SETTLING SPACE

HUMAN SETTLEMENTS IN THE SOLAR SYSTEM AND BEYOND

IN SUPPORT OF A PURPOSEFUL,
GOAL ORIENTED HUMAN SPACE PROGRAM

JOHN K. STRICKLAND JR.

WITH **SAM SPENCER**

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Co-Author: Sam Spencer

Special Art: Anna Nesterova

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V. Mars In-Situ Resource Utilization

An overview of the important requirements of In-Situ Resource Utilization (ISRU) can be seen in CHAPTER 3 (Asteroids), section III. To be self-sufficient and minimize the risk of Mars settlement or operational failure, a certain portion of essential material requirements must be produced directly on Mars. This is not a unique thought, and the same basis of development on Earth can be applied to Mars. The closer any settlement is to important resources, or to key trade or transport routes, the more well-equipped the settlement will be to handle accidents or unforeseen circumstances, and to grow and prosper accordingly. As shown in CHAPTER 3 (Asteroids), section III, ISRU production can essentially be broken down into the following major production areas:

- Life Support Requirements – Water, Oxygen, Hydrogen, Nitrogen, Phosphorus, Potassium, etc.
- Propulsion Requirements – Oxygen, Hydrogen, Carbon Dioxide, Hydrocarbons, Alcohols, Oxidizers, etc.
- Structural / Manufacturing Requirements – Plastics, Rubbers, Concretes / Cements, Metals, Glass, Ceramics, Bricks, Composites, etc.

But how can these materials be produced on Mars?

A. The Resources of Mars

As previously described Mars is the most likely off-earth settlement as:

- Temperature extremes are much less than many other locations.
- Mars has a thin atmosphere that provides some radiation protection, and can be used as a major feed-source for ISRU (carbon and oxygen).
- Mars gravity is probably sufficient for long-term human habitation but this is not yet proved.
- There is enough sunlight for solar energy production requirements and plant growth.
- Water is known to be available directly under the surface in many locations. More than half the surface area of Mars carries a permafrost layer that is rich in water.

The main characteristics of Mars can be seen summarized in the table below, compared to Earth. Also included in the table are the main raw components that can be put to use for ISRU processing and material production.

Table 2.1: Comparison between Earth and Mars

Description	Unit	Mars Value	Earth Value
Climate (Williams D. R., 2016) (Williams D. , Mars Fact Sheet, 2016)			
Temperature	K	140 – 300	200 – 320
Pressure	Pa	600	101,300
Gravity	m / s2	3.711	9.807
Rainfall	mm / earth year	0	0 – 10,000
H2O Snowfall	mm / earth year	0	0 – 15,000

Description	Unit	Mars Value	Earth Value
CO2 Snowfall	mm / earth year	<100	0
Average Wind Speed	km/h	8 – 26	0 – 360
Atmospheric Composition (standardized to 100%) (Williams D. R., 2016), (Williams D. , Mars Fact Sheet, 2016)			
CO2	%v/v	95.46	0.04
N2	%v/v	2.71	78.08
Ar	%v/v	1.60	0.09
O2	%v/v	0.13	20.95
CO	%v/v	0.08	0.00
H2O	%v/v	0.02	0.84
TOTAL	%v/v	100.00	100.00
Regolith Composition (average, oxide basis – NOT mineralogy) (standardized to 100%) (L. W. Beegle, 2007) (Clarke & Washingtion, 1924) (Stoker, et al., 1993) (Allen, Morris, Lindstrom, Lindstrom, & Lockwood, 1997) (Neal-Jones, Zubritsky, Webster, & Martialay, 2013)			
SiO2	% by weight	43.90	60.00
Fe2O3 and FeO	% by weight	18.10	7.00
Al2O3	% by weight	8.10	15.50
MgO	% by weight	7.10	4.00
CaO	% by weight	6.00	5.00
Na2O	% by weight	1.40	3.50
Cr2O3	% by weight	0.20	0.01
K2O	% by weight	0.50	3.00
TiO2	% by weight	0.60	0.80
SO3	% by weight	7.00	0.00
CO3	% by weight	3.00	0.00
Cl	% by weight	0.50	0.00
Water (LOI minus CO2/SO2)	% by weight	3.60	1.19
TOTAL	% by weight	100.00	100.00

