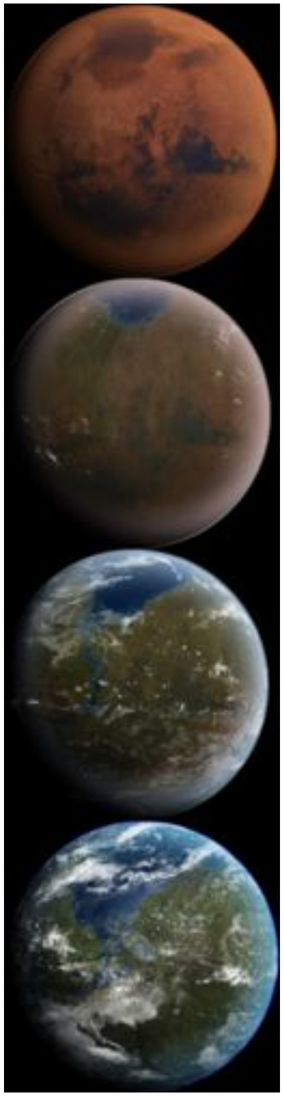
Outline

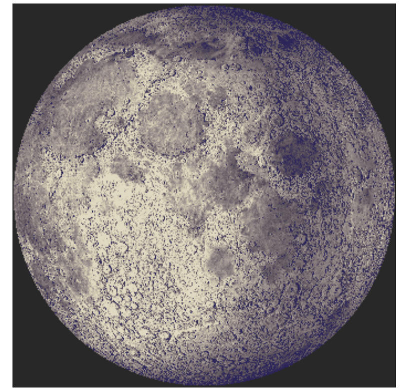
- Define Permanent, Self-Sufficient, Space Trading, Industrial Settlement on Mars
- Demonstrate Mars Advantage in Trade due to lower Transportation Cost to Space
- Predict the big market for Mars – Low Earth Orbit Hotels

- Describe how to build a Mars industrial civilization from scratch with minimal investment by
    - Bootstrapping processing equipment from Earth
    - Finding and mining the concentrated ores
    - Scaling processes and equipment appropriate to production rate requirements
    - Developing new processes appropriate to Mars resource distribution



Why a permanent settlement on Mars?

… and not the Moon?



Mars has

- Abundant, distributed sources of water (hydrogen and oxygen)
- Vast quantities of carbon and nitrogen in the atmosphere
- "Hot spot" volcanic activity that concentrates minerals
- Atmosphere (7 mb) as a partial shield against solar flares
- 24 1/2 hour day conducive to Earth plant growth

… The Moon doesn't…

Trade - The Economic Engine that drives self-sufficiency

Trade is rarely as simple as one to one. In US history we learn about the 18th century trade triangle between Britain, America, and the West Indies. Robert Zubrin ("Case for Mars") envisions that a Earth, Mars, Asteroid trade triangle would naturally develop.

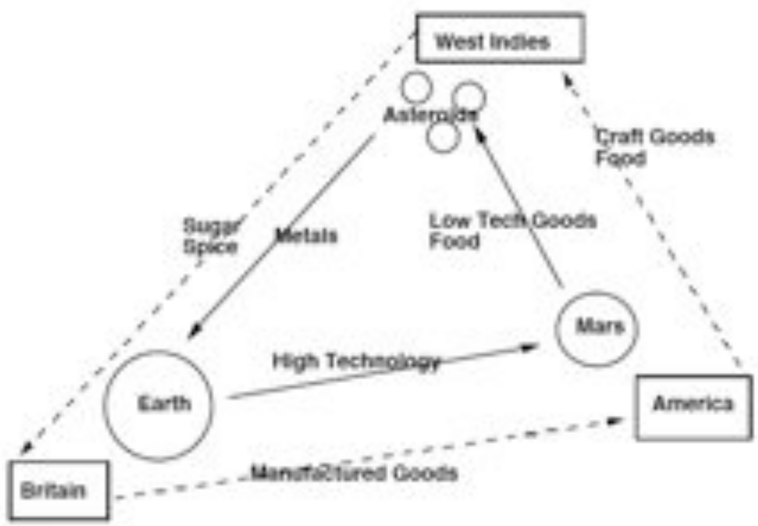


Fig. 1 The triangle trade: 18th Century and 21st Century.

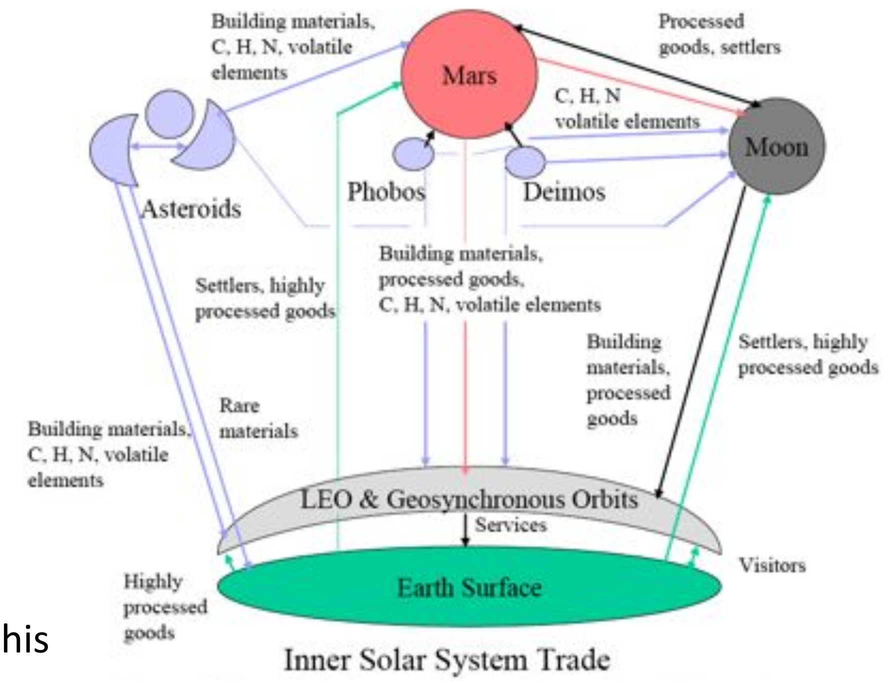


Figure 1. Inner Solar System Economic Domains and Interactions

4Frontiers Corp. has a vision of a more complex trade relation that I'll call a trade network. When this network operates effectively Mars will have the ability to acquire high tech goods from Earth and to sell low tech supplies to asteroids, Moon, and Earth orbits.

A trade network must be established within 25 years of the founding of the first permanent settlement on Mars for it to succeed.

Mars Needs People and Tourism

People migrate for many reasons

Religious or Ethnic Persecution
Natural Disasters
Famine
Economic Problems
War & Political Strife/Turmoil/Oppression
Following Family and Friends
Adoption
Slavery
Forced Relocation of Native Americans
Criminal Incarceration/Deportment
Not a First Son
Greater Financial Opportunity.

The most popular reason is Gold Rush reasoning. The economic advantage to migrating and settling off-planet must be self-evident to the average Joe or Juanita.

Space Tourism holds the key.

Tourism

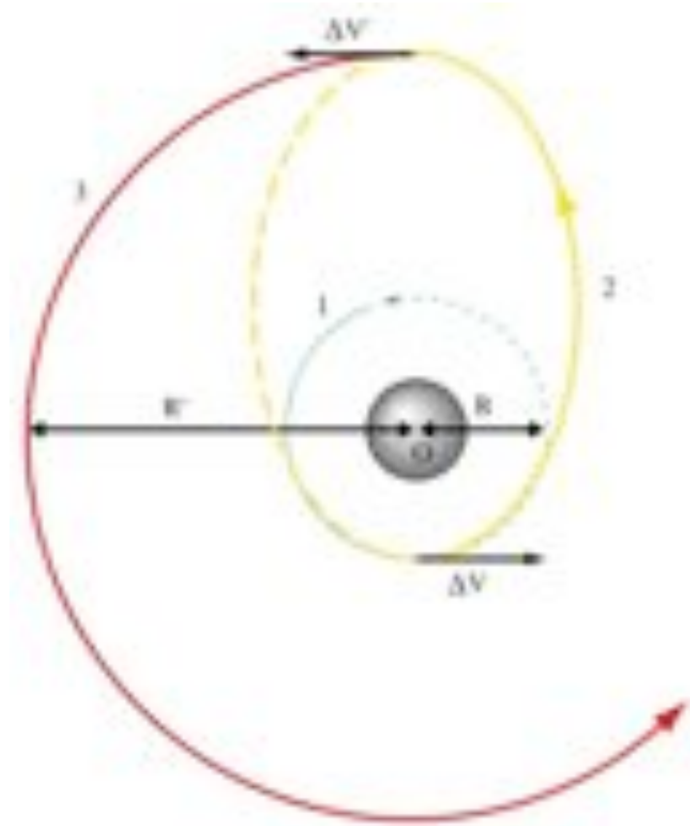
- generates 11% of the global Gross Domestic Product
- employs 200 million people,
- transports 700 million travelers annually - a figure expected to double by 2020.

(www.propoortourism.org.uk)

Space Tourism is a $20M to ISS business today. Bigelow LEO Hotels are next.

