-336MWh.	Dormant phase: 22MWh Emergency: 10kWh Operational: 1971MWh
Max. envelope	12m long x 4.5m diameter, inc. lander.	2 x 12m long x 4.5m diameter, inc. lander
Lifetime	1 year (main operation phase), + up to 15 years (supporting 3 manned missions)	15 years

The Table above details the selected static mission elements, these will be used immediately prior to and during the human exploration phase, HEP.

The ISRU plant power requirement is an estimate generated during the study. The initial 12-15 month production phase requires 31-38.5kWe continuously, then for consumable storage immediately prior to and during the HEP (23-26 months) approximately 4.5kWe is required.

Technical Note 4 indicated that the production phase power requirement might be reduced still further, to as low as 28kWe. Establishment of the optimum subsystems for minimum power consumption, and the resulting power and energy requirements is an essential part of further system design.

Further power is required for a greenhouse unit, 2.5kWe initially for 12 months in transit and dormant on the Mars surface, then 15kWe for a further 15 years operational phase. Since only the greenhouse dormant phase is likely to coincide with the ISRU production phase, a maximum of 38.5+2.5 or 41kWe is estimated. A margin of 20% suggests that a 50kWe power source will be required. This will ensure that when the ISRU production phase is complete and the greenhouse operational phase commences, an excess power of ~30kWe is available for other mission activities.

A further static power generation capability of 1kWe for 10 hours, or 10kWh is required for backup of the greenhouse unit in the event of (temporary) failure of the main power supply.

2.3 Other requirements

Life support system (LSS) issues have been examined in the context of power needs. Advanced, lightweight, low power extra-vehicular activity (EVA) suits will be required for extended planetary surface operations. A typical requirement may be as high as 300W for 8 hours, or 2.4kWh. This was found to be highly demanding using current technology, a more achievable requirement might be 300W (peak) for 2 hours, equivalent to an energy of between 600 and 750Wh.

The requirements for ISRU in the ESA reference mission have been generated by a mission architecture study, and are summarised here:

Product	Function	Quantity, metric tons (t)
Methane, CH_4	Propellant - fuel	7
Oxygen, O_2	Propellant - oxidiser	25
	Life support (breathing)	5
Water	Life support (drinking)	24
Nitrogen / Argon *	Buffer gas (replacement for leakage)	4.5

** or Nitrogen / Argon mixture, see ‘assumptions’ section*

The consumables in the above table must be manufactured in 15 months or less, this requirement is dictated by minimum energy Earth-Mars launch window opportunities and trip times achievable. A manufacture period of 12 months is preferred in order to leave a margin to account for any unplanned reductions in manufacture rate.

The need for ISRU generates a requirement for hydrogen as chemical feedstock, which is not known to be available on Mars and therefore must be brought from Earth. The amount of hydrogen required depends to some extent on the reaction chemistry chosen. Initial estimates indicated 4-5t of hydrogen might be required, but were subsequently been refined to between 1.75 and 2.1t. This dictates a storage volume in excess of 20,000litres, a lightweight container and a means of preserving the hydrogen during a 6 month transit to Mars.

3 The Mars environment: constraints

The key issues which the Mars surface imposes on power systems design are:

- Low pressure (~1% terrestrial) atmosphere, primarily CO_2. This has two main effects:
  - Potential for Paschen (voltage) discharge. Not thought to be a problem for correctly insulated cables transmitting power, but needs to be studied further for mobile mission elements and all electrical subsystems which will be exposed to (magnetic) Martian dust.
  - Wind: potential to provide energy, although low dynamic pressure compared to Earth reduces available power, and not well quantified. Fine wind borne dust particles also cover exposed surfaces, e.g. solar arrays (estimated to degrade array performance by 0.28% per day, based on Pathfinder data, unless dust removal methods are successfully implemented); dust may also pose abrasion problems for exposed machinery with bearings / rotating parts. Wind loading on structures also needs to be considered, this is not considered in this study.

- No water, and in particular hydrogen is freely available on the Mars surface. Subsurface reservoirs have been postulated but not confirmed. The atmosphere cannot provide oxidation for combustion or chemical reactions as on Earth, as CO_2 is inert. However potential exists for (forced) convective cooling using the atmosphere.
- Low gravity (0.38x terrestrial), reducing required motive power for vehicles.
- Low radiation compared with LEO/GEO, but UV higher than terrestrial. Not considered a radiation hazard or degradation factor to power systems.
- Considerably reduced solar flux: Each square metre of solar array can collect a mean energy of 590W/m^2 in Mars orbit, correspondingly reduced by photovoltaic cell efficiency. On the Mars surface, a simple, flat non tracking panel would collect between 100W/m^2 (worst case, 7.5% of AM0 or Earth LEO solar flux) and 300W/m^2 (best case, 22.2% LEO) over a 10 hour day, due to suspended dust. However values as low as 30W/m^2 (2% AM0) have been recorded in severe storms. Combined with low relative photovoltaic conversion efficiencies, this leads to very large array sizes (and masses) required for substantial power needs.
- Solar radiation also contains a large diffuse component due to scattering effects of airborne dust. Effectively renders solar concentrators useless and reduces benefits of tracked arrays.
- A typical Martian 'sol' (day/night period) is assumed to consist of a 10 hour day and a 14.5 hour night, as far as useable solar energy is concerned.
- Solar insolation variations (due to Mars' axial tilt), i.e. seasons effectively restrict manned bases from operating to within ~20° of latitude either side of the equator.
- The solar spectrum reaching the Mars surface is substantially more red, as blue wavelengths are absorbed by atmospheric dust. Atmospheric solar energy transmission is reduced by up to 30% at 350nm (blue) on a clear day, dust storms worsening this figure. This changes efficiency of photovoltaic cells, and may cause severe degradation in multi-junction cells optimised for the terrestrial solar spectrum.
- Low, variable temperatures, typically –80°C summer night to –130°C winter night, but rising to +30°C at noon in summer on the equator. A mean temperature of –30°C is assumed during the Martian day, for a base near the equator under clear skies (optical depth 0.5), diminishing to –60°C under a severe dust storm (OD >3.0). To a first approximation it is assumed that the lower temperature compensates for any reduction in efficiency due to the different spectrum (this is valid for dual junction GaAs cells, but is unlikely to be the case for triple or quad junction cells), and efficiencies are similar to those measured for LEO. However low temperatures may also damage cells.
- Power storage systems operating during the Martian night are assumed to be insulated such that temperatures not less than –40°C are reached.
- Mass is critical: a minimum of 7kg mass into LEO is required to launch 1kg payload to the Mars surface. This is based on other study work assuming all European mission elements will be launched to Mars using an evolved Ariane V with a using a cryogenic, restartable upper stage (Vinci) having a nominal 28t capacity to LEO. Assuming a chemical LH_2/LOX Mars injection stage, a single Ariane V++ could land up to 4t on the Mars surface, assuming aerobraking and reasonable landing system (e.g. heatshield) masses. Double or triple launches with Earth orbit assembly increase the Mars surface payload mass to 7.5 and 12t respectively. A nuclear (thermal) Mars injection stage with double the specific impulse of a LH_2/LOX might enable a slight increase to 5t for a single vehicle, equivalent to 5.6kg to LEO for 1kg to the Mars surface.

4 Technology Options (non-nuclear)

4.1 Power storage

The technology inventory, and an initial literature survey of power systems technology in the context of Mars exploration suggested that batteries and fuel cells were the key power storage technologies. Particular technologies meriting more detailed investigation were:

- High temperature batteries such as ZEBRA and Sodium Sulphur, which could provide combined heat and power and have as yet been unexploited in space applications despite extensive development efforts.
- Li-ion batteries, and (a) their performance at extreme low temperatures (-40 to –80°C), b) potential for size scale up beyond the current state-of-the-art which is focussed on portable consumer electronics, and c) lifetime (currently a few hundred to 1000 cycles).
- Regenerative fuel cells, or Redox batteries, where reactants such as hydrogen and oxygen are combined to form water in a fuel cell stack, generating power when needed (e.g. at night), then split back to their reactant forms by an electrolyser when power is available (e.g. in the day, form a solar array).

Li-ion batteries and regenerative fuel cell power storage technologies were selected as initial candidates for Mars surface power systems modelling, against a baseline of NiCd battery technologies. Li-ion batteries hold most promise for the future, since they are highly efficient at converting electrical energy, are widely available for terrestrial and shortly space applications, and numerous improvements are on the horizon. For mobile applications, e.g. microrovers, it was assumed that rechargeable (secondary) Li-ion batteries offer 150Wh/kg, and 100-1000W/kg, for 500-1000 cycles lifetime. For non-rechargeable (primary) lithium batteries, the energy and power densities were taken as 600Wh/kg and 60-130W/kg. Regenerative fuel cells or Redox batteries offer the potential for very high energy densities (200-800Whr/kg) but have a low efficiency for the hydrogen-oxygen reaction, ~60% compared with batteries at 90-95%. Redox batteries are also not favoured for frequent use applications, since they require a high electrolyser power, provided on Mars by solar energy, which is in short supply.

Alternative power storage technologies also have potential, although less data is available. Flywheels, supercapacitors (for peak power supply) and high temperature batteries such as Zebra and Na-S are also applicable to Mars surface power systems. Flywheels in particular offer a high energy density (possibly 3x that of Li-ion batteries), low temperature tolerant and long life alternative However, of the above, only Zebra high temperature batteries are considered mature in Europe.

In contrast, fuel cells which combine hydrogen and oxygen and vent of dump the resulting water are well suited to mobile (e.g. rover) and low energy applications (standby or emergency for base units). The Proton Exchange Membrane (PEM) fuel cell is preferred, offering a (stack) power density of 1 kW/kg and 1.5 kW/l. Solid oxide fuel cells operation at high temperature have the potential for also generating heat and are less tolerant to impurities such as CO found on Mars.

Reactant storage for fuel cells, in particular hydrogen is the major obstacle to use of this technology on Mars. Hydrogen storage can take a variety of forms, the most promising currently available method of storage being in ultra high pressure composite cylinders, with a mass of ~0.8kg per kWh of stored energy. In the medium to long term, hydrogen storage in carbon nanofibres offering perhaps 25% by weight H_2 storage may be realisable. Storage of 1kWh of energy in a carbon nanofibre system would require a storage system mass of 0.22kg, almost 75% less than as a high pressure gas.