For regolith in particular, it is important to note that the composition of Mars surface soil (regolith) is extremely consistent over the majority, but not the entirety of the whole surface, as quoted by Laurie Leshin (Neal-Jones, Zubritsky, Webster, & Martialay, 2013):

> "Mars has kind of a global layer, a layer of surface soil that has been mixed and distributed by frequent dust storms. So a scoop of this stuff is basically a microscopic Mars rock collection," said Leshin. "If you

> mix many grains of it together, you probably have an accurate picture of typical Martian crust. By learning about it in any one place you're learning about the entire planet."

In saying this though it is important to note that scientists are aware of certain surface deposits that will be more useful for processing into usable products, including (Ehlmann & Edwards, 2014) (Forni, et al., 2014) (Meslin, et al., 2016) (Abbud-Madrid, et al., 2016) (Niles, et al., 2013) (Stern, et al., 2015) :

- Mars Ice – Essential pure water with some solid and dissolved impurities.
- Mars Poly-hydrated Sulfate – Magnesium sulfate minerals with a higher proportion of gypsum then normal regolith, this provides an important source of calcium (for industrial processing) and Sulphur (for plants). This ore type also has the second highest concentration of water, and can be seen as an emergency backup water supply if the ice supply in a certain area is limited.
- Mars Clay – Higher proportion of Smectite, a clay mineral (seeTable 2.3).
- Mars Carbonates – High concentration of carbonates.
- Mars Spherules – High concentration hematite balls, identified in the media as ‘blueberries’, which are generally 100 to 250 micrometers in diameter (see Figure 2.6). The concretions tend to show up in images as bluish in comparison to the reddish Mars surface color.

Figure 2.6: Mars ‘blueberries’ as photographed by the MER Opportunity at Meridiani (NASA/JPL-Caltech/Cornell/USGS, 2004)

These are further detailed in the next table, with author estimations on unknown constituents (see Notes). Values of interest are highlighted.

Table 2.2: Potential Mars Deposits

Description	Unit	Mars Regolith	Mars Ice	Mars Poly-hydrated Sulfate (Note 2)	Mars Clay (Note 2)	Mars Spherules	Mars Carbonates
SiO2	% by weight	43.90	4.55	24.21	38.30	5.36	19.15
Fe2O3 and FeO	% by weight	18.10	1.88	11.90	16.60	90.00	26.20
Al2O3	% by weight	8.10	0.84	5.96	9.93	0.99	3.53
MgO	% by weight	7.10	0.74	4.15	11.17	0.87	23.67
CaO	% by weight	6.00	0.62	16.39	4.68	0.73	4.25
Na2O	% by weight	1.40	0.15	0.73	0.97	0.17	0.61
Cr2O3	% by weight	0.20	0.02	0.10	0.10	0.02	0.09
K2O	% by weight	0.50	0.05	0.25	0.25	0.06	0.22
TiO2	% by weight	0.60	0.06	0.30	0.31	0.07	0.26
SO3	% by weight	7.00	0.73	22.14	5.22	0.85	3.05
CO3	% by weight	3.00	0.31	1.51	1.53	0.37	17.18
Cl	% by weight	0.50	0.05	0.43	0.44	0.06	0.22
Ni (Note 4)	% by weight	0.00	0.00	0.09	0.09	0.00	0.00
F (Note 1)	% by weight	0.00	0.00	0.20	0.00	0.00	0.00
N (Note 3)	% by weight	0.11	0.01	0.06	0.06	0.01	0.05
Water (LOI minus CO2/SO2)	% by weight	3.49	90.00	11.57	10.34	0.43	1.52
TOTAL	**% by weight**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
Likely Availability for ISRU	Low / Medium / High	High	High	Medium	Medium	Low	Low