Transportation Costs can be derived from Delta-v

Orbital Mechanics 101 - Delta-v (Δv) Defined



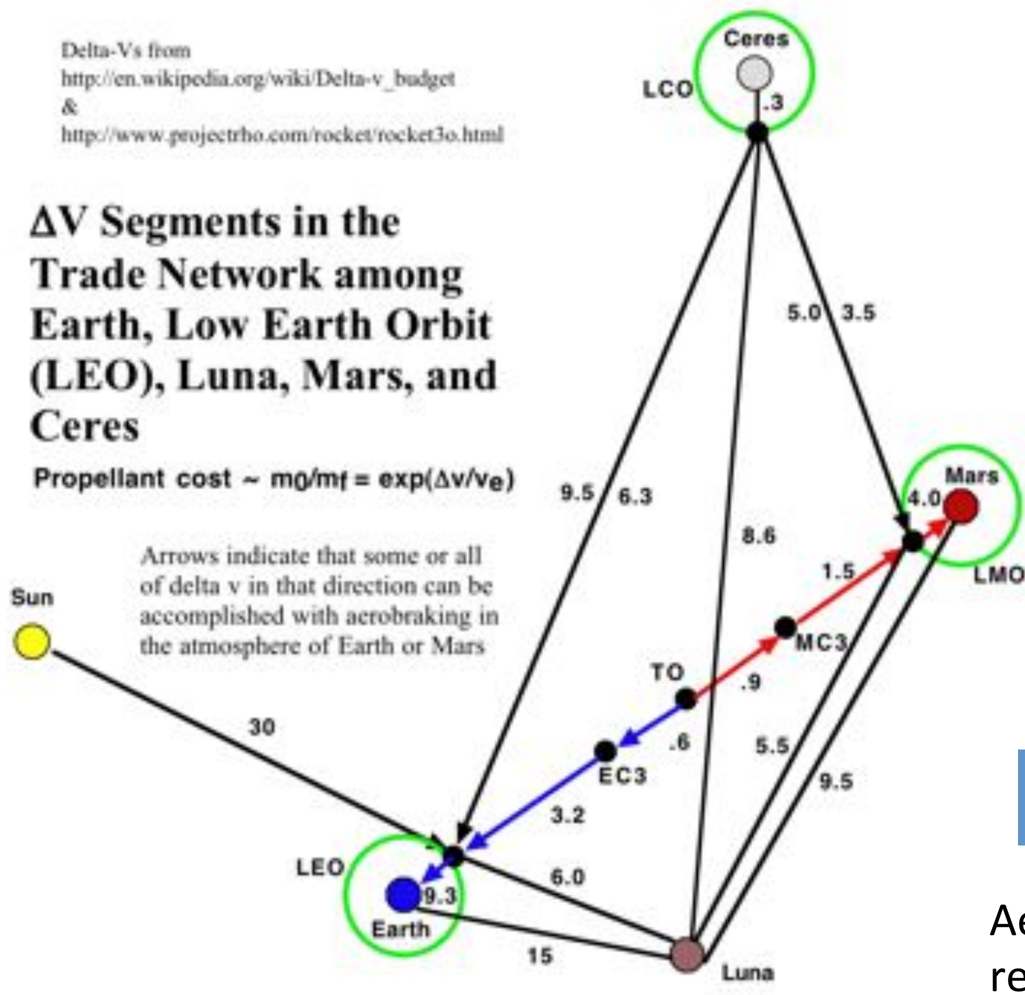
Sun

A Hohmann transfer orbit is the *lowest energy path* to move from one orbit to another via two high thrust firings that increase the velocity by Δv and Δv'.

As the circular orbit becomes larger the velocity is higher. But at larger orbital radii, the sun's gravity starts to dominate and the rocket escapes the Earth's gravitational attraction.

Δv_{C3} is the delta-v (km/s) needed to escape Earth's gravity and achieve an excess hyperbolic velocity to reach another planetary body.

Delta-v (km/s) Diagram for the Inner Solar System Trade Network



Transportation cost is proportional to the fuel used, which is proportional to the initial rocket mass m_0 divided by the final rocket mass m_f.

This mass ratio is an exponential function of Δv (Tsiolkovsky Rocket Equation)

$$\text{Cost} \sim m_o/m_f = e^{\Delta v/v_e}$$

Aero-braking to achieve delta-v reduces cost on some legs of the network, but not others

4FRONTIERS
EARTH MARS MOON ASTEROIDS

Comparison of Transportation Costs

Path	Earth		Mars		Mars vs Earth	
	delta v	mass ratio	delta v	mass ratio	Cost Ratio	Comment
Surface to LO LO = low orbit	9.3	12.35	4	2.95	0.24	
Surface to C3 of planet	12.5	29.32	5.5	4.42	0.15	
Surface to Luna surf	15	57.63	9.5	**13.03**	**0.23**	
LO to Luna surface	6	5.06	5.5	4.42	0.87	
Surface to LEO	9.3	12.35	6.4	5.64	**0.46**	with aerobrake
Surface to GEO	13.4	37.4	6.4	5.64	0.15	with aerobrake
Surface to Ceres	18.6	152.48	8.9	11.08	**0.07**	
Surface to Mars surface	16.5	86.44				no aerobrake
Surface to Mars surface	13.1	34.49				with aerobrake
Ceres LO to LO	9.48	12.95	4.96	3.82	0.3	no aerobrake
Ceres to LO	6.6	5.95	3.8	2.79	0.47	with aerobrake
Ceres surface to Luna surface	8.9	**11.08**				

Mars shipping costs beat Earth costs

Space Trade Economics - It’s all in shipping cost

It’s 2021. I’m building a honeymoon hotel (“*Forget water beds - try zero gravity!”)* in Low Earth Orbit (LEO)

I need 10 ducting elbows for air-conditioning.

The price on Earth is $2.15 ea and its mass is 0.1 kg. Total mass is 1 kg.

Elon Musk is offering a cargo delivery to LEO on his Falcon 9 heavy at $3000/kg (1/5 shuttle cost)

The cost to deliver the elbows to LEO from Earth is $21.50 + $3000 = $3021.50

The transportation cost from Mars to LEO is only $1500/kg (See delta v chart).

Total cost to deliver the elbows from Mars to LEO is ~$215 + $1500 ~ $1700

What does Mars charge? $2700 (undercutting Earth price by 10%)

Why? To make a $1000/kg profit and pay for all that investment of people and equipment on Mars!

Space Tourism - Where does Mars come in?

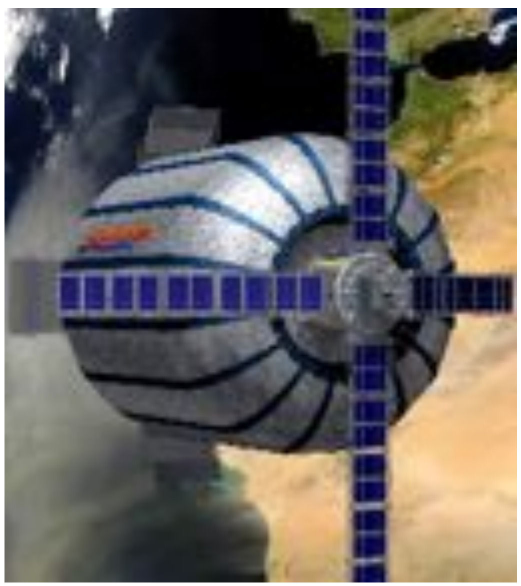
In 2021 the projected market for a $300,000 orbiting hotel stay is 2 million people with about 1400 per week going to LEO.

Suppose that each tourist to LEO in a Bigelow hotel requires 100 kg of mass in misc. clothes, materials, food services for guest and staff.

Carried from Earth this 100 kg costs $300,000

Carried from Mars this 100 kg costs $150,000

Where do you think Bigelow will acquire most of it?



Genesis Hotel concept- Bigelow Aerospace

Prototype is now in orbit

Bigelow Nautilus 23 ton hotel mockup - 3-6 persons

Profit stream 2021 and beyond

Every two years we'll bring 24 or more settlers to Mars, and we'll need to design, build, and bring machines to Mars that can not only copy themselves, but build bigger versions of themselves at a cost of ~$9M/tonne.

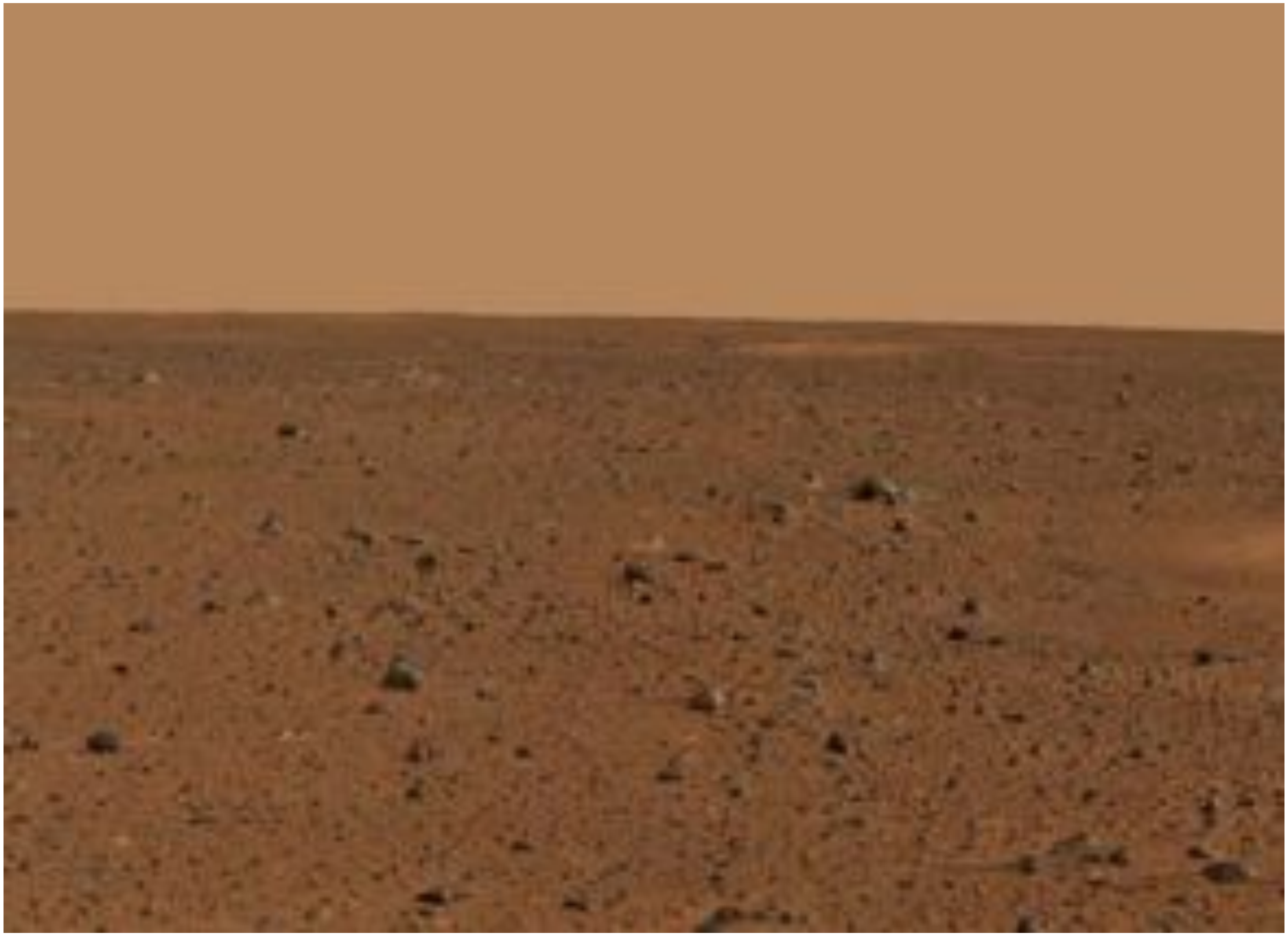
How is this biennial cost paid for?