The use of internal combustion engines running on stored hydrocarbons (e.g. Methane / CO) for surface mobility, suggested by Mars Society studies, is not favoured here. Fuel cells offer higher power densities and the benefit of no moving parts. However it should be pointed out that fuel cells and any other system combusting hydrocarbons requires both a supply of hydrogen (not freely available on the Mars surface), and a compact means of storing oxygen, unless a means of using CO_2 in-situ can be found.

Power storage for mobile mission elements can make use of any of the above technologies. However for larger, more power hungry static mission elements, if power storage is required for regular night-time operation, e.g. complementing a solar array, the required mass and volume rapidly becomes unmanageably large. This will be seen in Section [6], and is one of the prime reasons favouring nuclear power systems for static applications, since power storage overnight is not required.

4.2 Power generation

4.2.1 Static mission elements

The technology inventory and initial research into studies of power provision for future Mars missions indicated photovoltaic arrays as most promising for large, static mission elements. A number of options were considered. Crystalline silicon based arrays, whilst being the best spectrally matched to the available solar flux on the Mars surface, have a low efficiency (13% for standard Si, ~17% for HiETA under AM0) compared to GaAs multi-junction cells. However after accounting for likely spectral mismatch effects with multi-junction cells and the differences in temperature coefficients, current state-of-the-art GaAs triple junction cells show a likely end-of-mission-life performance of only 21%, compared with HiETA at 18.6%. Therefore on the basis of their much greater cost, and uncertain performance due to spectral mismatch effects on Mars, GaAs based PV cells lose out to crystalline Si. Approximate performance metrics for HiETA Si cells (not panels) on the Mars surface are a mass specific power of 107W/kg, an area specific power of 51.5W/m^2 and a cost of 35kEuro /m^2 of cell. In comparison, GaAs/Ge single junction cells offer 63W/kg, 46.6W/m^2 and cost 133kEuro/m^2. GaAs based triple junction cells perform better, 78W/kg and 58.2 W/m^2, but are likely to cost considerably more.

A number of alternative PV technologies were investigated, including concentrator arrays such as Scarlet (used on NASA's DS-1 mission), dye-sensitised, thin-film amorphous Si, LILT (Low Intensity, Low Temperature) Si, cleft (ultra thin) GaAs, and optimised quadruple junction GaAs cell technology (as yet only experimental and not yet optimised). The promising alternative photovoltaic technology offering minimum deployed area and minimum mass might be a flexible 'rollout' or inflatable/shape memory metal actuated array using thin film Copper Indium diSelenide (CIS) cells. These technologies, under development in the USA may offer substantial improvements, with a mass specific power of ~500W/kg and an area specific power of 28W/m2 available now, and over 1000W/kg and 55W/m2 available in perhaps 10-15 years time.

The cost of solar arrays has not been examined in detail in this study, since development costs cannot be factored in, and the long term viewpoint of the study reduces accuracy in assessing recurring costs. However, using 1999 figures, the recurring cost of Si HiETA cell based arrays is around 800Euro per watt of power required. Since a PV array based power system must generate additional power to store energy for night-time operation, the cost of a 50kWe array is likely to exceed the 40Meuro suggested, by a factor of 3-4x to account for the increased array size for power storage. In comparison, GaAs/Ge single junction cells (yesterday's technology) are ~4x the cost of HiETA Si, suggesting a minimum cost of 160MEuro for an array generating 50kWe instantaneous on the Mars surface, but excluding power storage needs. Use of state-of-the-art multi-junction GaAs based arrays is likely to raise costs considerably higher. The cost of thin film CIS arrays has not yet been established as this technology is barely available in Europe.

The following table summarises photovoltaic array performance figures:

Cell type	AM0 efficiency @ BOL (%)	Estimated Mars surface efficiency @ EOL (%)	W/kg @ cell (not panel) level, Mars	W/m2 @ cell level, Mars	Recurring cost 50kWe array, excluding power storage (MEuro)
Si 10 Ohm-cm BSFR	13	15	170	41	50
Si HiETA	17.3	18.6	107	51	93
GaAs/Ge (single jnct.)	18.5	16.9	63	47	390
GaAs Adv. Triple jnct.	30	21.1	78	58	N/A
CIS current	12	10	555	28	N/A
CIS projected	23	19.7	1090	55	N/A

Thermoelectric generators were considered in the context of temperature gap utilisation, i.e. exploiting the temperature difference between the Mars surface and immediate subsurface regions. However this is at present only a theoretical concept, and thermoelectrics offer low (4-8%) efficiency, suggesting this may be difficult to exploit. Thermoelectric may also offer secondary power where a source of low grade waste heat exists, but the low efficiency indicates they are unsuitable for providing large power levels.

Other power system technologies deemed of interest to static applications were satellite solar power systems and thermionic converters. Neither of these are European strengths, however they should be considered in further detail. Beaming power to the Mars surface from a satellite solar power array is, in theory, very attractive. However the effect of Martian dust on transmission efficiency has not been widely researched and may significantly affect performance. Thermionic conversion is highly relevant to nuclear reactor systems, and is covered in the section [5]. Geothermal power extraction may ultimately be feasible on Mars, although for early human expeditions it is impractical.

The most applicable static power system technologies in which European strengths exist which could be built on are wind energy and solar cells. A combined power system which makes use of the strengths of both may be the best way forward, if wind energy unknowns such as wind speed forecasting, operation at low Reynolds numbers, and an appropriate means of generator deployment can be established. These are examined in Section [6].

4.2.2 Mobile mission elements

Mobile mission elements such as robotic rovers are more constrained by area and volume than static elements, where, for example, solar arrays can be deployed.

Although array deployment is possible, it rapidly becomes impractical as the power required rises, if simultaneous movement is required. The technology inventory suggested a number of alternative power generation methods (although these are effectively power storage systems, consuming an on-board reactant supply to generate energy).

Fuel cells are the most favoured means of providing power for mobile mission elements, these have been discussed above, but offer high power densities, at the expense of a possibly bulky store of reactants, unless recharging or replenishment during a mission can be achieved. Thermophotovoltaics hold promise on a small scale (under development up to 3kWe), and MEMS microturbines have theoretical energy and power densities orders of magnitude larger than conventional power generation methods on a small scale, but are immature and have yet to demonstrate either small scale performance or operation outside the laboratory. The latter may be particularly suited to EVA suits and micro- or nano-rovers if their potential is realised. Supply of a hydrocarbon fuel and a suitable oxidiser on Mars is the major difficulty with implementing these technologies.

A number of other power generation options offering potential in terrestrial or deep space applications, including solar dynamic, solar AMTEC, radioisotope AMTEC and combustion engines have not been considered in detail as they are not suitable for Mars surface operation.

4.2.3 PMAD / heat rejection

Power management and distribution technology was not assessed in detail, but was assumed to be an integrated part of any power systems. Detailed PMAD considerations will have a significant impact on design and should therefore be included in future work. PMAD efficiency in this study was assumed to range from 85% (current) to 95% (15 years ahead) Each kg of PMAD mass was assumed able to deal with 45W of generated power (NASA figures), rising to 250W/kg in 15 years. Transmission voltages of 400V or more will be required to transmit large amounts of power over distances of several hundred metres or more. 1000V-5000V is considered feasible by NASA in the timeframe of the first manned expedition. However further study of cable insulation (requirements, masses, robustness), the merits of low resistance high temperature superconducting cables and high voltage (SiC) converters, high voltage (SiC) switches and regulators would be appropriate for follow-on study work.

Heat rejection capability carries a mass penalty. Upper and lower bounds were assumed to be 0.2kg per watt of rejected heat, and 0.005kg/W respectively, derived from Hermes data. More detailed estimates of heat rejection penalties are needed, and heat rejection needs to be assessed from a system point of view, since some mission elements will required heating for the Mars surface (e.g. fuel cells, batteries), others will generate heat (e.g. ISRU Sabatier reactors). The incorporation of convective cooling using the Mars atmosphere has been studied for nuclear reactors, section [5], but is also applicable to other systems.

4.3 Technology selection

The ranking scores for the key technologies identified by technology inventory of non-nuclear power systems are shown in the Table below:

Technology type *Max. Score 36* *Min. Score 22*	Cost	Physical Constraints	Satisfaction of performance requirements	Product Assurance	Environmental survivability	Introduction of new Technologies	Breadth of expertise in Europe	Total Technology Score
Batteries	5	5	5	6	6	2	3	**32**
Thermophotovoltaics	5	6	6	6	5	3	1	**32**
Thermoelectric generators	6	6	4	6	6	3	1	**32**
AMTEC cells	6	6	6	5	4	3	1	**31**
PEM fuel cells	6	5	6	5	4	2	3	**31**
High temperature fuel cells with CHP	6	5	6	4	5	2	3	**31**
Microturbines	4-6	6	6	4	6	3	1	**30-32**
Solar Satellite Power Systems	4	4	6	6	6	3	1	**30**
Flywheels	6	6	6	4	4	2	1	**29**
Regenerative fuel cells	5	6	6	4	4	3	1	**29**
Thermionic converters	6	5	5	5	5	2	1	**29**
Wind energy	5-6	4	4	4	6	2	3	**28-29**
Solar cells	4	4	4	6	6	2	2	**28**
Solar concentrators	4	4	4	5	4	2	2	**25**
Photocatalytic decomposition of CO_2	TBD	TBD	TBD	TBD	*4-6*	3	1	**8-10+**
Geothermal energy	TBD	TBD	TBD	TBD	4	1	1	**6+**

4.3.1 Technology ranking process

After an initial preselection of key technologies, a ranking system was derived, in part from a technology rating system covered in ‘Spacecraft Systems Engineering’ (eds. Fortescue, P., Stark, J; 3rd edition, 1997). There are 2 levels of ranking:

- The upper level consists of the primary evaluation criteria, and a rank of 4 (worst) to 6 (best) is applied to each of the categories in this level.
- The lower level contains the secondary parameters, and a rank of 1 (worst) to 3 (best) is applied to each of the categories in this level. An additive total score gives an initial shortlist of technologies to be further examined.