Notes:

1. Data from recent releases (Forni, et al., 2014) (Meslin, et al., 2016) indicate that fluoride is available on Mars, for this estimate it has been assumed that minimum detection is at 0.5% fluoride, in the form of fluorite, and is embedded within gypsum mineralogy (itself a percentage of total regolith).
2. Mineralogy from (Abbud-Madrid, et al., 2016) , with makeup of Mars Regolith. Smectite is assumed as saponite for calculation purposes.
3. Estimated from Stern (Stern, et al., 2015) in Mars regolith only.

4. As nickel/cobalt appears to be difficult to find, it is possible that specialized robotic vehicles can be used to collect metallic (iron or stony iron) asteroids that have landed on Mars. Multiple of these type of asteroids have been identified on Mars by the Mars Rover.

The mineralogy of the Martian surface has been defined as follows (Abbud-Madrid, et al., 2016) .

Table 2.3: Martian Surface Mineralogy

Type	Class	Type and Name		Color	Description
Primary	Framework Silicates	Mineral	Olivine	Olive-green to reddish	Mg2SiO4 (Forsterite) to Fe2SiO4 (Fayalite). This is a common mineral on Earth but wears quickly on the surface.
		Mineral Class	Orthopyroxenes / Cllinopyroxenes	Multiple, depending on elements.	Silicon oxide minerals low in Ca and high in Mg and Fe
		Mineral	Plagioclase (Anorthite, etc)	White or grey	Mixture of Anorthite(CaAl2Si2O8) and Albite (NaAlSi3O8). The most common of the rock forming minerals.
		Mineral Class	Alkali Feldspars		Mixture of Na, K, Al silicon oxide minerals. Crystallized from magma as veins in rocks.
	Sulfides	Mineral	Pyrrhotite	Bronze, dark brown	FeS. A common occurrence in sulphide rocks.
		Mineral	Pyrite	pale brass-yellow	FeS2, commonly called Fools Gold due to looking similar to gold.
	Oxides	Mineral	Magnetite	Black, Grey	Fe3O4. One of the main iron ores on Earth. The most magnetic naturally occurring mineral on Earth.
		Mineral	Ilmenite	Iron-black, gray	FeTiO3. The most common mineral for production of titanium on Earth.
Secondary	Oxides	Mineral	Hematite	Metallic gray, dull to bright red	Fe2O3, Mined on Earth as the main ore of iron.

Type	Class	Type and Name		Color	Description
		Mineral	Goethite	Yellowish, reddish, dark brown, black	FeOOH. Commonly used on Earth as a pigment.
		Mineral	Akaganeite	Yellowish brown, rusty brown	Fe(O,OH,Cl). Formed by the weathering of pyrrhotite.
	Phyllosilicates (clay minerals)	Mineral Group	Fe/Mg/Al Smectites	White, pale pink, blue, yellow, red, green, depending on elements	Most common is Montmorillonite, commonly called clay.
		Mineral Group	Kaolin Group Minerals	White, with red, blue, brown tints from elements.	Al2Si2O5(OH)4 repeating. Most common clay in hot moist climates on Earth.
		Mineral Group	Chlorite	Various shades of green; rarely yellow, red, or white	Complex aluminum silicates with Mg, Fe, Ni, and Mn.
		Mineral Group	Serpentine	Green, brown.	Complex silicon oxide hydroxides containing Mg, Fe, Ni, Mn, Al, Zn, etc.
	Other Hydrated Silicates	Mineral	Prehnite	Colorless, gray, yellow, yellow-green, white	Ca2Al(Si3Al)O10(OH)2. Can be used as a gemstone.
		Mineral	Analcime	White, gray, colorless, pink, greenish, yellowish	NaAlSi2O6.H2O. Commonly formed from cooling magma.
	Carbonates	Mineral Group	Mg / Ca / Fe Carbonates	Multiple, depending on elements.	CaCO3, MgCO3, FeCO3, etc Used on earth to neutralize acidic solutions or in construction.