Tourist supplies profit - In 2021 the annual profit from delivery of 100 kg/LEO visitor is $6.9B

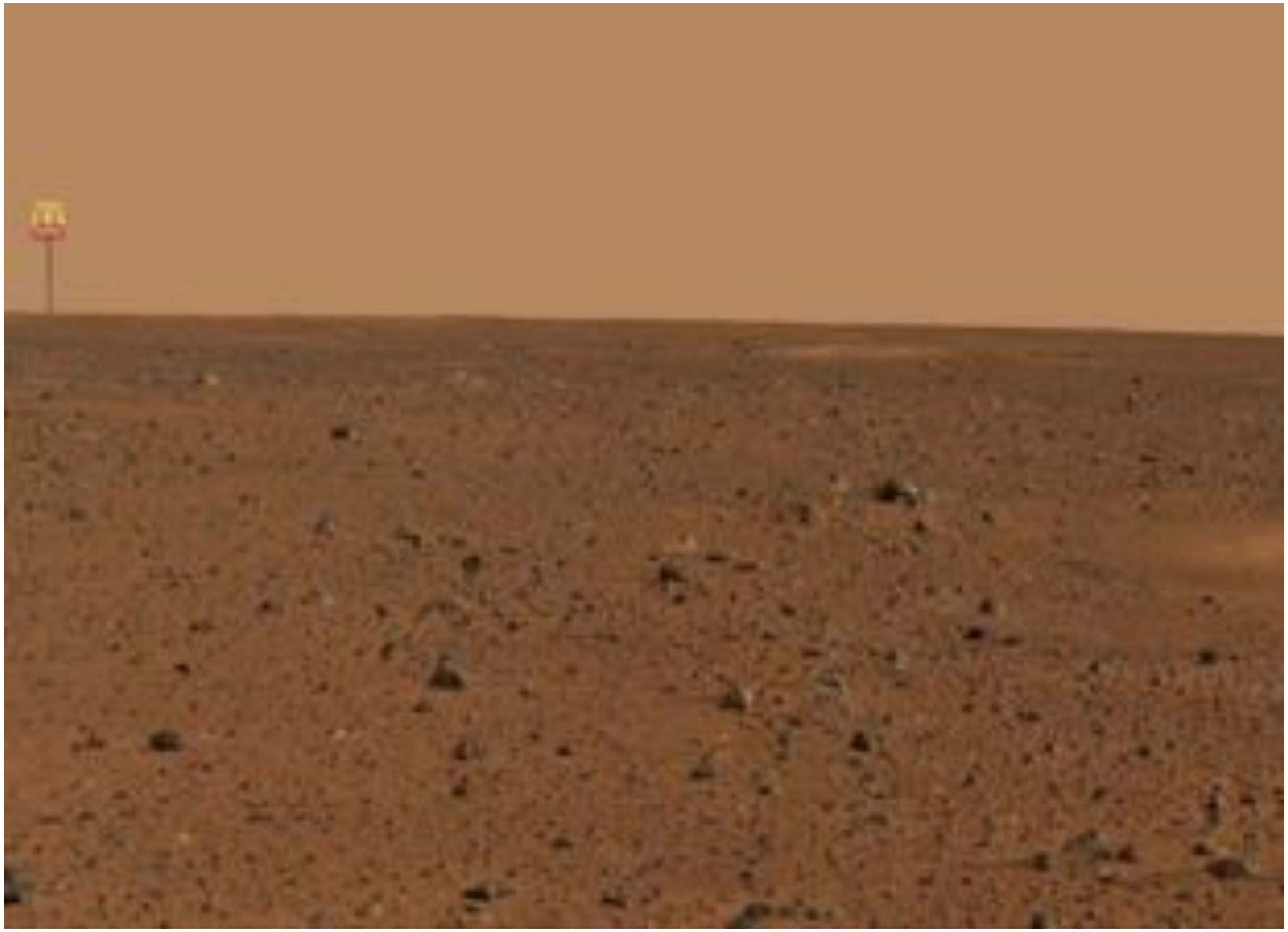
So… If a Space Tourism industry is established in LEO,
…then a permanent Mars Settlement is self-sustaining on Space trade of industrial goods.

Let's now look at how we build that settlement as cheaply as possible…

Problem - We want to take this barren Martian world



And establish a 21st century civilization!



Mars Homestead™ for 24 settlers

The Mars Foundation study in 2004-5 expanded on an MIT masters thesis in architecture to define the energy sources, skill sets and no. of personnel, materials and equipment to be brought from Earth to build a permanent settlement from at least 90 percent Mars resources.

The settlement was designed for linear expansion…

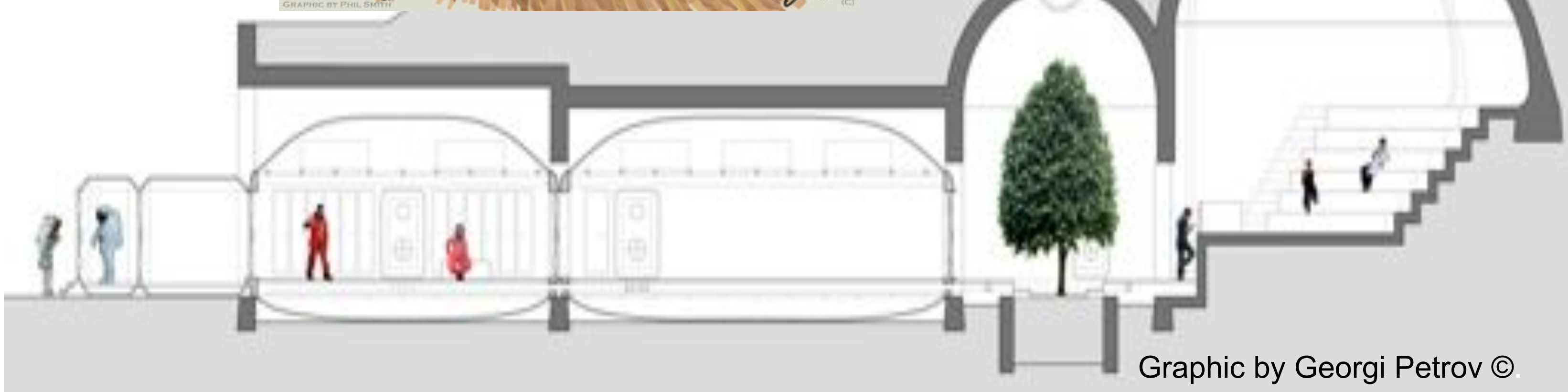
Mars Homestead™ for 48 settlers

Settlement Architectural Cross Section

Pressurized modules made with tensile loaded structures of composite and metals

Regolith overload puts brick/concrete construction in compression

Suites and common areas are designed for spacious, permanent living not as temporary dormitory space

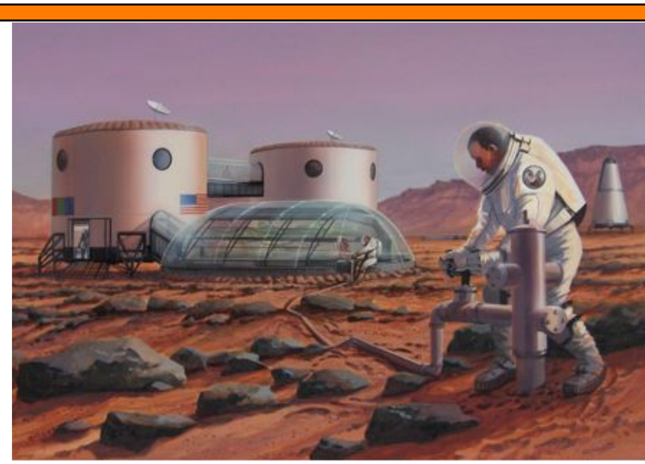


Graphic by Georgi Petrov ©

1.1 Mtonne Mars annual industrial output

A Partial List of Products	Mars Annual Production - tonnes
Water for aquaculture, consumption, making CH_4, O_2 and H_2	500
Cement (Magnesium oxy-sulfate based)	195
Basalt fiber for composite modules, gas pressure tanks	80
Steel for beams, sheet, rebar, pipes	78
Methane for furnace fuel and ICEs	70
Polyethylene for pipes, sheet and containers	48
Polycarbonate for windows	33
Polyester resin for composite modules, gas pressure tanks	28
Aluminum for electrical wire	12
Nitrogen (for fire extinguishing, breathable gas mix)	5
Silicon (eventually for photovoltaic cell production)	2
TOTAL PRODUCTION	**1100**

2004-5 Gen I Settlement - Key Resources and Assumptions



Key resources that must be found are:

- Water by drilling
- Mars atmosphere as a source of CO_2 and N_2 and all organic chemicals and polymers
- Minerals to be mined by scooping up the regolith (strip mining the local area) and then chemically separating, refining metals, ceramics, glass.
- Mass of processing equipment estimated at 35 tonnes

2006-7 Generation II Mars Settlement Study

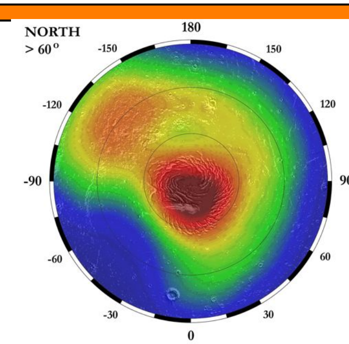
- Corporate funded design effort
- 30 engineers/scientists from Australia, Canada, Mexico, and US
- 2 face-to-face meetings in Atlanta, GA, weekly task team telecons
- Results presented at ISDC and MarsSocConf. 2007
- Summaries and pdfs at 4FrontiersCorp.com

Resource Assumptions were re-examined

What do we know about water?

- It is located near the poles as surface ice

But, **we want a spaceport for trade near the equator.**



LANL neutron spectrometer- Odyssey

Dark red -100% water

Dark blue -12%water

What about **subsurface ice (or water)**?