4.3.2 Primary evaluation parameters

The following parameters are essential to a successful mission, and are worth between 4 (lowest) and 6 (highest) points:

1. Cost
2. Physical constraints, considered from the point of view of:
    (a) Low mass
    (b) Compact dimensions (low volume)
    (c) Long operational lifetime, without maintenance
3. Satisfaction of performance requirements (e.g. specific power, efficiency, etc.)
4. Product assurance, considered from the point of view of:
    (a) Survivability
    (b) Reliability
    (c) Safety
    (d) Availability
5. Environment survivability, considered from the point of view of:
    (a) Thermal inputs, loads, ranges
    (b) Radiation
    (c) Atmospheric constituents (95% CO_2)
    (d) Low gravity
    (e) Absence of water vapour
    (f) Cleanliness/contamination (planetary protection)

4.3.3 Secondary evaluation parameters

The following parameters are important, but not essential to the success of the mission, and are worth between 1 (lowest) and 3 (highest) points:

1. Introduction of new technologies. A higher rank will be given to new technologies that will be brought to maturity within the time-scale and cost constraints of the mission.
2. Breadth of expertise in Europe – is the technology unique to one supplier who could be at risk?
3. Impact of technology on international mission.

Note that this system was not applied to nuclear power technologies, since complete reactor systems only were compared.

5 Technology options (nuclear)

Small nuclear fission reactors to power static mission elements were studied. Nuclear power sources were not studied for mobile applications, since the shielding required to prevent crew injury or component radiation damage is not considered portable.

An introduction to nuclear terminology was provided in *Technical Note 3*, to familiarise the reader with the detailed discussion of space nuclear reactor subsystem designs and subsystem interactions. It is intended to summarise all the nuclear power systems work carried out in this study in a single standalone reference document. This will cover all aspects of space nuclear power and serve as a reference for future European efforts.

5.1 Background

Extensive nuclear reactor technology development including flight tests of a number of different reactor designs, power conversion and waste heat rejection technologies has been carried out in numerous countries (in particular America, Russia, the UK and France) since the early 1950s. Nuclear reactor powerplants, unlike many non-nuclear devices, must be considered as systems and are less suited to a part-by-part examination. Nevertheless, several important issues must be covered when considering nuclear power options:

- Reactor core design and its integration with the primary heat transport subsystem.
- Shielding
- Power conversion options and (dynamic) cycles
- Power conditioning
- Waste heat rejection
- Safety, during all phases of reactor operation.

A key concern was to minimise reactor outlet temperature. In reactor designs optimised for space, radiation is the only means of rejecting waste heat. This favours the highest possible outlet temperature, in order to maximise heat rejection power and minimise the radiator size and mass. However a high reactor outlet temperature (1400-1500K), for example as employed in the US SP-100 design, requires the use of unusual materials, which must be developed and qualified (at considerable cost) to be reliable over the reactor lifetime. Such materials knowledge and technology is not available in Europe, therefore for a system with a lower (<1200K) reactor outlet temperature is required. This results in a large, correspondingly massive radiator, or the requirement to reject waste heat by some other means. On Mars the option to use the atmosphere to convectively cool the reactor is possible. This study therefore compares low outlet temperature reactors, which can be designed with confidence using conventional materials (e.g. stainless steel), and which reject heat using either forced convection or a deployed radiator.

A safety assessment covering ground and launch phases, operational phase and post operational phases was made. This demonstrated that reactor criticality and subsequent hazard to populations in the event of a launch failure (the highest risk event) compacting the reactor or immersing it in water could be avoided by careful design. A safety strategy for use of nuclear power in space was also proposed.

5.2 Comparison of options

Two reactor system technology options were examined in this study. A high temperature gas cooled, particle bed design with dynamic power conversion and forced convective cooling / heat transfer using the Martian atmosphere, was studied in parallel with a lower temperature liquid metal cooled fuel pin semi-fast design with static (thermoelectric) conversion, rejecting its waste heat via a more conventional radiator.

The two reactor designs are compared in the Table below, together with the preferred NASA design for a human Mars mission:

	Option (1): Liquid metal cooled reactor	**Option (2): Gas cooled reactor**	**NASA 'Escort' design**
Thermal power (kW)	1250	185	716
Electrical power (kW)	**50**	**50**	***160***
Energy conversion cycle	Direct, thermoelectric	Dynamic, recuperated Brayton	Dynamic, 95% recuperated Brayton
Lifetime	10 years	10 years	7.5
Core outlet temperature (K)	1025	1200	1300
Other details	ZrH_2/UO_2 : 3	Particle bed design, 75% UO_2	10kWe aux. power unit to deploy
Minimum Core mass, kg	186	1075 *(inc. control drums & reflectors)*	1302
Fuel mass, kg	26.1	~93	N/A
Power conversion subsystem efficiency, %	4	26.9 (35 possible)	~22
Power conversion subsystem mass, kg	371-712	340	3134, inc. radiator + 1131 PMAD
Radiator mass, kg	718	No radiator	
Packaging mass, kg	111-180 *(assume 20% of core and conversion subsystem mass)*	250 *(reactor pressure vessel)*	1566 cart for deployment
TOTAL MASS, kg (excluding shield)	**1386-1796**	**1665**	**7134** (6002 ex PMAD, 12009 inc. PMAD & shield)
Core dimensions	0.45 x 0.6m	0.9 ø x 1.5m high	0.675ø x 0.81 high
Power conversion subsystem dimensions	0.5 x 0.4m	0.8m ø x 1.2m high	Not available
Radiator dimensions	4.5 x 6.8m	No radiator	Not available Total reactor stowed volume $65m^3$

The NASA 'Escort' gas cooled design was also selected from two competing options, similar to those in this study. The gas cooled design, despite offering a slightly lower performance than the liquid metal cooled SP-100 alternative, was selected because of its potential for saving overall mission development costs by operating bimodally as a nuclear thermal propulsion unit. The European technology base is likely to favour nuclear electric over nuclear thermal propulsion, hence the argument in favour of the classical bimodal power-propulsion system is less valid in this study.

The NASA design is also considerably heavier, as it incorporates a tungsten / lithium hydride radiation shadow shield. This study looked at the possibility of providing shielding material using Martian soil, or regolith, to reduce transported mass.

5.3 Liquid metal cooled reactor, thermoelectric conversion, radiative heat rejection

A compact reactor core designed for liquid metal cooling and thermoelectric (static) power conversion, derived from a lunar mission study (LNPS) was optimised for Mars surface operation. An ideal neutron moderation ratio (ZrH_2 moderator:UO_2 fuel mass) of ~3:1 was determined. A fast reactor core (no moderation) was found to be significantly heavier even when a Be reflector was added. An initial optimisation of radiator design emphasised the need to use high cycle temperatures to give a compact radiator.

This reactor design has the advantages of:

- Good safety level.
- No maintenance, stemming from use of direct, thermoelectric converters.
- Proven technology.
- No use of external power for the starting phase (in theory).
- Compact, low mass core with 10 year lifetime readily achievable.

However, its disadvantages are

- A low overall efficiency factor, stemming from thermoelectric conversion.
- Thermoelectric conversion, although in theory very reliable stemming from its solid state nature, has not been demonstrated as such and should therefore be viewed as a technology risk area.
- Technology difficulties for the cold source (radiator). The radiator design as initially performed specified Al, which is unsuited to the coolant temperature required. Resizing using stainless steel or Inconel is required.
- For reasonable efficiencies (4% v. 1%), a high coolant temperature (i.e. liquid metal, and containment materials compatible with this over a long period) and a high temperature differential across the thermoelements (i.e. robust thermoelements) are required. This technology will need to be qualified for use in the Mars environment.
- Deployment of the radiator has not been addressed, and on a rough Mars surface following a hard landing, may be difficult.
- There may not be sufficient thermal energy available in the Martian atmosphere to melt the radiator’s mercury working fluid (Mercury) and permit circulation, especially if a dust storm is encountered, reducing the available solar heat.

5.4 Gas cooled particle bed reactor, dynamic power conversion

A He/Xe gas cooled particle bed reactor design derived from the 200-SNPS and Dragon studies for in-space power generation was adapted for Mars surface operation, eliminating the radiation shadow shield and utilising the Martian atmosphere for forced convective cooling and the secondary power conversion cycle.

The Brayton dynamic power conversion cycle was selected due to its relative maturity. Although the Rankine cycle offers superior performance, up to 65% efficiency, the Brayton cycle is competitive over a wider temperature range, which has important implications for a coupled waste heat rejection system using convection.

This reactor design has the advantages of:

- Reduced risk of criticality in the event of water immersion, should launch vehicle failure occur.
- A higher overall efficiency, reducing the requirement to reject waste heat, and removing the need for a large, deployable radiator by using forced convection of the Martian atmosphere..
- Compact heat exchanger turbomachinery, with the potential to achieve very high (~35%) efficiencies.

However, the disadvantages of this reactor design are:

- A highly thermal core design, requiring BeO axial and radial reflectors. This results in a high mass (>1000kg) bulky core, largely due to the reflector.
- The core neutron spectrum is hard and the fast neutron dose to the fuel particles will approach levels where failure of the pyrocarbon coatings of the fuel particles, leading to fission product release, would become significant. This effect could limit the concept to low thermal power and a life not greatly exceeding 10 years.
- A high fuel particle content (~ 74% UO2 by volume) is required in order to mitigate the reactivity increase due to water flooding. However such high fuel densities are beyond known operational experience.
- The control rod margin, while still probably adequate for the optimised reactor design, is still small enough to be of concern.
- Calculations performed during the current investigation have confirmed the existence of a small negative temperature coefficient for this type of small reactor intended for space applications. However, an evaluation of other temperature effects, in particular the thermal expansion of the system and the temperature of the reflector, is required as they will be more significant for this type of system.
- The long term corrosive effect of Martian atmospheric CO_2 on turbomachinery is not yet clear.

5.5 Reactor shielding

Both designs will require a radiation shield to protect workers in the vicinity. Since transporting such a shield from Earth will require approximately a further 10t to be landed on the Mars surface, use of indigenous Martian materials to construct this shield is preferable. A shield ~5m and 3m high is the estimated requirement to reduce reactor radiation emissions to 10x less than the 20mSev/ytear background level, at 100m distance. Such a shield would require the moving of ~900t of Martian regolith. Moving reactor to 1km distance reduces shield mass by 30-40%. The issue of binding the regolith to prevent wind dispersion is a problem which has not yet been addressed in detail. Simple covers, or synthesising and incorporating a component such as polyimide on the Mars surface might offer solutions.

5.6 General points

The long-term safety of the reactor following decommissioning must be demonstrated. This is of particular significance for the liquid metal system, as the fuel cladding could be vulnerable to corrosion by the Martian atmosphere. Fuel cladding resistant to CO_2 corrosion is therefore a key nuclear technology for Mars surface exploration using nuclear power.

Power management and distribution was addressed only briefly in the study. Consideration of power transmission distance, voltage and conductor material / insulation is needed. Total PMAD mass is likely to be a few hundred kg for reasonable reactor / user separations, which is small compared to reactor system mass.