Type	Class	Type and Name		Color	Description
	Sulfates	Mineral Group	Kieserite / Mg-Polyhydrated Sulfates	colorless, grayish-white , yellowish	MgSO4.H2O. Commonly occurs on Earth in evaporated water salts, and rarely in volcanic environments.
		Mineral	Dihydrate / Anhydrate Gypsum	Colorless, white, tinted depending on element.	CaSO4.2H2O, CaSO4. Common mineral in sedimentary rocks, used in agriculture and construction.
		Mineral	Alunite	Yellow, red, to reddish brown, colorless	KAl3(SO4)2(OH)6. Valuable ore for aluminum and potassium.
		Mineral	Jarosite	Amber yellow, dark brow	KFe3(OH)6(SO4)2. Common in sulfide minerals.
	Chlorides	Mineral Group	Chlorides	Multiple, depending on elements.	MgCl, CaCl, NaCl, etc. Common salts found in water and crystallized from evaporated solutions.
	Perchlorates	Mineral Group	Perchlorates	Multiple, depending on elements.	Chloride oxide salts. Commonly used as a propellant.

A.1 Mineral Deposit Locations

It also should be clearly noted that there are significantly large areas where the typical, uniform regolith does not exist at the surface, such as Meridiani, Columbia Hills in Gusev crater, and in parts of Gale Crater, where the mineral abundances and rock types are very different. The surface composition in any crater which used to have a lake in it and was filled with sediments would be different from the typical regolith. There are other smaller areas, such as those being investigated by the Mars rovers, which show unusual minerals in localized areas. These can include dried-up lake beds which could have mineral salt deposits, and areas of ancient hot springs with probable high silica concentrations.

Due to the probable lack of plate tectonics over most of Mars, but noting that volcanism and ground water seem to have existed during most of Mars geological history, it is reasonable to assume that there will be localized minteral deposits created in the past by hydrothermal fluids (volcanically heated water with dissolved minerals in it), but there will not be the ultra-processed type of deposits that require multiple geological events to create. The diversity if ores may be less and certain ores associated with plate tectonics, like those for copper, may be hard to find. Just like on Earth, many mineral deposits are not always obvious from the surface. On Mars, this can be an even greater problem due to the Mars dust which coats much of the surface, hiding the rocks and mineral types below. The presence of multiple water-altered minerals like the hematite "blueberries" show that the ground water was active in the crust, and volcanic heat would make it much more active.

It is probable that no settlement site will have all of the mineral resources it needs relatively close to it. That means that there will eventually need to be mining operations at locations far away from settlement sites, which could turn into minng towns. Earth has had long distance trading networks in both hemspheres, even in the new world where wheeled vehicles were unknown, and where copper and obsidian were moved over thousands of miles. Mars would be no different. A good example of one such site is the Eridania Basin, in a southern hemisphere area that has some of the most ancient crust on Mars. This is composed of a multiple, semi-overlapping set of about 5 old impact basins from almost 4 billion years ago. These are in a depression that once held 210,000 cubic kilometers of water (more than there is in the Caspian Sea), and formed a very large paleolake or fresh water sea, that was up to 1.5 km deep and ice-covered at times. The water from this sea once flowed north via the Ma'adim Vallis channel through Gusev crater on its way to the Boreal Ocean. About 3.7 billion years ago, there was active tectonics in the area, with extensive sea floor hydrothermal activity, resulting the the depotsition of multiple minerals on the sea floor. These include chlorides, sulfates, iron and magnesium minerals, talc, carbonates, serpentine, and silicates. The detection of serpentine could indicate significant tectonic activity, bringing rock up from deep in the crust, or it could have been merely coverted from olivine minerals in basalt (Joseph R. Michalski, 2017) . There may be other similar areas, but much of Mars surface is much younger and may not have had the same level of extensive volcanism and tectonics in the presense of water.