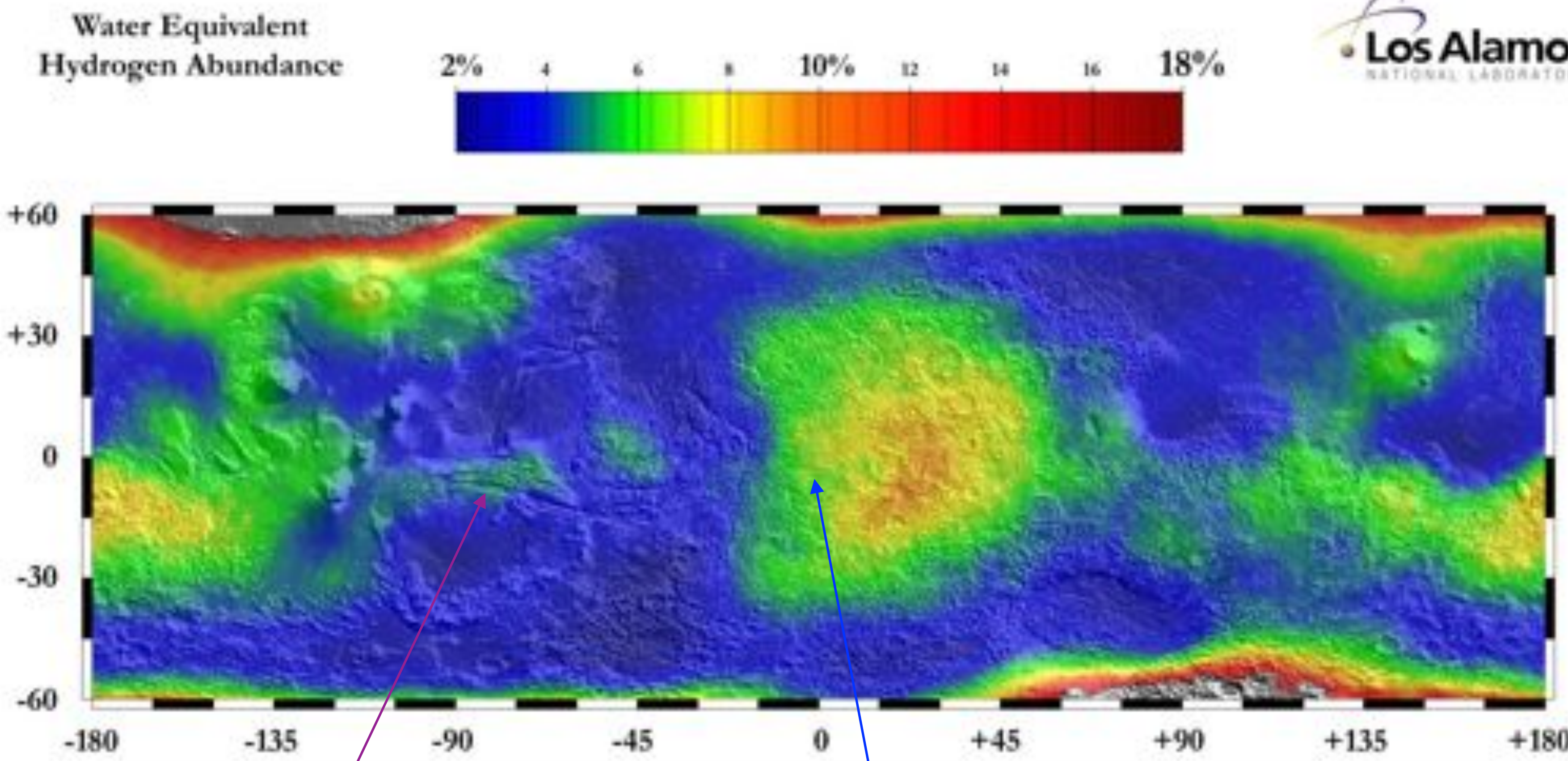
- Analysis by Aharonson et al. of near subsurface ice in porous regolith in equilibrium with water vapor in the atmosphere suggests that no free ice will exist in the regolith between 30/-30° latitude and subsurface ice will exist year-round only above ~50/-50° latitude.

- Radar instruments on two Mars satellites (MARSIS on Mars Express, SHARAD on Mars Reconnaissance Orbiter) have not located any non-polar reservoirs of water or ice (discontinuities between water saturated rock and other rock) to a depth of 3 km, so drilling is not a likely solution, although low concentrations (~1%) or low concentration gradients of water in regolith are not detectible by the radar method.

But **there is another source of water near the equator**…

Gen 2 Plans Change - Need to settle near water and iron ore

LANL Water Map (actually a map of hydrogen proton density)



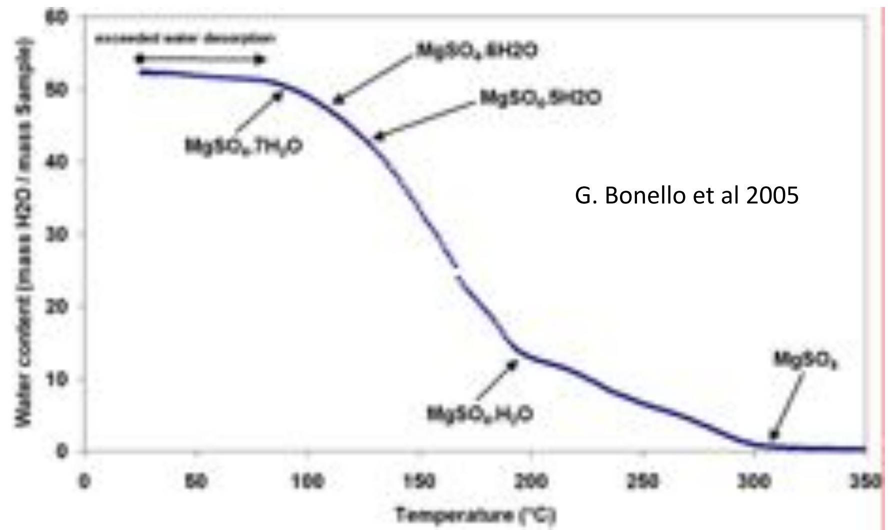
Original 2005 study site for settlement 2005 In Valles Marineris, but no subsurface water has been detected

Current 2007 study site for settlement at Meridiani Planum where water can be extracted from hydrated minerals and iron from hematite "blueberries"

Extraction of Water from Hydrated Gypsum

Extraction of water from hydrated minerals

- Kieserite-Epsomite $MgSO_4 \bullet 7H_2O$ (Epsom salt) to $MgSO_4 \bullet 6H_2O$ requires 304 kJ/mole and heating to ~100°C.
- Gypsum $CaSO_4 \bullet 2H_2O$ to $CaSO_4 \bullet 1/2\ H_2O$ requires 317 kJ/mole and heating to ~150°C $CaSO_4 \bullet 1/2H_2O$ to $CaSO_4$) requires an additional 117kJ/mole.
- Kieserite or $MgSO_4 \bullet H_2O$ is stable to ~300°C



G. Bonello et al 2005

Water Extraction Process

- Hydrated minerals are separated and extracted with front-end loader and transport.
- Hydrated minerals are loaded into a pressurized (600mbar) oven at 200°C.
- Hold at temperature for one hour while collecting and condensing out the released water.
- Heat exchanger used to preheat next batch.

- The **process is simple, but the energy is significant because of the large mineral mass heated and the low percentage of water** (~5%) yielded.
- Energy required is ~10 MJ/kg of water produced

Energy Costs - Alternate Sources of Water

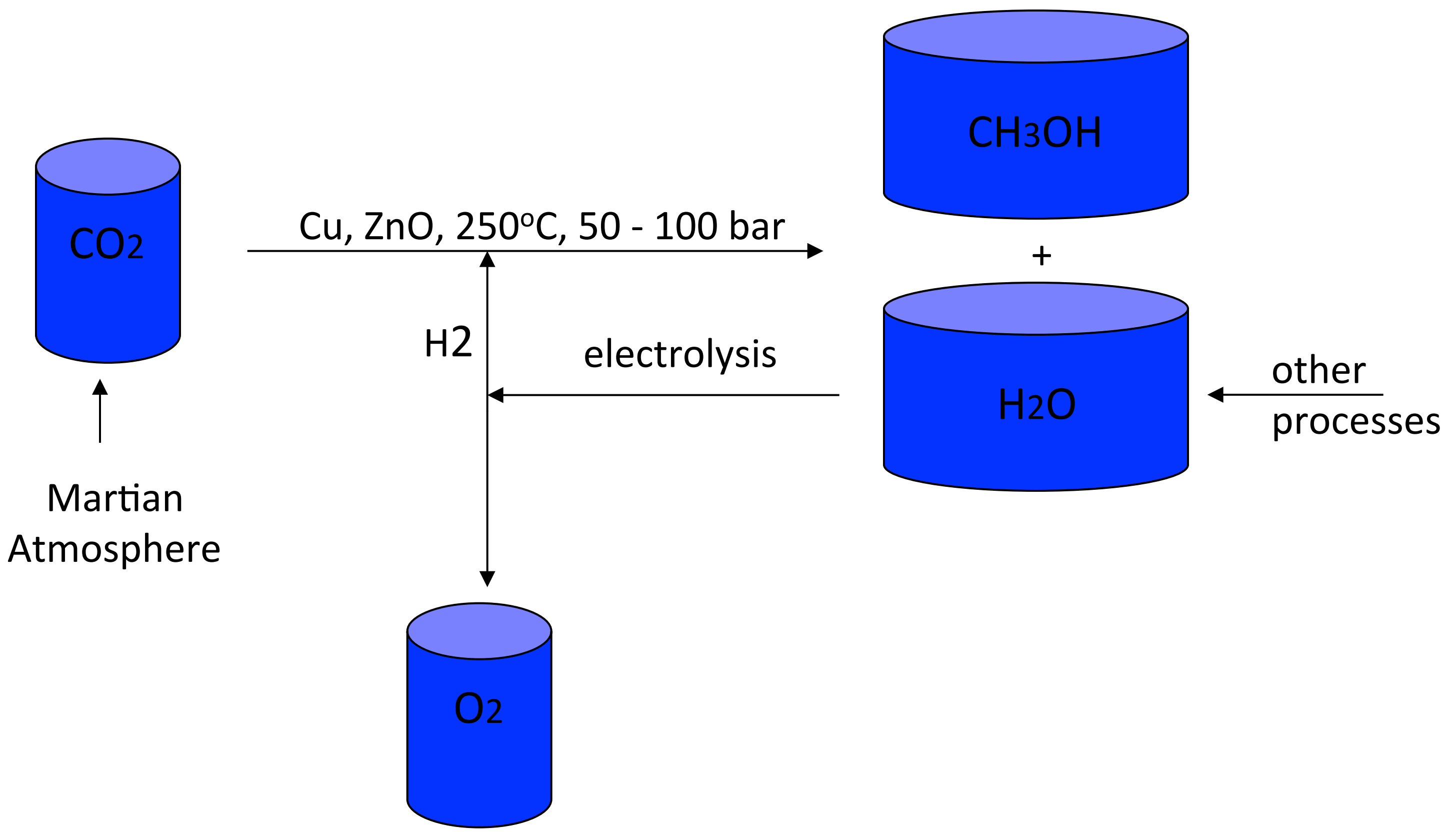
Process	Details	Energy to produce water
Water from hydrated minerals at Meridiani	Separate minerals containing 5% hydrated water. Heat to 200°C, Condense out water. Heat exchange to preheat incoming minerals	**~10 MJ/kg water** ~ the same energy to make steel!
Water ice trucked from polar regions +/-50° latitude to settlement at Meridiani	Transport 3000 km in 50 tonne methane/oxygen ICE truck. Heat from -40°C to 20 °C.	**~3 MJ/kg water** ~ 0.5 MJ/kg to heat water ~2.5 MJ/kg to transport
Water from > 3km deep wells (Not proven to exist!)	Make 90 tonne of 3 in diam steel well casing. Amortize over 10 years. Extract at 1 gałmin or 3.8kg/min with 1 kW power pump	**~0.1 MJ/kg water**

Resources - Differences

- Mars has no Coal, no Oil, no Biomass.
- The Only Readily Available Source of Carbon Available on Mars is its CO_2 Atmosphere.
- "This, Along with Electrolysis of Water to Provide Hydrogen, Proves to be Entirely Adequate for Our Needs" (Bob Milligan 2007).

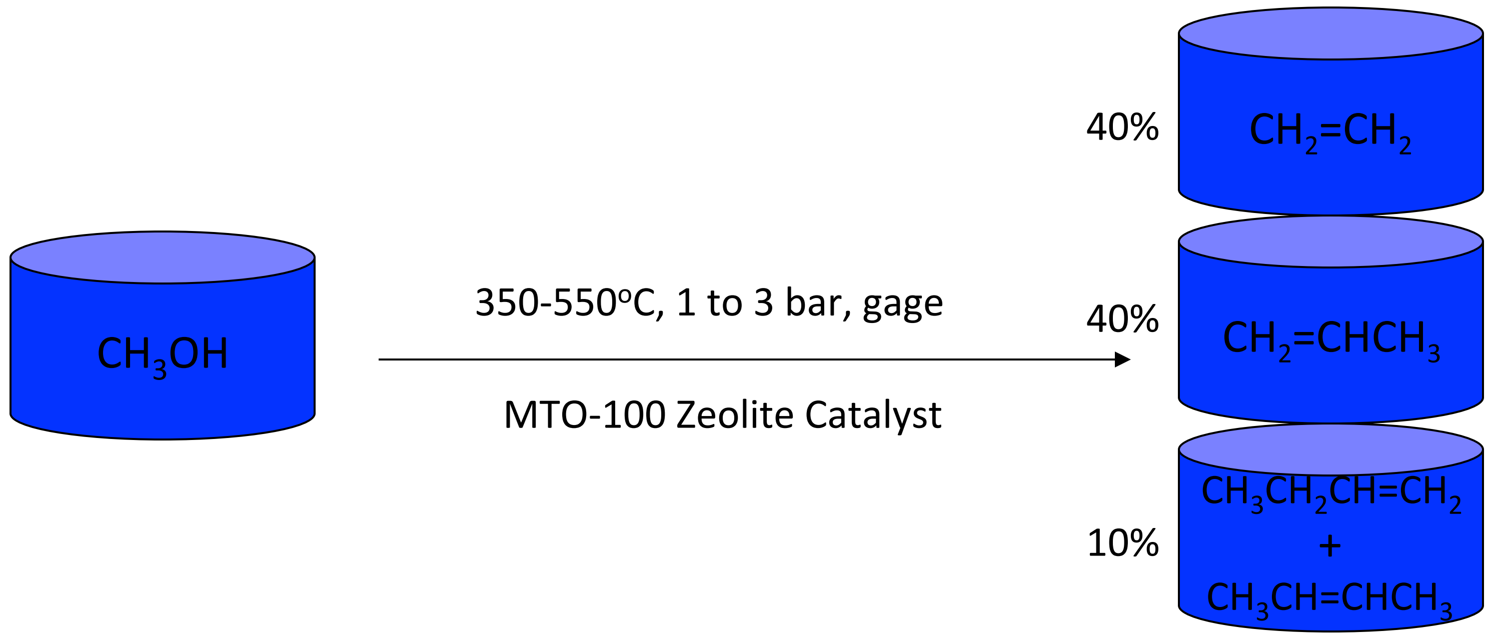
METHANOL SYNTHESIS ON MARS

Synthesis Charts from Milligan, 2007 Mars Soc. Convention presentation

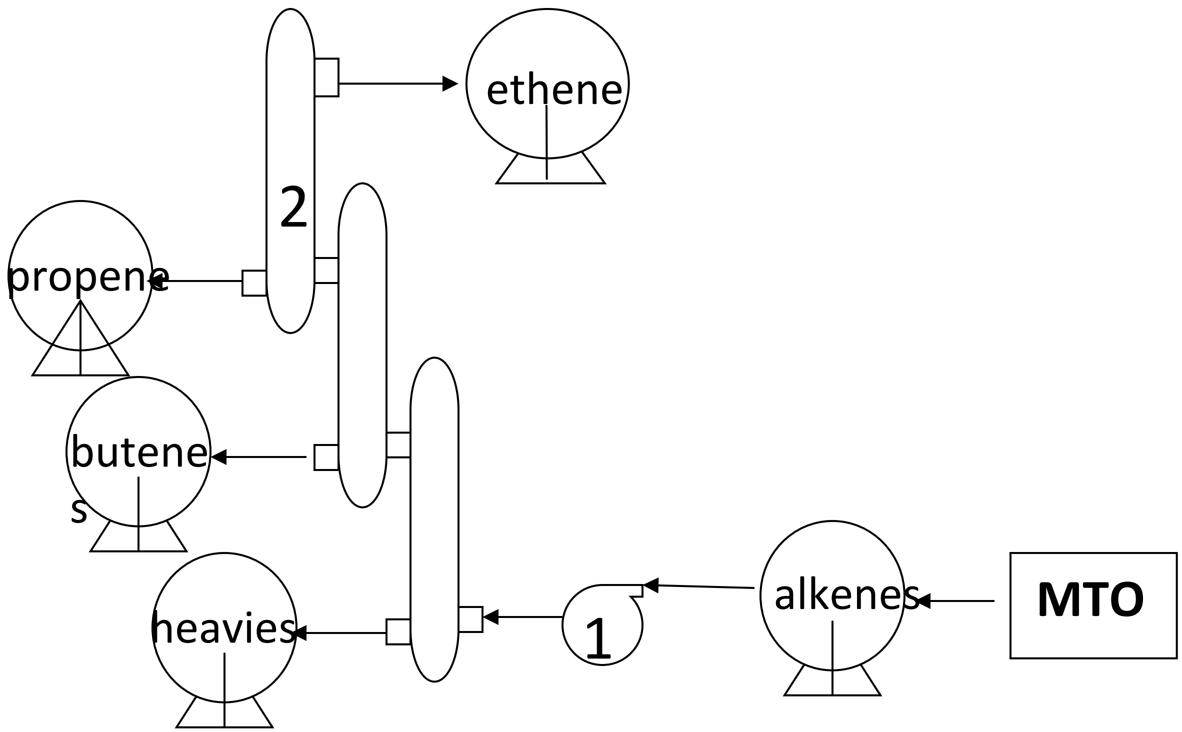


METHANOL TO OLEFIN (MTO) REACTION

Methanol to ethylene, propylene and butene



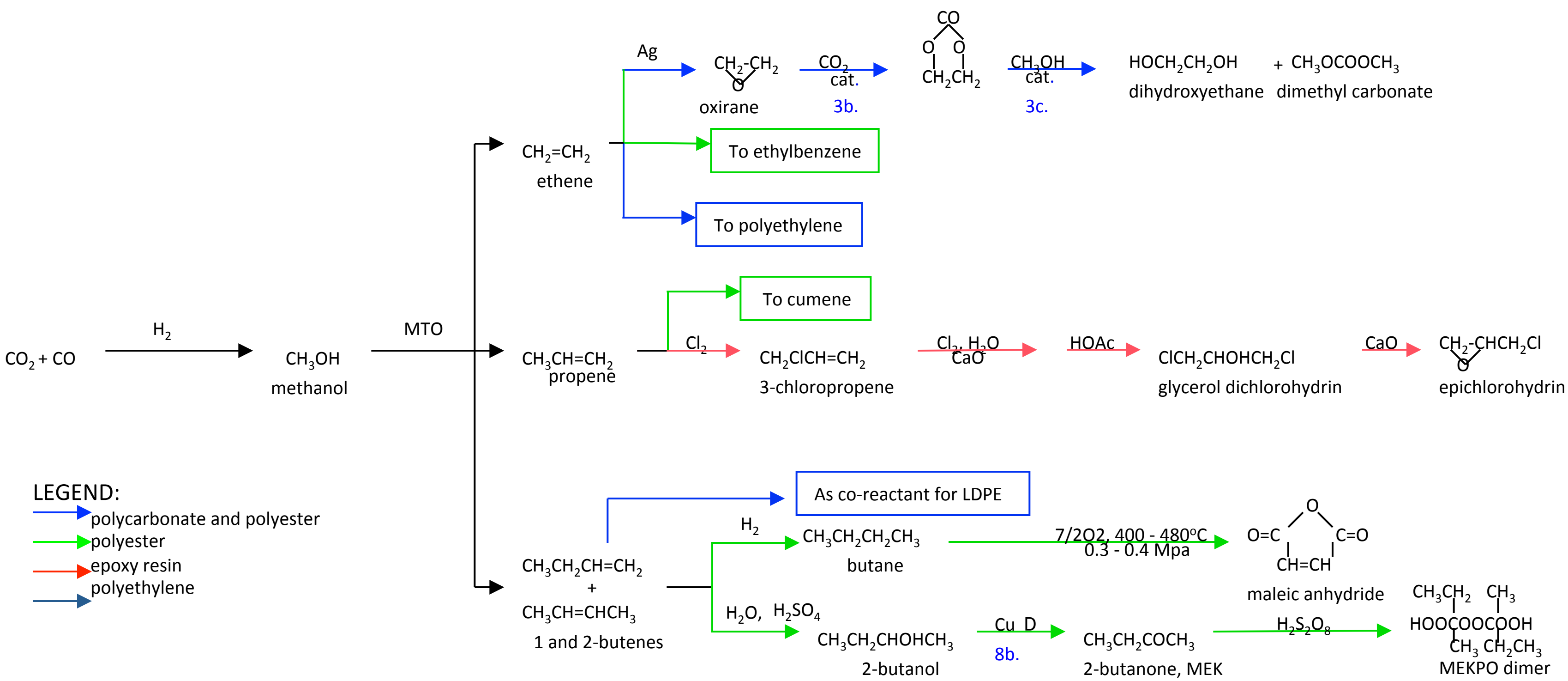
SCHEMATIC FOR SEPARATING OLEFINS



1. Compressor
2. Distillation Columns

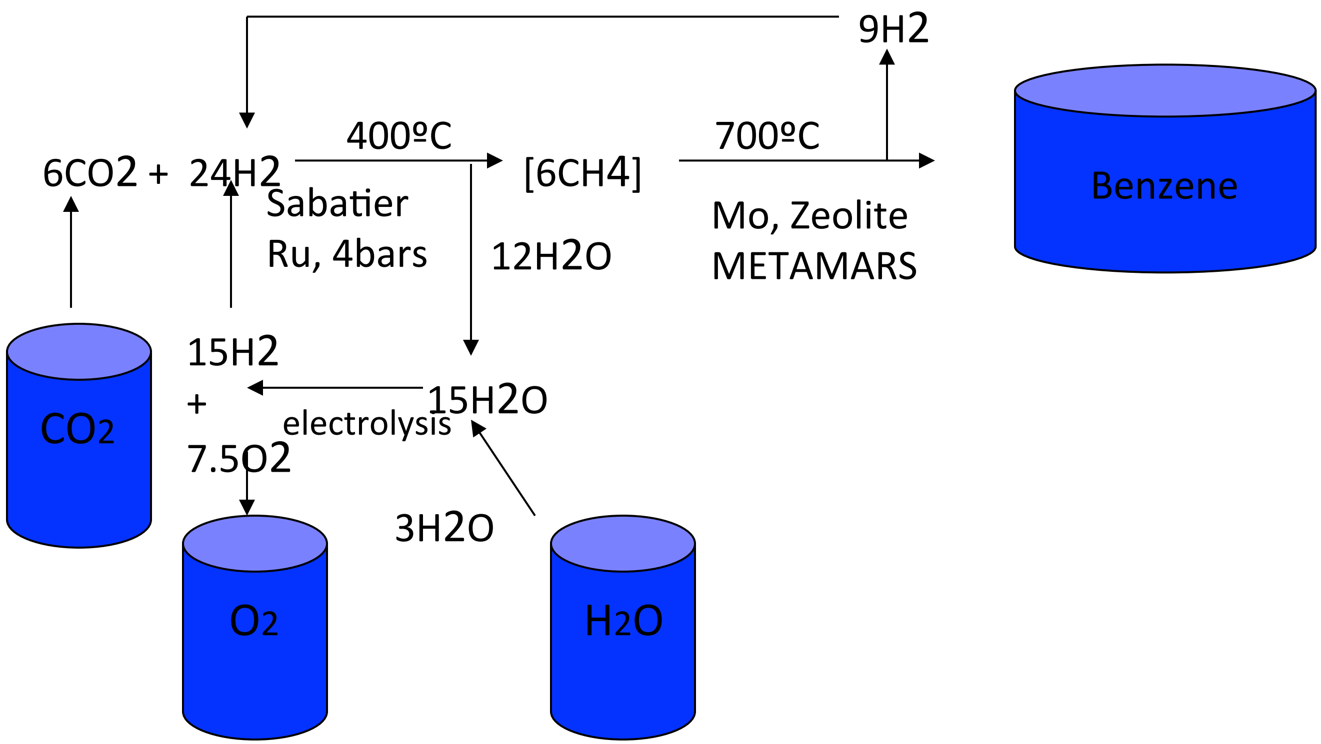
ALIPHATIC SYNTHESES FROM METHANOL

Aliphatic – open chain (non-aromatic-ring)

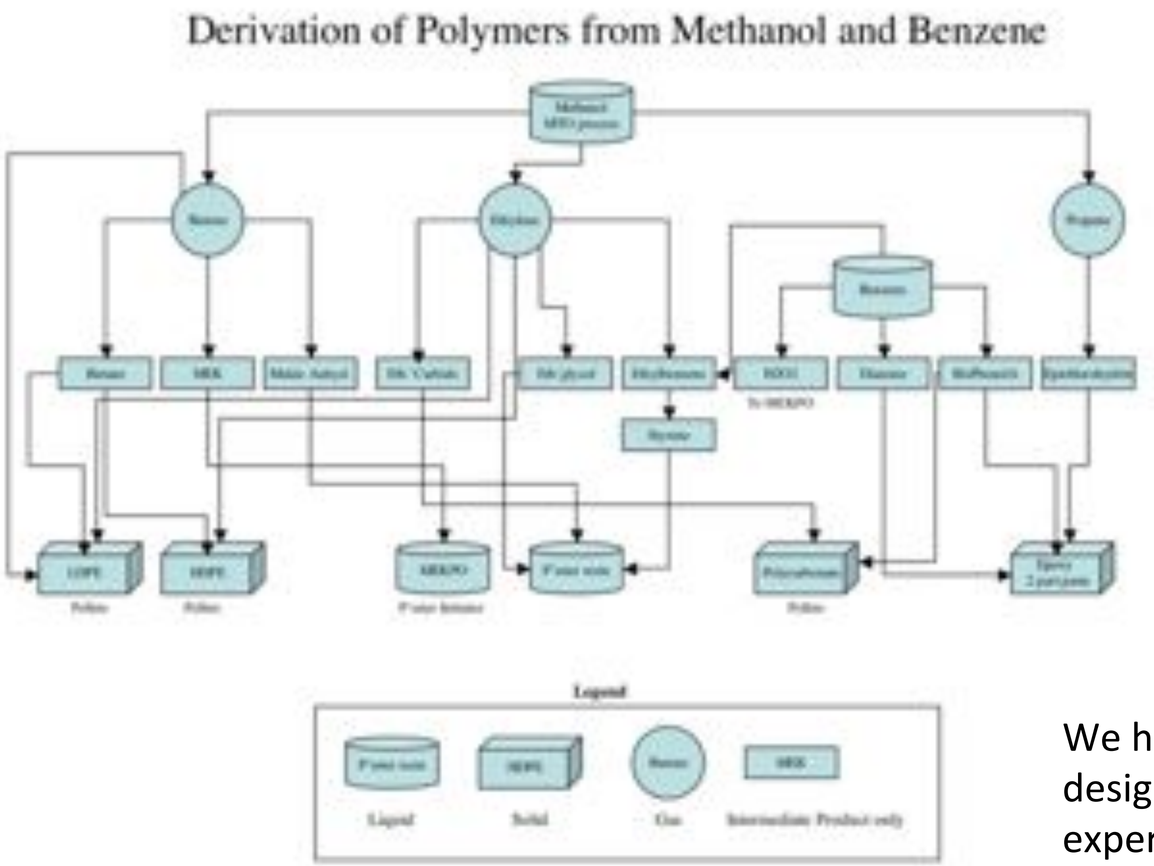


BENZENE FROM CO_2

Aromatic Ring Chemistry



Depth of Analyses - Example - Synthesis of Chemicals and Polymers



From hydrated minerals, atmosphere, gypsum, methanol and benzene we synthesize (with all reaction temperature/ pressure/ catalyst conditions defined)

- 8 inorganic reagents
- 30 organic chemicals
- 4 structural polymers

We have not conducted detailed design of the chemical plant nor experiments to define the kinetics of reaction in pilot scale production lines appropriate for Mars needs

Sizing the Chemical Plant

Phase 2 Design studies have estimated the quantity materials needed to build a habitat sufficient to house 12 settlers.

- 115 tonnes of fiber glass polyester composite,
- 46 tonnes of polyethylene
- 5 tonnes of epoxy adhesive

These materials are produced during a 400 day period at average daily production rates of

- 70 kg/day - Unsaturated polyester resin and styrene for crosslinked polyester
- 116 kg/day - Polyethylene
- 12 kg/day - Epoxy

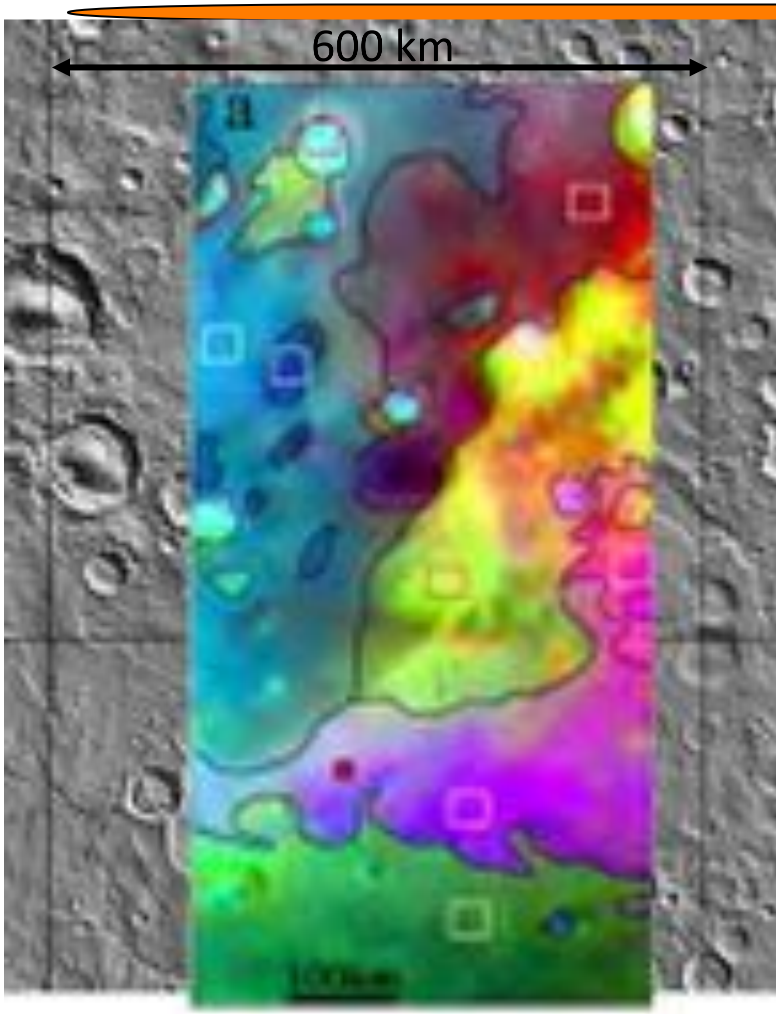
The size of the chemical reactor to produce 45 kg of unsaturated polyester resin (a viscous liquid) in a one batch a day process is

Volume = mass/density = 45/1.2 = 0.038 cubic meters or 9.4 gallons

Conclusion: The chemical plant needed to produce these quantities is more than laboratory scale but less than that of many pilot plants on Earth.

Pdc Machines, Inc.

Finding concentrated minerals at Meridiani

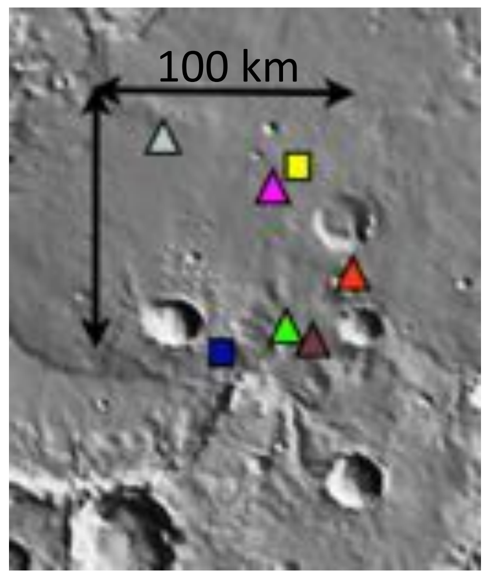


Ref: M. Zhu et al. Lunar and Planetary Science XXXVII (2006) 2173.pdf, Mineral and Lithologic Mapping of Martian Low Albedo Regions Using OMEGA Data

Based on OMEGA matching of thermal spectra to mineral spectral end members (see map to left).

Below close-up view where 4FC Meridiani settlement site is dark blue square. Opportunity site is yellow square.

Triangles are Omega determined locations of high priority mining exploration sites for



ENE of site,
- hematite - gray-red,
- clay - bright red
- chalcopyrite* - light green

NNE of site,
- anorthite - magenta

NNW of site.
- gypsum - light gray

* Presence of end member chalcopyrite is considered suspect by many

Specific Energy to Produce Methane Fuel and Metals

Material	Specific Energy - MJ/kg of end material	Comments
Methane	39.4	75% electrolysis production efficiency
Hematite to DR iron	10.0	Midrex Process heat from 75% efficient CH4 burning
DR iron to medium carbon steel cast ingot	2.1	Electric arc furnace
Alumina powder from Plagioclase (Anorthite)	16 Bayer Process plus 7.3 for CaO from gypsum	Requires 3 moles of CaO for every mole of Al_2O_3
Aluminum wire from Plagioclase/Alumina	99.4	Hall-Heroult; includes energy to make carbon electrodes
Aluminum wire from spacecraft skin	5.9	Remelt, cast, roll, draw to wire
Copper from chalcopyrite	17.3	Smelting then electrolytic refining of copper

4FRONTIERS EARTH MARS MOON ASTEROIDS

Specific Energy to Produce Chemicals, Polymers, Fibers

Material	Specific Energy - MJ/kg of end material	Comments
Ethylene	22.5	Dominated by energy of electrolysis of water to get H_2
Benzene	12.1	Ditto
Polyethylene	3	Starting with ethylene
Epoxy	9.5	Starting with ethylene and benzene
Polycarbonate	9.5	Starting with ethylene and benzene
Polyester	7.3	Starting with ethylene and benzene
Basalt	1.2	Melting at 1450°C with CH_4/O_2 burn then drawing/spinning to fiber

Specific Energy to produce Cement, Firebrick, Water, Silicon

Material	**Specific Energy - MJ/kg of end material**	**Comments**
MgO from kieserite	14.4	Calcining $MgSO_4$ to 2750°C in two steps to form firebrick
MOS cement from kieserite	2.3	Calcining to 1600°C and mixing with $MgSO_4$ and water
CaO from gypsum	4.0	Calcining $CaSO_4$ at 1500°C
Water from hydrated minerals (eg. gypsum)	10.2	200°C heating of mineral mass to release 5% water content
Silicon from silicate minerals	122	MAPS to produce silica (lack thermo data) or React silica containing silicate minerals with C at 1900°C to form impure Si; Then react with H_2 at 350°C to form silane; react silane at 420°C to produce electronic grade Si

Energy to Scoop Regolith (Mars simulant) and Process with MAPS

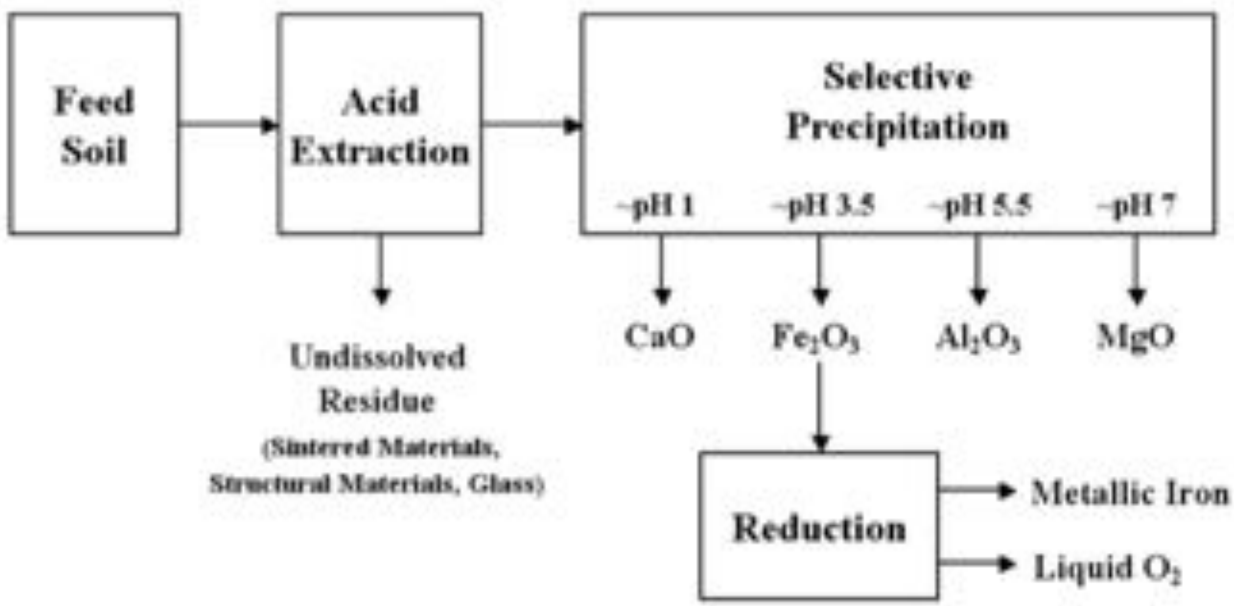


Fig 21.1 Mars Aqueous Processing System schematic

Steel -	22 kwh/kg vs	3.5 kwh/kg by Hematite mining and refining
Oxygen -	56 kwh/kg vs	8.5 kwh/kg by electrolysis of water
Alumina-	46 kwh/kg vs	4.5 kwh/kg from modified Bayer process
Magnesia-	64 kwh/kg vs	4.0 kwh/kg from calcined kieserite
Silica-	2250 kwh/kg vs	38 kwh/kg from steel slag or silicates

Undissolved residue is ~50% of the input mass

Alternate materials may be dictated by the rarity of Silica

Replace use of Glass fiber with Basalt continuous fiber http://www.albarrie.com/Filtration/fil-basalt.html

Aqueous pressure cooker cleaning of marble sized crushed basalt, melt at 1200-1350 deg C, spinnerets to spin fiber from melt, sizing applied to protect fiber surface and enhance bond to polyester resin.

Replace silica glass windows with polycarbonate windows (Milligan, this conference)

Replace silica firebrick with MgO (Milligan, this conference) or Al_2O_3 firebrick

Produce small quantities of silica for silane sizings and silicon chips from slag or silicates followed by purification to silane and electronic grade silicon

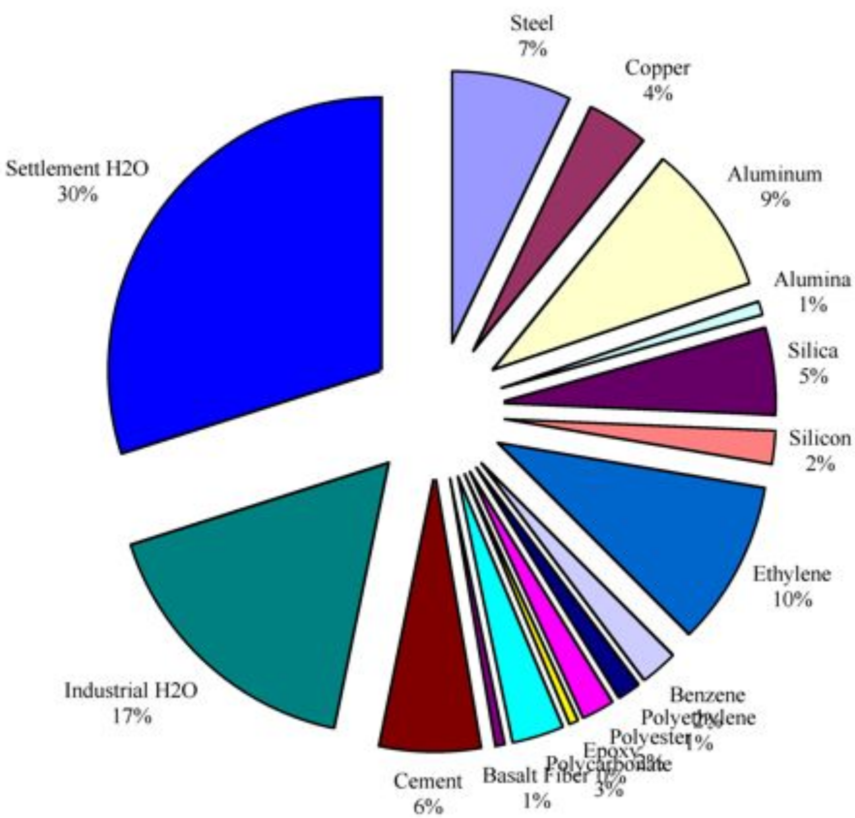
MOS SOREL CEMENT

- A Less Cumbersome Cement to Make on Mars is that Known as Magnesium Oxy-Sulfate (MOS) Sorel Cement.
- Only One Material, $MgSO_4 \bullet H_2O$ (Kieserite), needs to be Beneficiated.
- Kieserite is Purified, Dehydrated and a Portion is Calcined to Form MgO (Magnesia).
  - Reductive Calcination takes Place at a Lower Temperature than That for Calcium Oxide
  - Magnesia is also useful for the preparation of refractory brick for steelmaking.

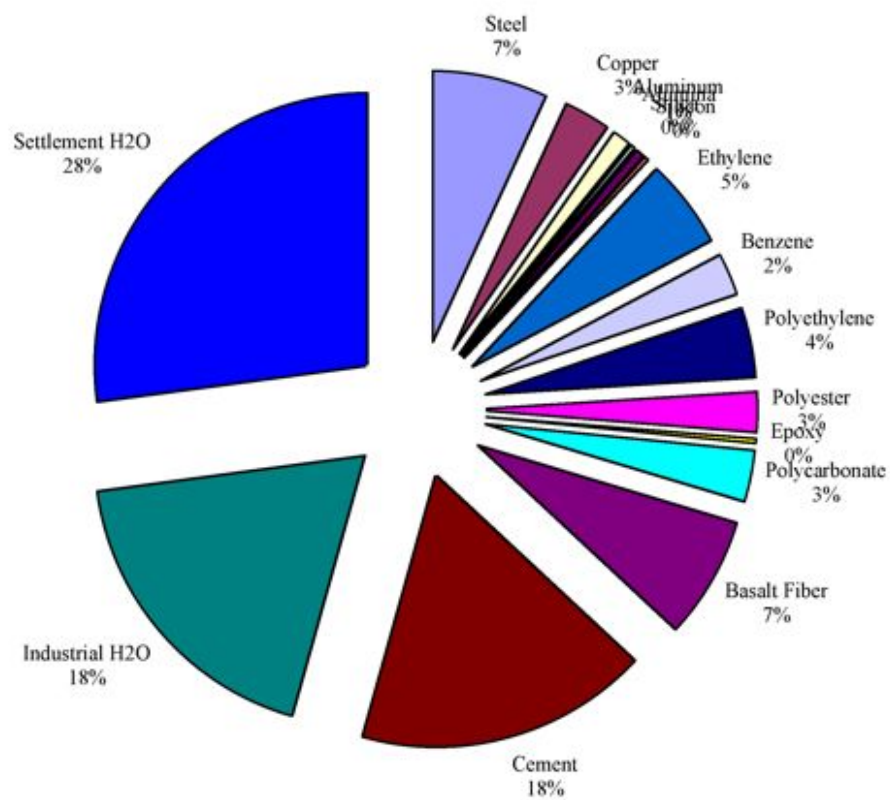
Comparison of Energy and Mass Requirements of Each Material

1100 tonnes of materials produced in 400 sols with one 400KW nuclear reactor

Percent of Total Energy Needed by Each Material



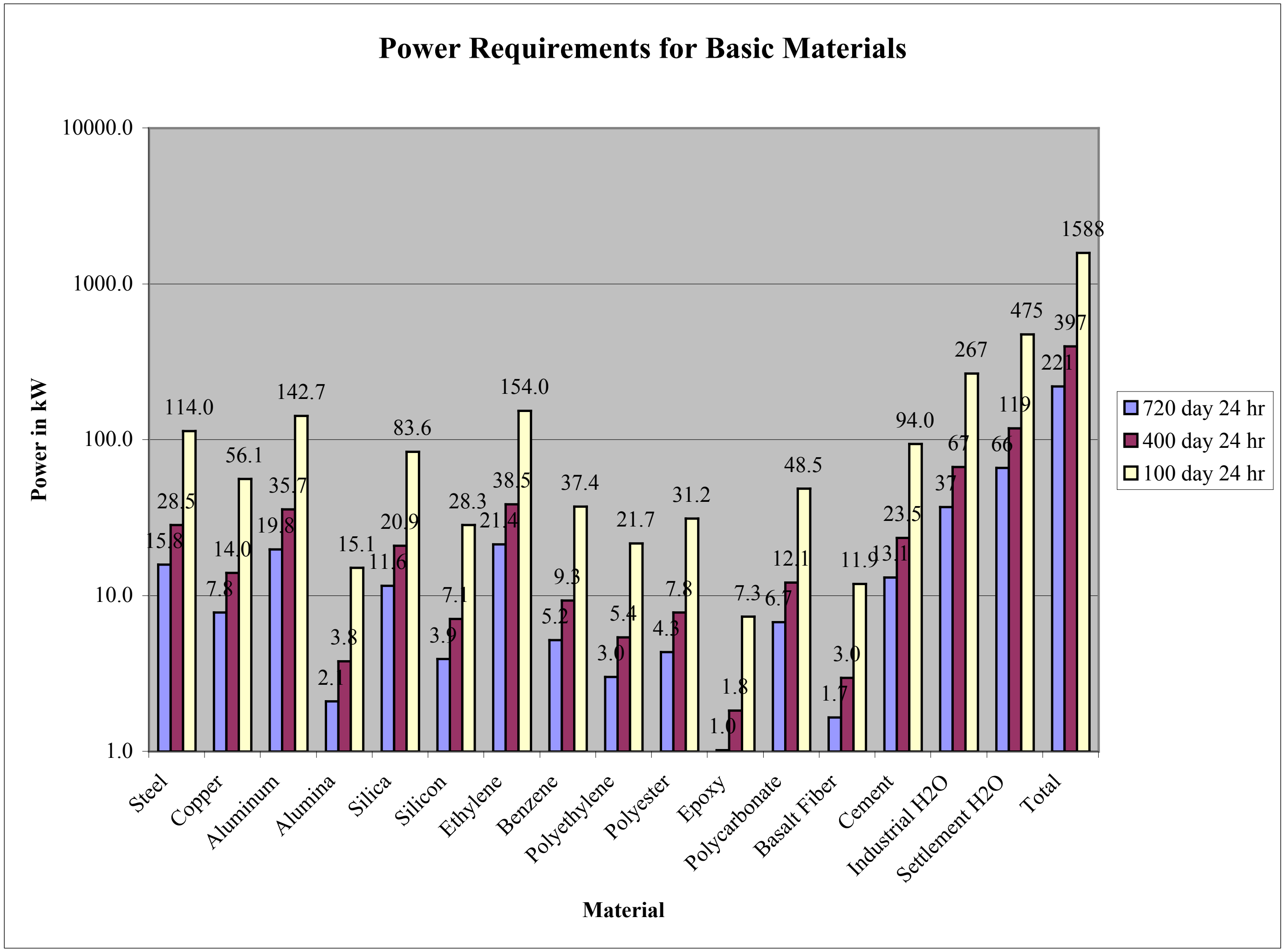
Percent of Total Mass by Material



Available Power Constrains the Rate of Production

A 400 sol continuous production cycle requires 400 kW of continuous electric power. 1 of the 3 settlement reactors supplies this power.

Alternatively 800 sols of 12 hr/sol requires 400 kW of peak electric power.



Estimating the Mass of Processing Equipment Imported from Earth

First define the Sequential Processes in Mining, Refining, Manufacturing

Operation	Process	Equipment	Comments
Iron Refining and Steel Processing	Wash hematite	cooker, heater, stirrer	
Fig. 9.5 in Smith	Evaporate water recover salts	evaporator	
	Hematite crushing	Crusher/grinder & sieve	
	Hematite Ore charging	Double bell hopper	
	MIDREX iron reduction	MIDREX shaft furnace	
	Dust removal	Dust catcher, Cyclone, Precipitator	
	Unburned Gas recycling	3 stage Scrubber CO2 removal	
	Gas heating for furnace entry	Gas Heater	
	Desulfurization	Stirred ladle with flux added to DR Fe	
	Addition of hot metal, scrap to Electric Arc Furnace	Ladle and arc melter	
	Liming of Hot metal in EAF	addition of lime flux for steel making	
	Oxygen blowing	To reduce C content to 0.5%	
	Vacuum Degassing	In EAF	Pressure dropped to Mars ambient
	Ladle extraction from EAF	Ladle furnace	
	Continuous Casting	Continuous cast line	blooms, billets, 5-150 mm slabs
Steel parts Manufacture	Preheating furnaces for hot working	CH4/O2 and Resistance furnaces	discontinuous throughput requires reheating
	Milling	multiple hot rollers, mandrels, and (perhaps) hot extrusion equipment	reduction in thickness, increase in length, change of shape
	Final shaping	multiple cold rollers, mandrels, and cold drawing equipment	I beams, channels, plates, sheets, rebar, wire, pipe
	Annealing and quenching	Furnace and water quench	For final heat treatment of part

Imported mass of equipment scales with required production rate

		Days for total production			equip mass/	Days for total production		
	Total need	**720**	**400**	**100**	daily production	**720**	**400**	**100**
Material	**kg**	**Daily production mass in kg**			**mass ratio**	**Equipment mass in kg**		
Indust. Water fr. Hydrated min.	203160	282	508	2032	72	20316	36569	146275
Cement mine-manuf	195000	271	488	1950	77	20854	37538	150150
Hematite mine	156000	217	390	1560	122	35000	35000	72000
Basalt Fiber mine-manuf.	80033	111	200	800	68	7559	13606	54422
Iron/Steel Refine-Manuf.	78000	108	195	780	228	24700	44460	177840
Ethylene synth.	58981	82	147	590	30	2458	4424	17694
Polyethylene synth. - manuf.	46400	64	116	464	60	3867	6960	27840
Polycarbonate to window manuf.	33092	46	83	331	119	5469	9845	39379
Alumina mine-manuf.	30382	42	76	304	79	3334	6000	24002
Copper mine-manuf.	28303	39	71	283	80	3145	5661	22642
Polyester synth-comp. Manuf.	27840	39	70	278	80	3093	5568	22272
Benzene synth.	26569	37	66	266	30	1107	1993	7971
Aluminum refine-manuf.	12391	17	31	124	61	1050	1890	7559
Silica mine-manuf.	5280	7	13	53	28	205	370	1478
Epoxy synth-bond manuf.	5000	7	13	50	84	583	1050	4200
Silicon refine	2000	3	5	20	38	106	190	760
Total	988431	1373	2471	9884		132845	211121	776485

- **Massive equipment needed for mining, classifying, transporting of metal bearing ores and hydrated minerals**
- **Massive metal working & manufacturing equipment specialized for rolling beams and sheet, producing bar and re-bar stock, piping**
- **400 sol production equipment is now estimated as 211 imported tonnes vs 35 tonnes in 2005 study. Cost to transport 211 tonnes to Mars is ~$2B.**

Conclusions

Alternative resource strategy established for

- water
- conductive wire
- silica containing products

The mining, refining, and manufacturing requirements defined

- chemical reactions
- temperature
- pressure
- catalysts

for members of each material class

- metals
- basalt fibers
- cement & ceramics
- chemicals and polymers

Quantities of each served as input to MRM equipment mass and production energy/power analysis.

Mars surveillance/exploration programs have enhanced the accumulation of knowledge of high grade ore locations, but these programs are science focused and not likely to answer the siting and assay questions required by an industrial permanent Mars settlement.

Several processes needed for Mars processing are, at best, at pilot plant demo stage only and are not commercial systems on Earth.

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