Improved knowledge of the regolith and atmosphere properties is required in order to validate the models used. Radiation shield mass and geometry, and power conversion cycle performance cannot be optimised until further data is obtained.

The study also showed that combining the best features of both types of design, i.e. the compact, high burnup UO_2 /ZrH core proposed for the liquid metal cooled reactor design, and the high efficiency, compact Brayton cycle power conversion subsystem with convective cooling of the particle bed reactor design, will offer the best solution to the constraints of providing power on the Mars surface. This is examined further in the next section.

6 Power system solutions for static mission elements

6.1 Non-nuclear

6.1.1 Solar electric power generation

Parametric models were developed to evaluate mass and area of different solar power generation options.

Early models, assuming worst case Mars atmospheric conditions (100W/m^2 daily mean solar flux), and based on NiCd battery energy storage, 85% PMAD efficiency and a 10hour day/14 hour night showed a daytime power generation demand of 191kWe, almost four times the continuous power requirement. A Mars surface solar electric system is significantly enlarged by the need to generate power for storage to supply the needs of mission elements during the night. For 50kWe continuous, a minimum array area of 10000m^2 for advanced triple junction GaAs based arrays, and over 20000m^2 for Si HiETA cells was determined. Assuming a single square geometry array this equated to side lengths of 100m and 150m respectively. For comparison, the recently deployed ISS arrays are only 2 x 400m^2 in area (33 x 12m each). These array sizes will pose significant deployment problems on the Mars surface.

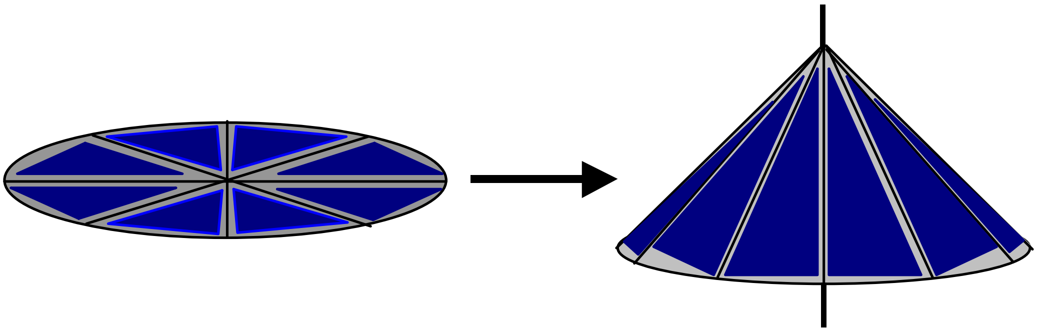
A more advanced system with 95% efficient PMAD and Li-ion batteries requires a daytime power generation capability of 150kWe, three times the continuous power requirement. Array size is reduced to 8000m^2 (95m side) for advanced GaAs cells, and to 17000m^2 (130m side) for Si Hi-ETA cells, assuming worst case solar irradiance.

Array sizes were found to be reduced to at best 2500m^2 (50m side) for advanced GaAs cells if a higher solar incidence (300W/m^2 v. 100Wm^2) could be relied upon, as later shown this is unlikely to be the case.

More detailed models examined advanced, lightweight array technology, employing ultra thin film CIS cells deployed using novel mechanisms. The likely system masses dictated by the power requirements of an ISRU plant or a Greenhouse module, with either the most suitable current technology, or that or projected to be available after 10-15 years development are detailed below:

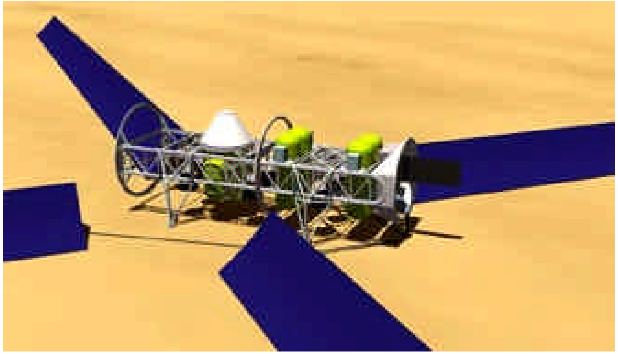
Mission Element	Mass (kg) / *array area* using current technology	Probable mass (kg) / *array area* using future technology, 10-15yrs
ISRU plant (50kWe)	Array: 3700 *($4450m^2$)*	Array: 750 *($2270m^2$)*
	Storage: 5550 *($2.6m^3$)*	Storage: 1850 *(N/A)*
	PMAD: 2400	PMAD: 600
	TOTAL: 11650kg	**TOTAL: 3200kg**
Greenhouse (15kWe)	Array: 1100 *($1350m^2$)*	Array: 220kg *($680m^2$)*
	Storage: 1670 *($0.78m^3$)*	Storage: 560 *(N/A)*
	PMAD: 762	PMAD: 150
	TOTAL: 3532kg	**TOTAL: 930kg**

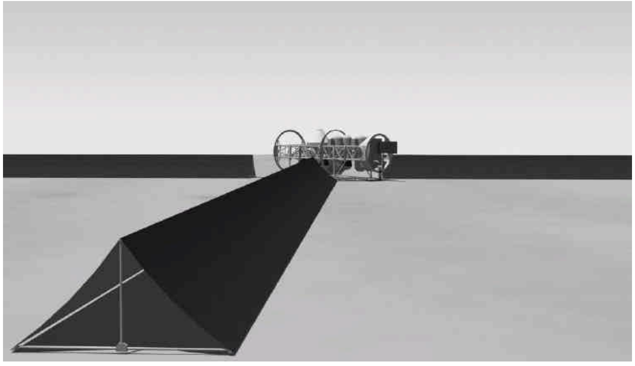
A possible method of deployment would use a modified AEC-Able ‘Ultraflex’ circular array design, inflated as a cone shape around a central mast (to reduce dust accumulation and achieve the best compromise of sun angle) as shown below:



An area of $4450m^2$ (current array technology) could be achieved with 15 x 10m radius array modules, or 57 modules each 5m in radius. More advanced CIS array technology could allow this to be reduced to ~7x10m radius modules or 29x5m radius modules. This design would require careful design of its supports to ensure they could resist environmental and deployment loads. A 10m spar would be required to support the stowed array; landing this on Mars could be difficult.

An alternative, incorporated in the current NASA design reference solar-electric power system, would be to use an inflatable array using tents to support thin film cells. Based on a design called ITSAT, this would require either 4 tents, each with 2 segments ~3m wide (0.5m extra at base to prevent soil accumulation) and ~220m long; or 8 segments each ~2.5m wide and 140m long, similar to the NASA design. More advanced CIS array technology could allow boom lengths to be reduced to ~115m (4 segments) or 71m (8 segments). Deployment of segments 70-150m long would require careful thought if obstructions on the surface or excessively heavy inflation/deployment mechanisms are to be avoided. This approach is shown schematically below:





Note that the above solar electric system is sized for clear sky conditions, i.e. with an optical depth of 0.5 and ~300W/m^2 solar flux.. Realistically this is unlikely to be the case for 100-200 days per Martian year, due to dust storms. A solar electric system sized to function under an OD of 3.0, i.e. a moderately severe global dust storm, would increase system mass to ~20t (current thin film array / power storage technology), with perhaps a minimum mass of 5t using technology conceivably available in 10-15 years (primarily ultralightweight, inflatable solar arrays and high energy density, robust flywheels). However the practical difficulties of deploying a large array telerobotically on the Mars surface do not favour photovoltaic power generation. Although use of quadruple junction GaAs cells optimised for the Mars spectrum on rigid support panels could reduce deployed area, this would not reduce mass. Furthermore, severe dust storms have been reported, with optical depths of or exceeding 6.0, which would render any solar array design practically useless on the Mars surface and severely increase mission risk.

6.1.2 Solar electric power storage

Currently batteries represent the only viable power storage concept for a large solar array system. However in the future, development of flywheels with 3x the energy density of current Li-ion batteries has been predicted. These present an option for substantially reducing power storage mass, to ~1.85t.

Although regenerative fuel cell size and mass could be reduced by storing oxygen in liquid form, and advanced (e.g. carbon nanofibre) hydrogen storage, the high power consumption of the electrolyser required to convert water back into reactants would drive the solar array size to an unacceptable level.

The Greenhouse module backup power of 1kWe for 10 hours could be provided by a PEM fuel cell, which would weigh 1kg and be less than 1litre in volume. Assuming a fuel cell efficiency of 60%, reactant storage of oxygen and hydrogen stored as gas in composite cylinders would add another 18.5kg, a total mass of less than 20kg and a volume of less than 40litres.

6.1.3 Wind boosted solar-electric power generation

The principle problem with pure solar-electric power generation on the Mars surface is that it cannot be relied on to produce the required power if persistent dusty, i.e. low solar flux conditions arise. NASA studies have demonstrated, and this study has confirmed that relying on pure solar-electric either increases mission risk (probably to an unacceptable level), or dictates array size / mass, and power storage mass / volume increases to the point where the power system greatly exceeds the parameters of the mission elements it is designed to support! In order to guarantee adequate power during dusty conditions, solar electric power systems must be supplemented.

The most near-term, low risk and non-nuclear means of achieving generating an energy rich scenario for the first human expeditions to Mars is to use wind energy to boost solar power when dust storms reduce the solar radiation reaching the surface. This is practical because high wind velocities and dust storms generally occur simultaneously. A (hydrogen containing) balloon supported wind generator design has been examined in most detail, and can generate 10kWe for a mass of 1900kg without posing any major deployment difficulties. Combining 3 such balloon supported generators (30kWe) with an array sized to generate the remaining 20kWe under severe dust storm conditions leads to total system parameters as follows:

- Array: 4.5t mass / 5600m^2 area (current) – 0.93t mass / 2850m^2 area (future). Former equivalent to 18 x 10m radius deployable array units, or 70 x 5m radius units, latter to 9x10m radius o36 x 5m radius units, as described in section [6.1.1].
- Power storage: 1.95t mass / 0.6m^3 volume Li-ion batteries, or, potentially 0.65t for high energy density flywheels. Note that the latter are not yet available in Europe.
- PMAD: 0.6-2.4t mass, as per an all solar electric system
- Storage vessel mass for 240kg H_2 to deploy balloons: 2.23t, if stored in gaseous form at 100MPa in composite cylinders; 1.25t if as LH_2, decreasing to 815kg if stored in C nanofibres with 50% storage density. Alternatives to hydrogen balloons for lifting, e.g. kites may be possible.