Based on the data shown in the previous two tables it can be identified that he following Mars surface deposits can be used to produce settlement requirements:

- Life Support Requirements:
  - *Water for propellant, plastics, oxidizer and life support production:*
    - Mars Ice
    - Mars Poly-hydrated Sulfate
    - Mars Clay
  - *Oxygen can be produced via the electrolysis of water.*
  - *Nitrogen for fertilizer and life support production:*
    - Mars Regolith
  - *Sulfur for fertilizer and sulfuric acid production for industrial processes*
    - Mars Poly-hydrated Sulfate
  - *Phosphate for fertilizer:*
    - Availability Unknown
- Propulsion Requirements:
  - *Carbon for propellant and plastics production:*
    - From the atmosphere
    - Mars Carbonates (limited areas)
    - Recycled from human waste
  - *Superheated water can also be directly used as a propellant.*

  - *Water and carbon can be used to produce oxygen (via water electrolysis) and either hydrogen (via water electrolysis) or methane (via carbon dioxide and hydrogen using Sabatier reactor)*
- Structural / Manufacturing Requirements:
  - *Iron for structures:*
    - Mars regolith
    - High iron oxide areas like the Mars “blueberry” spherules as at Meridiani
  - *Nickel and Cobalt for stainless steel structures:*
    - Possible collection of iron / stony iron asteroids that have landed on Mars.
  - *Silicon for solar panels:*
    - Mars Regolith
    - Silica deposits
  - *Germanium and other specialty semi-conductors for silicon panels:*
    - Unknown
  - *Aluminum as light metal for structures:*
    - Mars Regolith
    - Mars Clay
  - *Magnesium as light metal for structures:*
    - Mars Poly-hydrated Sulfate
  - *Titanium as light metal for structures:*
    - Mars Regolith
  - *Platinum Group Metals, only material likely to be sent back to Earth:*
    - Unknown
  - *Plastics and complex organics via additional processing of carbon and hydrogen produced in first steps.*

- Terraforming Requirements for future use:
  - Fluoride / Fluorite
  - Sulfur / Poly-hydrated Sulfate

B. Resource Definition

Based on the complete list of Mars ore types identified in Table 2.2, and knowing that both Mars Regolith, and the high carbon dioxide Mars atmosphere is available at all locations, the most important near term ore types to identify and locate would be:

- Mars Ice, for the production of water, oxygen, hydrogen and methane
- Mars Poly-hydrated Sulfate for sulfur, and if ice is not available (second best source).
- Minerals with higher levels of Nitrogen for making air and for plants
- Iron oxide, hematite or other iron ore for structural component production.

Using air-borne surveys likely locations can be identified on Mars that have large deposits of these materials in close proximity. After an initial survey, the top five likely locations will then need to be surveyed in-situ, likely via robotic autonomous or remotely controlled vehicles with drilling rigs, analyzers, etc. These surveys may take years, and require multiple vehicles. The accuracy of the definition of the resource (location, amount, depth, purity and concentration) could make or break the settlement. In the global mining industry two main standards are used to define this accuracy: National Instrument 43-101 (Canada) and the Joint Ore Reserve Committee (JORC) code (Australasian). In principle most of the codes/standards are very similar in relation to actual resource definition and classification (Ramcharan, 2016) (Noppe, 2014) :

- Mineral Resources are resources that are potentially valuable, and have a reasonable prospect of being profitable after extraction / treatment.
- Mineral / Ore Reserves are valuable and are technically feasible to economically extract.