A total power systems mass of 15.8t (current technology), or 8.7t (future technology) and a deployed area of 5600m^2 or 2850m^2 respectively might therefore be achievable for a wind / solar electric power system sized to generate 50kWe reliably, i.e. under optical depths of up to 3.0. For reference, the comparable solar-electric system, without wind turbines, sized for dust storm conditions would have a mass of 20t (with a 15000m^2 deployed area) using current technology, and ~5t with more advanced technology.

Based on current technology and estimates of wind patterns on Mars, a wind-solar-electric system is more competitive than a pure solar-electric system. However, projected advances in solar array technology may reduce the difference. Further study of wind energy on Mars is strongly recommended to determine whether an optimised wind energy system might be realistic, and could remain competitive with a pure solar-electric system, given projected advances in solar cell efficiency.

The uncertainties of wind energy availability and forecasting on Mars, and the limited payload capability to the Mars surface using the European Ariane V++ (4-5t) indicate that based on current knowledge of Mars, a non-nuclear primary power generation system presents too high a mission risk.

6.1.4 PMAD

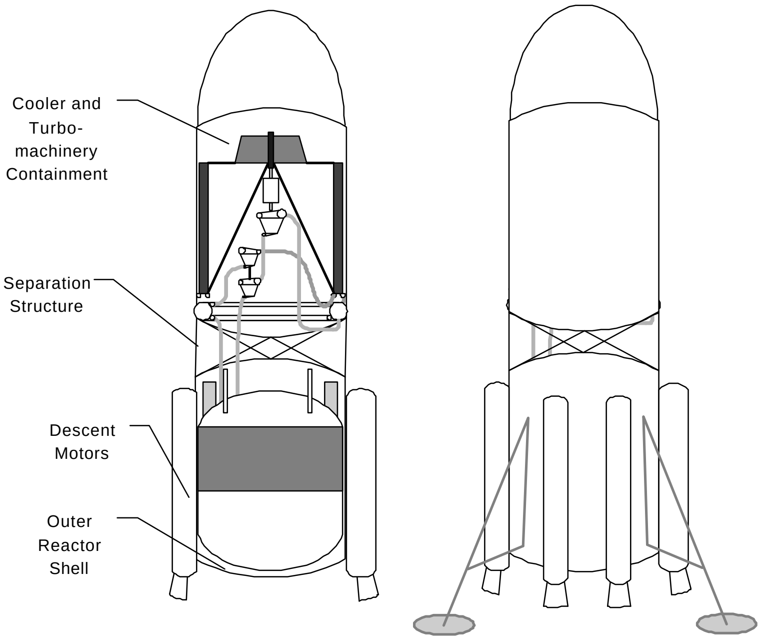
Assuming an Al cable mass (200m length) of 225-282kg, including a 10% insulation mass margin, total PMAD mass for a solar electric power system generating a constant 50kWe of power will lie somewhere between 600kg and 2400kg. Approximately 2.2kWe of waste heat will need to be removed from the PMAD system. Superconducting cables could potentially reduce the mass of cabling.

6.2 Nuclear

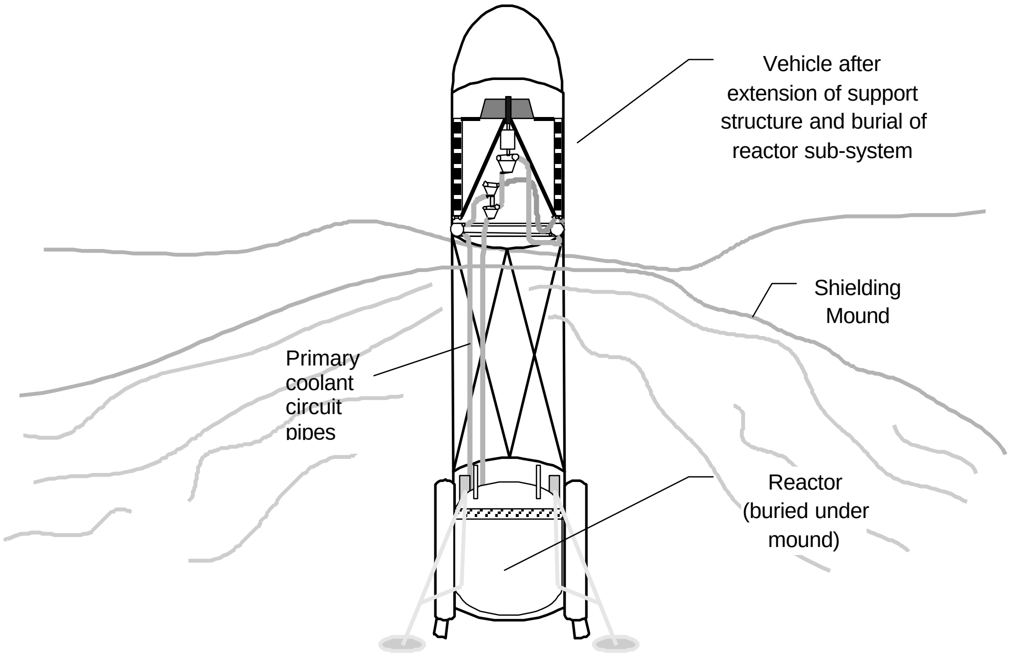
In contrast to the solar (-wind)-electric system described above, a combination of French and UK nuclear technology can be used to provide a compact (1.18m^3 undeployed), lightweight (<1t excluding radiation shield), reliable alternative for generating 50kWe (or more) of continuous power on the Mars surface. Combining the compact UO_2/ZrH fuel pin core plus Be reflector of the liquid metal cooled design, with the recuperated dynamic (Brayton) cycle conversion, and Martian atmosphere CO_2 blower for convective cooling of the gas cooled design has a number of benefits. It will alleviate the need for a large, heavy and (potentially) difficult to deploy radiator, as well as any concerns about the reliability of thermoelectric conversion, and will offer a much more compact, lower mass core than can be obtained using a Dragon type gas cooled particle bed reactor core.

The reactor system uses a primary coolant loop of NaK to give a low exit temperature of 1025K (750°C) allowing the use of conventional materials and offering confidence in reliability over the 10 year reactor design life. The reactor system lifetime is projected as 10 years, optimised electrical power conversion efficiency is 18.2%, and no (deployable) radiator is required. Given present technology readiness and knowledge of Mars environment conditions, this presents the lowest risk solution to the power demands of initial manned Mars expeditions. It can also be scaled to higher power levels (>100kWe) for minimal increase in mass and volume.

The total reactor system mass is likely to be in the vicinity of 1500kg, excluding shielding. The core and power conversion system should be deployable from a volume not exceeding 1m diameter and height 2.5m, contained within a lander stage, injected to Mars and landed by a single Ariane V++ launch to a low Earth orbit. This is shown schematically below:



The main nuclear power issues which need to be evaluated further are (1) prevention of reactor core criticality in the event of a terrestrial launch failure and water immersion (this has bee evaluated for a gas core particle bed reactor); and (2) the logistics of arranging a Martian regolith radiation shield around the reactor, which may present some significant practical difficulties. A schematic of the reactor system after landing is shown below, the assumption being that the reactor core will be buried under regolith, leaving the secondary cooling loop and power conversion unit exposed:



7 Power system solutions for mobile mission elements

7.1 Robotic outpost phase

7.1.1 Micro inspection rover

Assuming good weather operation only is required, the most compact power system for a micro inspection rover uses an array sized for daytime peak power (14W), and a fuel cell, recharged at base for night-time operations consuming up to 45Wh. The total power system mass ranges between 1.9 and 3kg, depending on the technology applied, with an array area of 0.25-0.4m^2, and a fuel cell and reactant volume of 0.1 to 0.14litres, using NiMH or C nanofibre hydrogen storage technology.

If poor weather operation is required, a battery is better than a fuel cell for power storage (unless the array can be downsized). The mass budget will have to increase to between 2.75 and 5kg, and an array area of 0.6-0.9m^2 will be needed. Battery volume will be between 0.1 and 0.3litres.

If mass and volume on the rover (but not otherwise) are at a premium, and operation in dusty areas (e.g. southern hemisphere Hellas Basin, Martian spring) is required, then a fuel cell on board with no other power source is an option. However this will require 67 to 230kg reactant storage at a local base station. A pure battery option would require a mass of 1.5-1.8kg, but would restrict night-time operations.

7.1.2 Autonomous research island

The autonomous research island requirements were not available. However, it is believed that the most significant design challenge would be a power source for a 3kg micro-rover (nanokhod). Possibilities include either a primary battery (LiSOCl2 at 600Wh/kg, higher energy densities possible), a rechargeable Li-ion battery (150Wh/kg), a tether, or a micro fuel cell.

7.1.3 Long range exploration rover

In good weather, the preferred power subsystem for a larger, long range exploration rover has a total mass of 16-36kg, employing a deployable solar array (area 2.2-3.3m^2), using a fuel cell with a mass of 7.5-20kg, and battery of mass 2.8kg, with a total fuel cell/battery volume of 8.5 - 33 litres. A PV array / battery system without the fuel cell has comparable mass but requires a much larger array, which might be difficult to deploy from the rover. In dusty weather, a solar array/fuel cell/battery system is still the most effective, with a total mass between 26.3 and 62kg (compared to a rover mass of 200kg). Array area however is large, with a minimum of 6.9m^2. Battery and fuel cell volume is 8.5 – 33 litres.

Operation without solar arrays is not efficient, unless fuel can either be ‘mined’ en route, or a shorter mission duration with refuelling stops is specified.

7.1.4 Drilling station

A smaller (500W) PV array sized for mean power requirements, and an additional fuel cell system for peak power delivery is the preferred power source for a fixed, autonomous drilling station. This will have a total mass of between 150 and 315kg. However the required array to maintain mean power levels during all weather conditions will be large, at least 25m^2. Deployment of this size of array is likely to require human assistance, in which case the array could be simplified and a further 9-15% in mass reduction achieved. More than half the mass of the optimum system is fuel cell reactant storage, emphasising the need for compact, efficient means of storing hydrogen and oxygen, or fuel cells which can use Martian derived reactants obtained in-situ.

Solar arrays enable considerable mass savings for small mobile missions when light conditions are good. When high power is required, or light levels are poor owing to dust present at certain times of year, fuel cells are much more competitive. Fuel cell mass and size are only sensitive to mission duration and not to instantaneous power requirements. For shorter missions, e.g. a few days, and where refuelling of reactants is possible, fuel cells will be superior to solar arrays in most cases. Where energy / power must be guaranteed, e.g. for a manned pressurised rover or utility truck, fuel cells are likely to be the only suitable choice. Regenerative fuel cells are rarely suited to Mars missions as defined, since recharging from solar arrays is required during daytime and both conflicts with mission operations, and suffers from the low solar flux levels on the Mars surface. If continuous duty is not required, i.e. if a non-operating recharge period during the day can be tolerated, regenerative fuel cells offer some potential.

Array deployment will be problematic if large power levels are required, e.g. the drilling station if required to use a solar array to generate its peak power of 2kW under dusty conditions will require a 100-150m^2 array, equivalent to the largest arrays used in Earth orbiting satellites. Man tended deployment may be required.

Primary batteries are not suitable for any of small telerobotic missions owing to the long duration required, which leads to unacceptable mass.

7.2 Human exploration phase

7.2.1 Mobile pressurised laboratory

Options examined for a large, mobile pressurised laboratory included combinations of batteries, fuel cells and solar arrays. In order to provide an energy of 1550-2800kWh for a 20 day mobile pressurised laboratory excursion, (PEM) fuel cells with no-board reactant storage are the only viable option amongst those examined. Batteries are too heavy, solar arrays too large, and RFCs require too much electrolyser power. If hydrogen can be stored in an advanced medium such as carbon nanofibres, with a storage efficiency of the order of 50%, and oxygen stored in liquid form, the fuel cell system mass might be brought as low as 2.3t for 2800kWh energy. Since the vehicle mass is not designed to exceed 8t, this is significant, possibly impractical fraction of system mass. In comparison, NASA has suggested a dynamic (nuclear) isotope power source (DIPS) which can generate 10kWe from a 1.1t mass for an effectively infinite number of missions. However such a system is bulky, does not yet exist and may be politically undesirable to test.

An alternative solution is possible if oxidiser can be drawn from the Martian atmosphere, thus avoiding the need to store it on board. This might reduce MPL power system mass to below 1t. However at present methods for producing O_2 (and CO) from CO_2 are too energy intensive for this to be practical. Alternative methods, or fuel cells which can operate on CO_2 (mixed with some Ar, N_2 and CO) must be derived. Other options which might be considered include use of balloon supported, towed solar arrays to generate power, or a modified, less energy intensive mission profile.

A deployment power system will be required to take the MPL from its landing site, up to 5km away, in no more than 1 day to the ISRU plant for initial filling of fuel cell reactant tanks. This will require a power of up to 7kWe and an energy of up to 19kWe. The most practical energy source for all landing scenarios is a Li-ion rechargeable battery, with a mass of 134kg and a volume of 61litres. Other, more compact or lighter options exist but present greater uncertainties.

7.2.2 Utility truck

A utility truck has an overall energy requirement of ~1500kWh, extending to 3000kWh if a return journey is required without recharging. Similar to the mobile pressurised laboratory, the optimum power system for the UT is a hydrogen-oxygen fuel cell. A total system mass of 1.2-1.6t, with a volume between 1 and 3m^3 depending on the type of hydrogen storage, will give an energy of 1458kWh. If oxygen can be obtained from the Martian atmosphere, system mass and volume drops considerably.

For emergency power, a regenerative fuel cell system is most suitable. A solar array could cover the truck load floor, or be deployed as side panels, and reactants could be stored as gases from an initial water cache weighing 50kg. Such a fuel cell would have a mass not exceeding 270kg and a minimum volume of 460m^3. However a recharge time of 6-10 days would be required to generate 120kWh of stored energy. This recharge time would be increased by up to a factor of 3 in dusty conditions.

The MPL and UT required energy for extended missions is a major constraint, this is partly due to mission duration / length, and also due to the large mass of these vehicle driving power and energy needs to high levels.

High density hydrogen storage and an effective, low energy means of withdrawing oxygen from the Mars atmosphere are key aspects of providing power for large (heavy), mobile mission elements.

The tables below summarises power source suggestions for mobile mission elements:

	Mini inspection rover	**Autonomous research island** ***- inc. micro rover***	**Long range exploration rover**	**Static drilling platform**
Power source	**14W PV array + Li-ion battery (sized for sunlight)**	**PV array for island, 1°/2°battery of micro fuel cell for rover**	**90W PV array + fuel cell + battery**	**500W PV array + peak power fuel cell**
Mass (kg)	2.75-5	~0.25 (rover)	10-23	150-315
Volume (litres)	0.1-0.3	~100 x 20mmø (rover)	8.5-33	80-300
Array area (m^2)	0.6-0.9	TBD	7+	25+

	Mobile Pressurised laboratory	**MPL deployment power source**	**Utility truck**	**U/T emergency power source**
Power source	**PEM fuel cell, LOX *(Martian CO_2)*, H_2 stored in carbon nanofibres**	**Li ion rechargeable battery** *(+ optional small solar array)*	**PEM fuel cell, LOX, H_2 stored in carbon nanofibres**	**RFC + solar array** (requires 6-10 day recharge)
Mass (kg)	2300 *(710)*	134	1200 *(355)*	270 (fuel cell only)
Volume (litres)	2000 *(not calculated)*	61	1020 *(370)*	460 (fuel cell only)
Array area (m^2)	N/A	Not calculated	N/A	62 (load floor or deployable side panels)

8 Other issues

8.1 Life support systems (EVA suits)

Life support systems were not the subject of this study. However during the initial evaluation of power systems, it became apparent that provision of power for manned extra-vehicular activity (EVA) would be demanding. High power and energy density sources developed for long endurance battlefield soldiers are highly applicable technologies to meet these needs. Li-ion rechargeable batteries could supply 750Wh for a Mars surface weight of 2-3.8kg. A fuel cell system could generate 3kWh for <5kg assuming a hydrogen storage medium capable of storing >800Wh/kg can be developed. Thermophotovoltaic power generation is an alternative. Lightweight heat rejection mechanisms for EVA suits also need to be evaluated.

8.2 ISRU

ISRU, or In Situ Resource Utilisation is the use of Martian resources to generate, typically, life support consumables (e.g. water, oxygen, buffer gases), and propellant for a return journey to Earth. The high delta V required to launch payloads from Earth to the Mars surface is demonstrated by application of Tsiolkovsky's rocket equation, which shows that 4kg of mass must be launched to LEO to send 1kg to Mars orbit, reducing still further if deceleration to land on the Mars surface is required. This results in very high transportation costs to Mars, so there is a major incentive to reduce payload mass sent to Mars by generating consumables on the surface. The term 'ISRU plant' was used in this study to denote a system, essentially a small chemical factory, converting feedstock brought from Earth (hydrogen), and Martian atmospheric gases (CO_2 and trace quantities of nitrogen and argon) into both propellant and life support consumables.

ISRU technology has been examined in collaboration with the S51 study. The goal was to specify subsystem elements, power mass and volume requirements, and technology development needs for an ISRU plant capable of providing a set quantity of rocket propellant and life support consumable needs. ISRU requirements are listed below:

Product	Function	Quantity, metric tons (t)
Methane, CH_4	Propellant – fuel	7
Oxygen, O_2	Propellant – oxidiser	25
	Life support (breathing)	5
Water	Life support (drinking)	24
Nitrogen or Nitrogen/Argon mix	Life support buffer gas (replacement for leakage)	4.5

A tentative design has been specified, based on centrifugal compression of Martian air, separation of buffer gases argon, Ar and nitrogen, N_2, and feeding of compressed carbon dioxide, CO_2 together with hydrogen, H_2 from a supplied storage unit into a Sabatier reactor. The Sabatier reactor produces water and methane, CH_4. The CH_4, together with the N_2 and Ar, are cryocooled and stored as liquids in surface tanks. The water is electrolysed to oxygen, O_2 and H_2. The H_2 is recycled back into the Sabatier reactor to maximise hydrogen leveraging. The O_2 is passed through a countercurrent heat exchanger with H_2 from the liquid H_2 tank, which cools the O_2 for minimum power expended, and raises the H_2 temperature to that required by the Sabatier reactor.

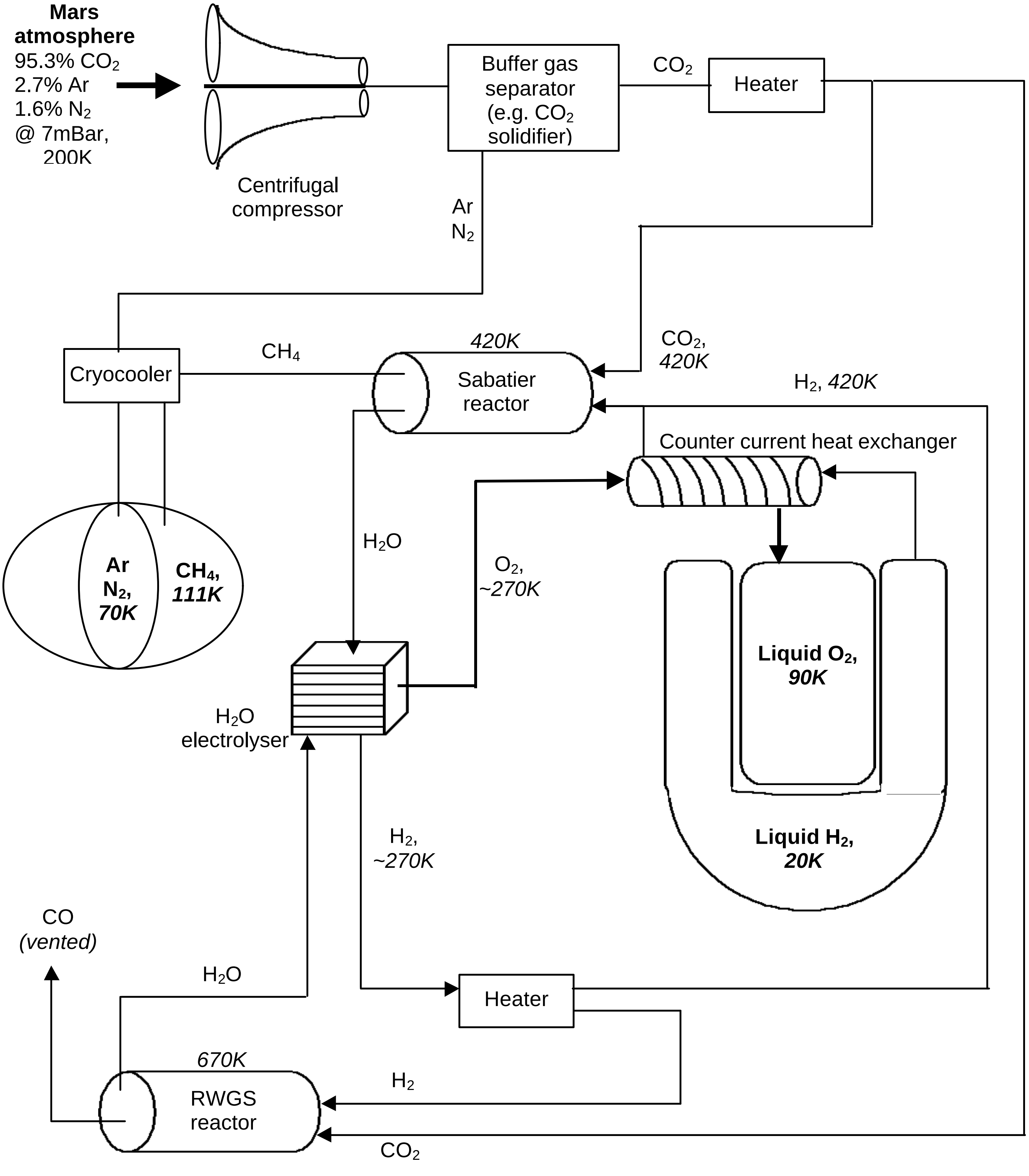
Additional oxygen can be generated by either the reverse water gas shift (RWGS), which converts CO_2 to water without losing H_2 as CH_4; or by catalytic or thermal decomposition of CH_4, or by high temperature direct reduction of CO_2, e.g. solid oxide electrolysis.

The key ISRU technologies which need to be assessed and developed further are:

- Additional oxygen production, RWGS, methane reduction, or direct CO_2 reduction
- Buffer gas separation
- Martian atmosphere collection and compression: lightweight, compact compressor
- Low power, lightweight cryogenic coolers

There does appear to be good potential for reducing the power required for manned mission ISRU below the 50kWe estimated by current NASA studies. Tentative estimates (which are highly dependent on the reaction chemistries selected) are between 31 and 38kWe, slightly less than the minimum NASA estimate of 40kWe. As low as 28kWe might be possible, although this is speculative within the 15 months available to manufacture the consumables needed.

A schematic of the currently preferred reactions for ISRU in the context of this study is given below:



8.3 Materials, structures, thermal control

Materials and structures, and the related issue of thermal control are clearly of great importance to efficient power generation and storage on the surface of Mars. Unfortunately there was little opportunity to explore them within the scope of this study due to its already broad nature.

However, some note needs to be made of certain assumptions on which the parametric models used to derive the study results were based, as these are related to materials, structures and thermal control. In particular:

- The deployment of vertical axis wind turbines and circular or tent shaped solar array modules (Section [6.1.1]) will demand light, stiff strut and tube structures. Composite materials present, made for example by filament winding present an ideal solution. However the application of composite materials on Mars has received little consideration in the open research literature. Further research is recommended.
- Inflation mechanisms for solar arrays are a relatively new technology, but show great promise for reducing solar array mass, whilst potentially easing deployment of large arrays over irregular ground. Inflation technology, and gas bladders in particular could also be employed to store gases such as hydrogen and oxygen, either as reactants for fuel cells or for other uses such as lifting. Inflation bladders and materials are clearly beneficial and multiple use technology worthy of further consideration.
- The thin film Copper Indium diSelenide photovoltaic cells which might make large scale solar power generation on the Mars surface are dependent on a suitable substrate. Lightweight, strong and robust polyimide membranes with a mass as low as 0.2kg/m^2, and stainless steel are undergoing extensive development at AFRL in the USA. Europe lags behind in this area, and should consider investment if solar-electric systems are to be specified for the Mars surface.
- Insulation for batteries and fuel cells will be required to prevent temperatures less than –40°C being reached, as this limit has been set by the parametric models. Numerous lightweight, low thermal conductivity materials have potential for battery insulation, for example silica aerogels. Detailed requirements for thermal control materials and appropriate European expertise needs to be determined.
- Heat rejection for power management systems, nuclear reactors and EVA suits will be critical on the Mars surface where large temperature swings occur, but conduction, convection and radiation are available heat transfer mechanisms. More detailed parametric modelling than was possible in this study will be needed to ensure confidence in subsequent designs.
- High temperature, long lifetime materials for nuclear power systems with high reactor outlet temperatures have been developed in the USA, e.g. for the SP-100 programme. These allow greater power conversion efficiencies and a wider range of reactor subsystem options. Europe has an inferior technology base where high temperature space reactor systems are concerned, consideration should be given to whether development is merited in this area.

9 Summary table of power system options

	Power system	**Mass** (total power system, kg)	**Area** (array, m^2)	**Volume** (power storage system, m^3)	**Risk**
		Current – future technology			
Static elements					
ISRU plant + Greenhouse	Nuclear	670-740 (ex-shield)	No array	1.18 (ex-shield)	Development cost, shield construction, political acceptability
	Solar-electric, OD 1 *(OD 3)*	3200 – 11650 *(5000-20000)*	2270 – 4450 *(6600-13000)*	<1.0 *(est.)* – 2.6	Power limited, energy storage limited, large deployed area, cell performance.
	Solar-wind-electric *(OD 3)*	8700 – 15800	2850 - 5600	0.6 + 1.5-8.0 (hydrogen for balloons)	Wind energy viability, general deployment
Mobile elements					
Micro inspection rover	Solar-electric (day) + fuel cell for night op'n	1.9-3	0.25-0.4, body mounted	0.1-0.14 $x10^{-3}$	Power limited: Increased size for dust storm day operation
Autonomous research island – nano rover	- Tether - Primary / secondary battery - Micro fuel cell	Not evaluated in detail			More detailed requirements needed.
Long range exploration rover	Solar electric – fuel cell – battery *(OD 0.5)*	16-36	2.2-3.3, deployable	$8.5\text{-}33 \times 10^{-3}$	Energy limited, Solar array deployment / retraction in motion
	Solar electric – fuel cell – battery *(OD 3.0)*	26-62	6.9 min, deployable	$8.5\text{-}33 \times 10^{-3}$	
Drilling station	Solar electric – fuel cell	150-315	25 min.	$80\text{-}300 \times 10^{-3}$	Power limited by array, array deployment, provision of reactants for fuel cell
MPL (primary)	PEM fuel cell, LOX + CNF H_2 reactant store	710 (uses in situ O_2) – 2300 (on-board LOX)	No array	2.0 (on board LOX)	Energy limited. Carbon nanofibre storage of H_2 uncertain, in-situ Martian O_2 extraction uncertain
MPL (auxiliary)	Li-ion rechargeable battery	134	Optional, for later recharging	61×10^{-3}	Battery discharge en route to Mars, availability in large size.
Utility truck (primary)	PEM fuel cell, LOX + CNF H_2 reactant store	355 (uses in situ O_2) – 1200 (on-board LOX)	Array only for backup	1.02 (stored LOX), or 0.37 (in situ O_2)	As per MPL.
U/T backup	Regenerative Fuel cell + solar array	270	62 (floor of U/T)	0.46	RFC technology, array robustness

10 Technology development suggestions

In the Short term, over the next 5 years, it is recommended that Europe concentrate on:

1) Testing of current state-of-the-art (SOA) PV array systems using high efficiency (GaAs based, or crystalline Si Hi-ETA and LILT) cells, under simulated Martian conditions – low solar flux, diffuse lighting conditions, low and variable temperatures and after dust deposition.

   CIS cell manufacturing facilities are needed, with a view to enabling production of large area arrays. Investigation of inflatable arrays for deployment of large areas both in space and on planetary surfaces should proceed in parallel.

   Alternative, non-nuclear methods of power generation should focus on the addition of wind generators to solar-electric systems in order to provide power during dusty periods when solar array efficiency is drastically reduced. The use of the Mars diurnal temperature variation to generate power using subsurface heat exchangers should also be studies carefully, particularly if more efficient means of extracting the thermal energy (than thermoelectrics) can be applied.

2) Power management and distribution is a required supporting technology. Planning for component development and qualification for higher voltage (>120V, ideally 600V or more) operation is needed. Establishing detailed PMAD requirements, and performance figures for available and near-term development systems is required. Evaluating the applicability of European high temperature superconductor technology, for use in power transmission cables should also be performed.

3) Power storage system development in the short term should focus on batteries and fuel cell systems. The latter need to be (a) tolerant to CO_2 and CO, (b) integrated into combined heat and power systems, and (c) optimised for performance under Mars environmental conditions. A means of improving efficiency beyond the ~65% limit for hydrogen-oxygen should be sought, perhaps using alternative chemistries. Li-ion secondary battery technology is proceeding rapidly, although optimised performance at –40°C, operation (even if degraded) at –80°C, in space testing of battery systems with an energy density of 150Wh/kg, and improvements in cycle life to at least 1000cycles are needed.

   The flywheel has considerable potential, possibly as high as three times the energy density of Li-ion batteries, with a wider operating temperature range and a longer cycle life. European flywheel technology has to date been wholly developed for terrestrial needs but should be considered for planetary surface usage.

   An evaluation of the suitability of thermophotovoltaics to Mars surface mission elements with a range of energy needs, and a means of providing the required fuel and oxidiser is recommended.

4) Excavation and earth moving techniques, applicable to habitat construction / reactor shielding and powerplant erection and support need to be tested on Earth in Mars analogue environments.

5) Active thermal control systems, in particular low energy, low mass cryocoolers are required for liquefaction of propellants, oxidisers and life support gases.

   However for the robotic exploration missions under development at present, technology development should be focussed on passive thermal control systems using lightweight materials and structures. Power limitations in the short term will probably prevent use of active thermal control systems. Coatings with a wide range of absorptivities/emissivities are desirable to compensate for the wide diurnal temperature variation on Mars; as are aerogel based insulation materials. Aerogels have been developed in Europe, but may not necessarily have been widely considered by the space industry.

6) The availability, in Europe, of space rated liquid hydrogen storage vessels capable of storing at least 30000litres and preferably 60000litres, for long term containment during a transit to Mars (~6mths), and then for 12-15mths on the surface of Mars will need to be evaluated. These dewars will also need to be robust enough to survive a Mars landing with minimal loss of contents. Terrestrial technology is currently too heavy, although NASA studies suggest that reducing dewar and hydrogen content mass to the capacity of an Ariane V++ to the surface of Mars may be feasible, although development is likely to require 5-10 years if Europe determines it requires an independent capability in this area.

7) Novel methods of powering mobile mission elements with power needs in the 100-1000W regime need to be assessed in detail. Deployable / inflatable solar arrays, gas balloon / inflatable bladders storage of hydrogen/oxygen reactants for fuel cell power, and energy efficient means of reducing CO_2 to CO and O_2 are options. Scaling of hydrocarbon (methanol / diesel) reformers, and detailed models of mass, size and power may be required if such vehicles are to be powered by hydrocarbons rather than fuel cells. In this case, means of supplying hydrocarbons on the surface of Mars need to be determined.

   A more detailed examination of both life support and thermal control requirements for an manned Mars based is needed. This could not be conducted within the budget of this study, but is necessitated by the extreme conditions on the Mars surface.

   A primary life support systems objective should be to establish a realistic energy budget for EVA activities on the Mars surface. Resolving whether N_2 and Ar mixtures are safe to breather over long periods on the Mars surface is also necessary.

8) ISRU technology subsystem design and testing forms a key part of manned Mars mission planning because of he mass leveraging it offers. Subsystem development needs to begin now in order to design, build, test and qualify systems for the 2020-2030 timescale.

   Initially, a more detailed system study should aim to select the critical chemical reactions and the technology needed to carry them out efficiently, produce a thermal balance and estimate the mass and volume for a prototype ISRU plant.

   Subsystem development activities should focus on areas not being considered by NASA, including: Lightweight CO_2 collection / compression technology, N_2/Ar separation systems, and alternatives to the reverse water gas shift reaction for additional oxygen generation, e.g. catalytic decomposition of methane. Breadboard tests are to be instigated as soon as possible.

9) Nuclear power systems development should focus on refining the system designs developed in *Technical Note 3*. In the short term it would be premature to select between either the liquid metal cooled or gas-cooled reactor options as both are attractive for particular operating regimes. For example, the NaK cooled reactor moderated with ZrH_2 offers the prospect of a low mass system but is restricted in its maximum operating temperature. Higher operating temperatures are possible with a

gas-cooled system but at the expense of increased system mass. In both cases further research to optimise subsystem performance and establish component selection criteria are recommended.

A significant conclusion from the study has been that both reactor systems benefit significantly, in terms of efficiency, from using a dynamic Brayton cycle and rejecting waste heat using the Martian atmospheric CO_2. Such a forced convection blower heat rejection system has been demonstrated in theory and at subsystem level within the study. However, a number of assumptions needed to be made when calculating heat transfer and pressure loss properties required to size the heat exchanger because of the lack of real data. Consequently, small scale heat transfer and pressure loss experiments at low Reynolds numbers should be made to enable the validation of existing transport models, increasing confidence in the current design.

At the same time the feasibility of other power conversion systems should continue to be examined, particularly concerning reliability. Reliability will be important in determining whether static systems (lower efficiency but higher reliability, currently) will be preferred over dynamic systems (higher efficiency but uncertainties over long term reliability). However it should be noted that many of the components such as pumps, compressors, fluid loops and generic rotating machinery which a dynamic cycle power converter will require are also essential to ISRU operation, therefore confidence for the Mars surface will have been developed prior to reliance on a nuclear power source.

The synergy with nuclear electric and nuclear thermal propulsion systems should also be estimated. In fact, electric propulsion is another application for nuclear reactors. The best would be a dual-use reactor system that can fulfil both planetary surface and propulsion missions. If such a system feasibility has to be proven, we also can imagine that this system will not have the best design for planetary surface operation or the best design for propulsion. It will be a compromise with different missions requirements. Nevertheless, there will be likely common technologies. It is necessary to identify them and these technologies could lead to design options for the both applications.

Safety issues, which will be key to the acceptability of nuclear power systems in space, should be further addressed. This should be performed within the context of the Mars exploration scenario where the clear benefits of nuclear power systems can be demonstrated.

In addition, validation of the model used to derive minimum radiation shield thickness will need to be carried out. This is dependent on a better understanding of the Martian regolith characteristics at future manned mission landing sites, which is in turn reliant on the success of future robotic Mars landers.

9) Cost models should be developed which can be used as a ranking parameter in determining the preferred technologies for safe, efficient and timely human exploration of Mars. Historically, the space industry has been poor at estimating development costs, and often does not make use of sufficient already developed terrestrial technology. This will need to change, an example being the use of terrestrial Li-ion cells in spacecraft, demonstrated by DERA (QinetiQ) on the STRV microsatellites, and thus validating a new space power source at a considerably lower cost than, for example, the development of NiH2 cells. Mars technologies will need to be selected also on the basis of their wider applicability (as stated in *Technical Note 2)*, if the costs of a Mars mission are not to become prohibitive.

   Four proposals for near term study activity and small scale technology development have been made separately to ESA. These address some of the key questions which have been raised in this study, and should be seen as a means of maintaining momentum prior to the commencement of more in-depth activities under Aurora.

   Long term technology development (5-30 years timescale) plans will need to be prepared once the S51, S54 and S56 studies have all completed.

In the Medium term, over the next 5-15 years, Europe should focus on

1) ISRU system design and terrestrial breadboarding will need to be taken further, towards a scaled down system which can be demonstrated on a robotic Mars lander. It is recommended that an integrated system, employing CO_2 collection, a hydrogen dewar, a Sabatier reactor, a water electrolysis unit, buffer gas separation, additional oxygen generation and cryocoolers / storage dewars for CH_4, N_2, (Ar), O_2 and H_2O should be assembled and run in a simulated Martian atmosphere (impure CO_2, to evaluate the effect of impurities) as early as possible.

2) If a conscious decision is taken not to develop a surface nuclear power plant technology for powering human / energy rich expeditions to Mars, Europe will require solar array systems capable of reliably generating 100kWe on the Mars surface under OD 3.0 or greater conditions, and with mass not exceeding the capacity of a single Ar V++ launch to the Mars surface. CIS cells capable of being fabricated over a large area, with lightweight flexible backing, minimal protection and high efficiency will likely be critical to this. The development of a suitable deployment mechanism and dust mitigation methods will also be essential support efforts.

   To render solar array design studies for the Mars surface of use, an accurate model of the Mars surface solar flux variation and weather (dust storm) patterns will be needed. This will enable optimisation of array size. However a careful risk assessment of reliance on solar arrays will be needed.

3) In a non-nuclear scenario (which is unlikely to be energy rich) supporting technologies for photovoltaic power generation will also need to be given considerable development support. Geothermal energy, power beaming from space, and temperature gap utilisation need to be re-examined. Detailed wind profiles for preferred landing sites need to be compiled, culminating in a Mars surface test of a wind generator.

4) Power management and distribution needs in the medium, and long term, are the ability to operate at terrestrial voltages on the Mars surface (>1000V), efficiencies in the 95% region, and low parasitic masses and powers. Exact performance goals will be established by earlier study work.

5) Advanced hydrogen and oxygen storage for fuel cells, in particular focussing on carbon nanofibres as a non-cryogenic, high density means of storing hydrogen. The system should be capable of providing up to 3MWh, for a total system mass of <2t. Low loss portable dewars capable of storing 140kg of hydrogen and 1000kg of oxygen in liquid form (sufficient for a 3MWh endurance) should also be investigated for mobile applications, in the event that carbon nanofibres do not prove to be practical. Small fuel cell systems for EVA units, capable of delivering 2.4-3kWh for a total system weight (on Mars) of <2.5kg will also be required, to compete with Li-ion battery systems.

6) Li ion batteries with a cycle life exceeding 6000cycles will be need to support a 10 year programme of manned missions. An energy density exceeding 300Wh/kg, and a specific energy approaching 700Wh/kg should be sought. Achieving this performance below –40°C will be a requirement.

7) Flywheel power storage systems, as a long life, high energy density, more scalable alternative to Li-ion batteries should be given serious consideration, provided that they can survive launch, transit to Mars, and a surface landing.

8) A means of reducing CO_2 to CO and O_2, without reliance on high energy consumption, structurally weak ceramic reactors will need to be found, if long range surface mobility is to be achieved. Currently the reliance of fuel cells on stored hydrogen and oxygen limits the range / endurance of mobile mission elements due to the bulk and mass of storage vessels required. Fuel cells which can operate at high temperature, generating useful heat, and are tolerant or can even use CO/CO_2 are highly desirable. The technique of photocatalytic decomposition of CO_2, covered in *Technical Note 2*, should also be reviewed in this timescale.

9) Active thermal control systems able to deal with several kW of rejected or required heat will be needed for energy rich robotic missions immediately preceding human exploration. Design and research should be carefully integrated with systems requiring high temperature operation, e.g. Na-S and Zebra batteries, and solid oxide fuel cells.

10) A nuclear reactor system capable of being tested on Earth in conditions representative of the surface of Mars, generating an electrical power of at least 50kW. This demonstration system must satisfy all operational requirements and must clearly demonstrate all safety issue including launch safety and disposal. If nuclear electric or nuclear thermal propulsion is a pursued option, a test on Earth has to be also performed. Provision for a space test should be made. Safety issues will be critical in planning the details of such a space test.

In the Long term, 15-30 years from now, European technology needs are likely to be:

1) In a nuclear scenario, development and a full space test of <u>a nuclear reactor system</u> capable of producing at least 50kWe, and preferably 200kWe of power after a landing on the surface of Mars will need to occur. Supporting robotic systems capable of erecting a man-rated radiation shield effective at 100-200m distance, using Martian regolith; and linking to other static mission elements for power distribution will be required.

2) The <u>nuclear reactor should be linked to an ISRU system</u>, to approximate as closely as possible the operation of these two key mission systems, in a manned Mars exploration scenario.

3) A <u>demonstration of power beaming</u> to the Mars surface should be considered, as a backup to the primary power system. This could also be integrated with a solar or nuclear electric propulsion system for transporting goods on low energy trajectories to Mars.

4) <u>Microturbines</u> for portable power applications, currently little more than a laboratory curiosity, may have demonstrated viability during the 2001-2010 period. Therefore this timeframe may be appropriate for investment in this technology with a view to particular missions.

5) On a broader scale, <u>integrated system tests of key technologies</u> developed during the 2001-2015 timeframe (‘near-‘ and ‘medium-term’) should validate performance, reliability, cost and technology readiness, in preparation for a commitment to a human Mars exploration mission sometime post-2025.