The JORC code has the following useful diagram to explain the differences (JORC, 2012) :

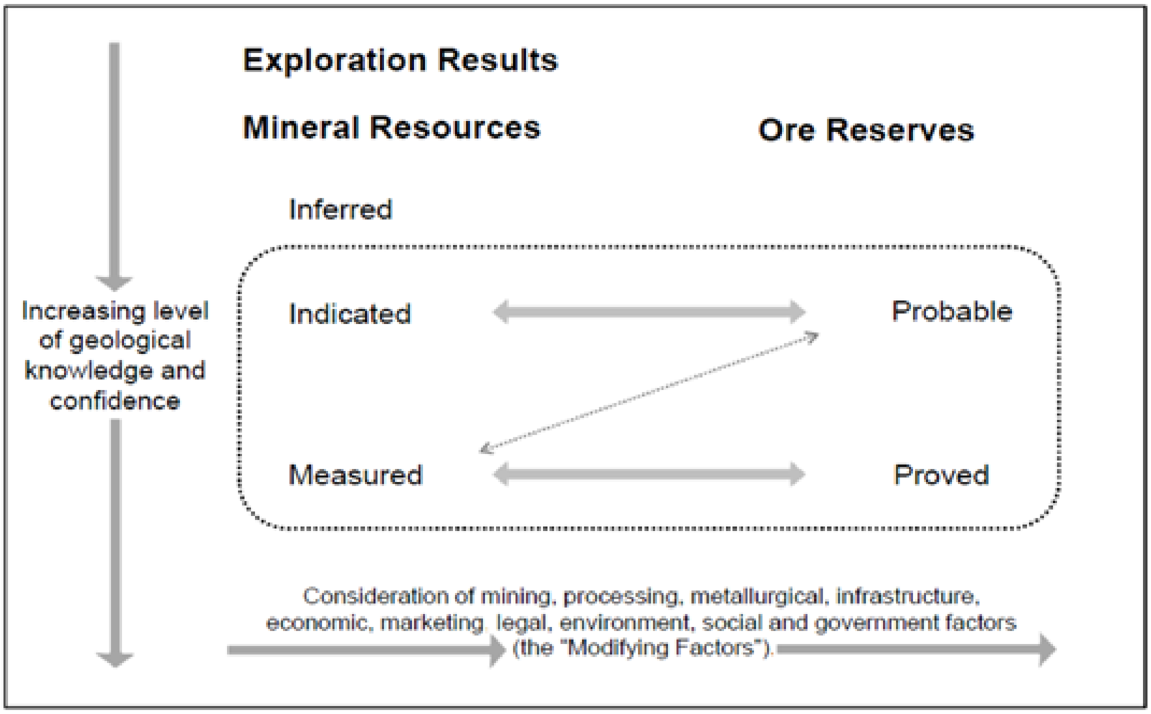

Figure 2.7: General relationship between Exploration Results, Mineral Resources and Ore Reserves (JORC, 2012)

This figure shows the progression of confidence on the deposit from a geological perspective (vertical) against the economic and other considerations (horizontal). For example if the ore-body is well known, however the economic considerations have not yet been determined then it is classed as a "Measured Resource". In general, the following provides examples on the accuracy of the resource deposits and production (Domin, Mark A, & Annels, 2002) :

- Measured Resource / Proved Reserve:
  - Over a 12 month production period actual production will be within planned production by +/- 5 to 10% (at a 90% confidence level)
- Indicated Resource / Probable Reserve:

  - Over a 12 month production period actual production will be within planned production by +/-15 to 25% (at a 90% confidence level)

- Inferred:
  - Over a 12 month production period actual production will be within planned production by +/-35 to 100% (at a 90% confidence level)

For ISRU purposes we need our resources to be a “Measured” resource or a “Proved” reserve.

The location of these deposits will be one of the major decision points on where settlements should be located, as the future operation and growth of the settlement will depend on the recovery of raw materials for life support, propulsion and future construction and growth purposes.

Chapter 2 (The Settlement of Mars) starts with the following sections, available in the full book:

After Mars ISRU this chapter continues with the following sections, available in the full book: