THE REVERSE WATER GAS SHIFT PROCESS

The Reverse Water Gas Shift (**RWGS**) process is a candidate technology **for water and oxygen production** on Mars. RWGS uses carbon dioxide and hydrogen as reactants to produce oxygen and carbon monoxide with a copper on alumina catalyst.

$$CO_2 + H_2 = CO + H_2O$$

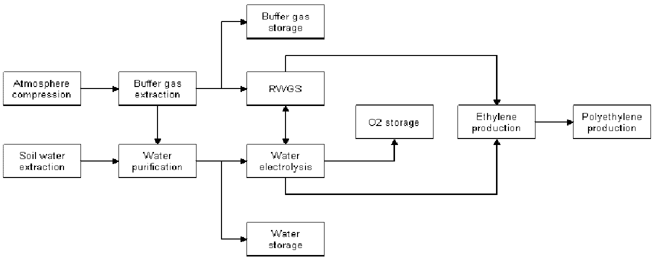
RWGS reactor can be used either as the sole component in a loop with an electrolyser as an "**infinite-leverage oxygen machine**" on Mars, or it can be used in tandem with an **SE based Mars in-situ propellant production system** to increase the leverage of such a system from **10.3/1 to 20/1**. In addition, it should be obvious that, operating without an electrolyser, a RWGS reactor can be used to leverage **imported hydrogen into water on Mars** (to augment crew consumables) with a mass leverage ratio of **9/1**. However the RWGS reactor opens up additional remarkable possibilities - RWGS based **ethylene production** system. The ethylene can be used on Mars for other applications than rocket, rover and welding fuel. It can also be used as an anesthetic, as an aid to crop production, and as the basic feedstock for the manufacture of plastics for structures, fabrics, implements, and many other uses.

Because the RWGS reaction is only mildly endothermic (9 kcal/mole for RWGS compared to 57 kcal/mole for water electrolysis), system power requirements are dominated by the water electrolysis step, the available technology for which is highly efficient. Moreover, since the thermal power required by the RWGS is less than that produced by the Sabatier reactor and their operating temperatures are comparable, a **Sabatier reactor can be used to provide the heat required to drive the RWGS reactor**.

Initial Summary:

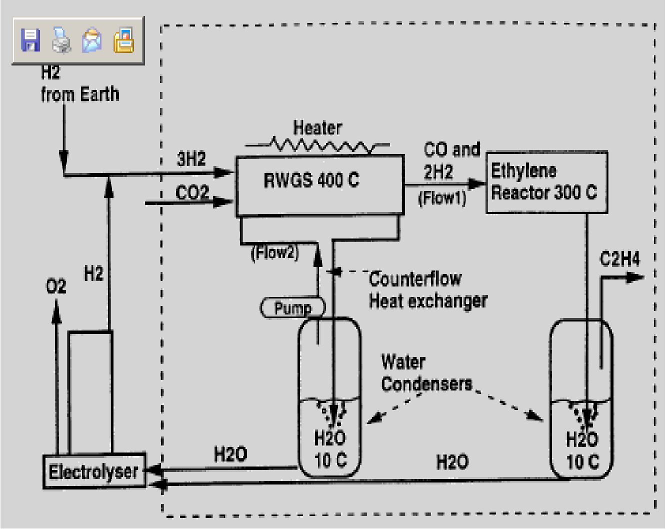
For the purposes of CO_2 separation, the RWGS is far more efficient and requires a fraction of the power, compared to solid-oxide or molten carbonate electrolysis. It is also more rugged and reliable because it uses a simple steel pipe instead of multiple brittle tubes.

- RWGS **runs on low temperature**, but **complex and heavy**!
- Integrating the Sabatier-Electrolysis Process and RWGS processes into a single unit would greatly reduce equipment mass and complexity.
- Still experimental verification is largely missing – **relatively immature technology**



Further Research:

- If ethylene is final objective in our ISRU architecture, RWGS + Ethylene Reactor should be considered. If H2 is not from Earth additionally electrolyses is probably required.
- RWGS + Sabatier Reactor = Methane, additionally separate reactor is required to produce Ethylene (from RWGS CO).
- Which scenario is economically more feasible RWGS/SE or RWGS Ethylene (See Appendix 1)?
- RWGS Ethylene has no clear experimental verification tests.



Summary of Applications and Advantages of RWGS Systems[1]:

1. The ability to manufacture any amount of oxygen on Mars. RWGS should be able to do it with a much more rugged and reliable system, on a much larger scale, with a power consumption about an order of magnitude less (compare to zirconia). If CO should be desired as a fuel, RWGS has to potential to produce it at least an order or magnitude more efficiently than a zirconia-electrolysis system.

2. RWGS reactors can also be used in tandem with electrolysis units to provide physical- chemical life support for oxygen regeneration and CO2 disposal on space stations. Compared to zirconia-electrolysis such a system is much more rugged and efficient. Compared to an SE based life support system, it has the advantage of wasting no hydrogen, and thus no water.

3. RWGS reactors offer the ability to leverage imported **hydrogen into water** on Mars with a mass leverage of **9/1**. Using a Sabatier reactor for this purpose would only produce a leverage of **4.5/1.** Using a Bosch reactor would give 9/1 leverage, but would also produce solid graphite wastes that would be difficult to manage.

4. Used as an adjunct to a **SE** Mars in-situ propellant system, the **RWGS** reactor increases net propellant leverage from **10.3:1 to 20:1**. This reduces tankage size and mass, and makes the hydrogen importation requirement for the system tractable.

5. Used as the front end of an RWGS/ethylene reactor system, the RWGS enables construction of a Mars in-situ propellant production unit which produces a high-energy propellant combination with a net leverage as high as 31/1. This is more than triple the leverage of a state of the art SE system. Moreover, the fuel produced is both denser than methane and storable on Mars without refrigeration.

6. The product ethylene can be used on Mars for other applications than rocket, rover and welding fuel. It can also be used as an anesthetic, as an aid to crop production,

---

[1] http://spot.colorado.edu/~meyertr/rwgs/rwgs.html

and as the basic feedstock for the manufacture of plastics for structures, fabrics, implements, and many other uses.

7. The RWGS/ethylene system may have important terrestrial applications as a way to produce relatively storable fuel whose combustion adds nothing to overall atmospheric CO2 concentrations.

Appendix 1

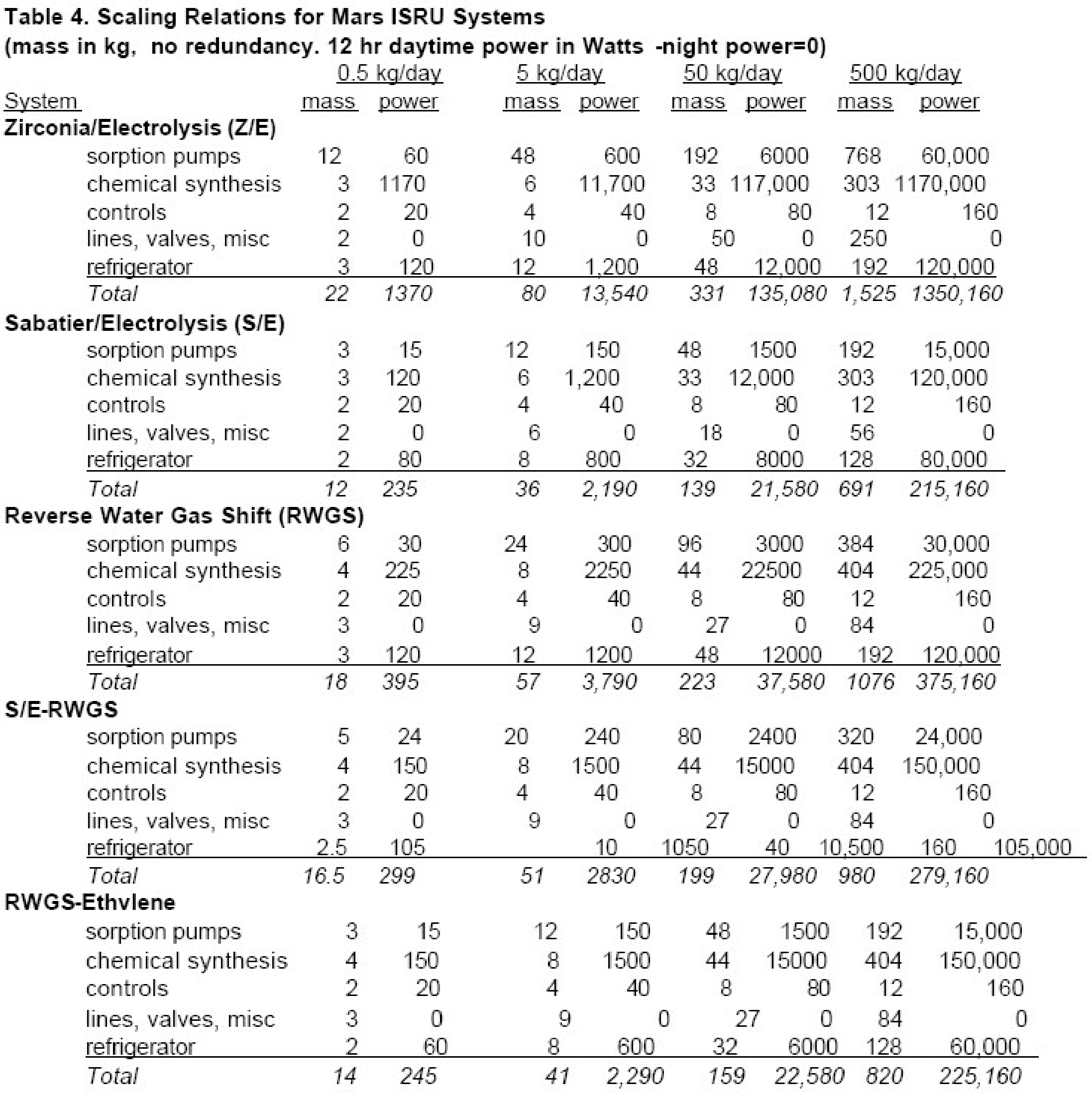
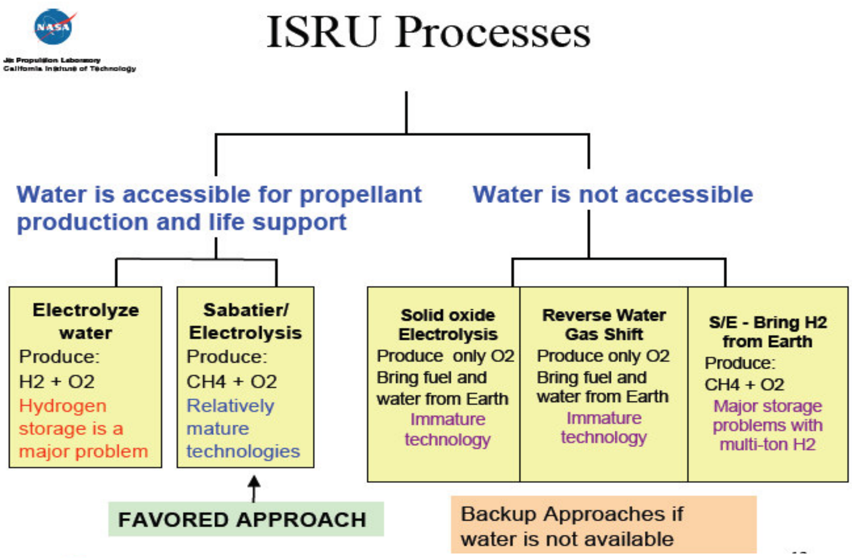


Table 4. Scaling Relations for Mars ISRU Systems
(mass in kg, no redundancy. 12 hr daytime power in Watts -night power=0)

	0.5 kg/day		5 kg/day		50 kg/day		500 kg/day		
System	mass	power	mass	power	mass	power	mass	power	
Zirconia/Electrolysis (Z/E)									
sorption pumps	12	60	48	600	192	6000	768	60,000	
chemical synthesis	3	1170	6	11,700	33	117,000	303	1170,000	
controls	2	20	4	40	8	80	12	160	
lines, valves, misc	2	0	10	0	50	0	250	0	
refrigerator	3	120	12	1,200	48	12,000	192	120,000	
Total	*22*	*1370*	*80*	*13,540*	*331*	*135,080*	*1,525*	*1350,160*	
Sabatier/Electrolysis (S/E)									
sorption pumps	3	15	12	150	48	1500	192	15,000	
chemical synthesis	3	120	6	1,200	33	12,000	303	120,000	
controls	2	20	4	40	8	80	12	160	
lines, valves, misc	2	0	6	0	18	0	56	0	
refrigerator	2	80	8	800	32	8000	128	80,000	
Total	*12*	*235*	*36*	*2,190*	*139*	*21,580*	*691*	*215,160*	
Reverse Water Gas Shift (RWGS)									
sorption pumps	6	30	24	300	96	3000	384	30,000	
chemical synthesis	4	225	8	2250	44	22500	404	225,000	
controls	2	20	4	40	8	80	12	160	
lines, valves, misc	3	0	9	0	27	0	84	0	
refrigerator	3	120	12	1200	48	12000	192	120,000	
Total	*18*	*395*	*57*	*3,790*	*223*	*37,580*	*1076*	*375,160*	
S/E-RWGS									
sorption pumps	5	24	20	240	80	2400	320	24,000	
chemical synthesis	4	150	8	1500	44	15000	404	150,000	
controls	2	20	4	40	8	80	12	160	
lines, valves, misc	3	0	9	0	27	0	84	0	
refrigerator	2.5	105		10	1050	40	10,500	160	105,000
Total	*16.5*	*299*	*51*	*2830*	*199*	*27,980*	*980*	*279,160*	
RWGS-Ethvlene									
sorption pumps	3	15	12	150	48	1500	192	15,000	
chemical synthesis	4	150	8	1500	44	15000	404	150,000	
controls	2	20	4	40	8	80	12	160	
lines, valves, misc	3	0	9	0	27	0	84	0	
refrigerator	2	60	8	600	32	6000	128	60,000	
Total	*14*	*245*	*41*	*2,290*	*159*	*22,580*	*820*	*225,160*	



Jet Propulsion Laboratory
California Institute of Technology

ISRU Processes

Water is accessible for propellant production and life support

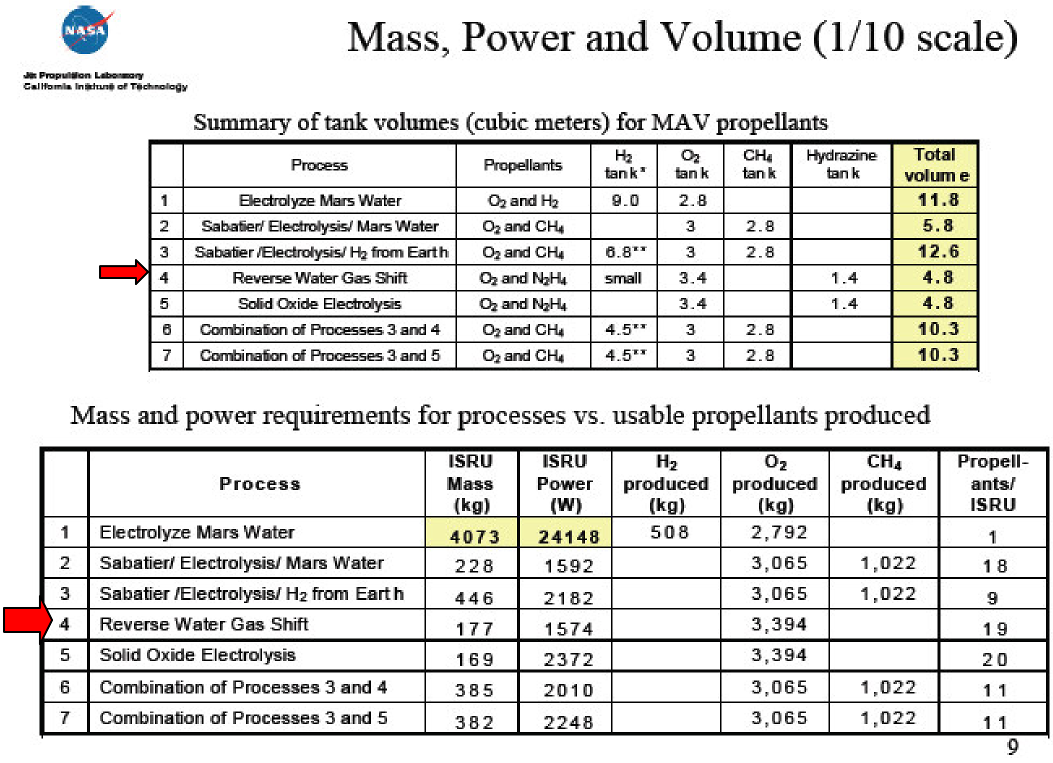
- **Electrolyze water**
  Produce:
  H2 + O2
  Hydrogen storage is a major problem
- **Sabatier/ Electrolysis**
  Produce:
  CH4 + O2
  Relatively mature technologies

↑
FAVORED APPROACH

Water is not accessible

- **Solid oxide Electrolysis**
  Produce only O2
  Bring fuel and water from Earth
  Immature technology
- **Reverse Water Gas Shift**
  Produce only O2
  Bring fuel and water from Earth
  Immature technology
- **S/E - Bring H2 from Earth**
  Produce:
  CH4 + O2
  Major storage problems with multi-ton H2

Backup Approaches if water is not available



Jet Propulsion Laboratory
California Institute of Technology

Mass, Power and Volume (1/10 scale)

Summary of tank volumes (cubic meters) for MAV propellants

	Process	Propellants	H_2 tank*	O_2 tank	CH_4 tank	Hydrazine tank	Total volume
1	Electrolyze Mars Water	O_2 and H_2	9.0	2.8			**11.8**
2	Sabatier/ Electrolysis/ Mars Water	O_2 and CH_4		3	2.8		**5.8**
3	Sabatier /Electrolysis/ H_2 from Earth	O_2 and CH_4	6.8**	3	2.8		**12.6**
➡ 4	Reverse Water Gas Shift	O_2 and N_2H_4	small	3.4		1.4	**4.8**
5	Solid Oxide Electrolysis	O_2 and N_2H_4		3.4		1.4	**4.8**
6	Combination of Processes 3 and 4	O_2 and CH_4	4.5**	3	2.8		**10.3**
7	Combination of Processes 3 and 5	O_2 and CH_4	4.5**	3	2.8		**10.3**

Mass and power requirements for processes vs. usable propellants produced

	Process	**ISRU Mass (kg)**	**ISRU Power (W)**	**H_2 produced (kg)**	**O_2 produced (kg)**	**CH_4 produced (kg)**	**Propell-ants/ ISRU**
1	Electrolyze Mars Water	**4073**	**24148**	508	2,792		1
2	Sabatier/ Electrolysis/ Mars Water	228	1592		3,065	1,022	18
3	Sabatier /Electrolysis/ H_2 from Earth	446	2182		3,065	1,022	9
➡ 4	Reverse Water Gas Shift	177	1574		3,394		19
5	Solid Oxide Electrolysis	169	2372		3,394		20
6	Combination of Processes 3 and 4	385	2010		3,065	1,022	11
7	Combination of Processes 3 and 5	382	2248		3,065	1,022	11

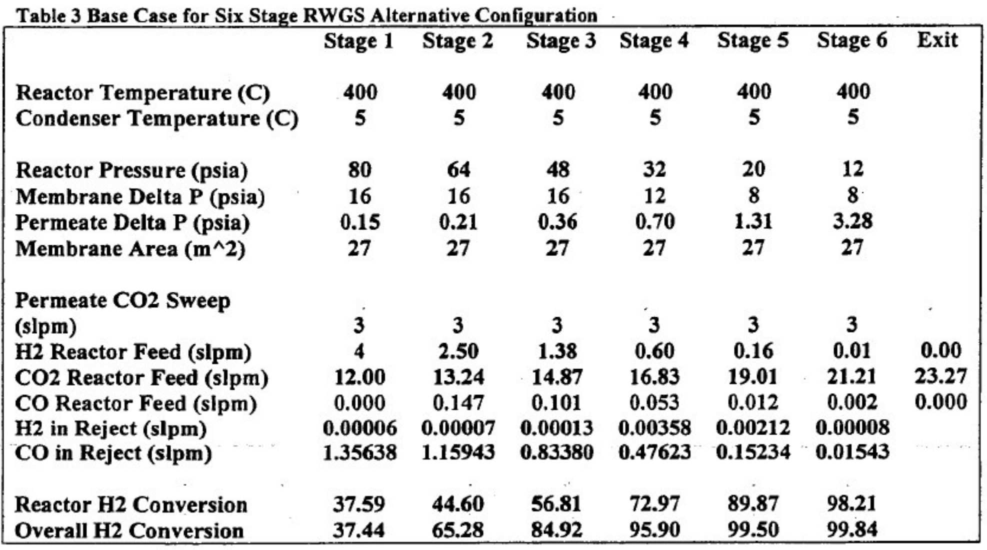


Table 3 Base Case for Six Stage RWGS Alternative Configuration

	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**	**Stage 6**	**Exit**
Reactor Temperature (C)	400	400	400	400	400	400	
Condenser Temperature (C)	5	5	5	5	5	5	
Reactor Pressure (psia)	80	64	48	32	20	12	
Membrane Delta P (psia)	16	16	16	12	8	8	
Permeate Delta P (psia)	0.15	0.21	0.36	0.70	1.31	3.28	
Membrane Area (m^2)	27	27	27	27	27	27	
Permeate CO2 Sweep (slpm)	3	3	3	3	3	3	
H2 Reactor Feed (slpm)	4	2.50	1.38	0.60	0.16	0.01	0.00
CO2 Reactor Feed (slpm)	12.00	13.24	14.87	16.83	19.01	21.21	23.27
CO Reactor Feed (slpm)	0.000	0.147	0.101	0.053	0.012	0.002	0.000
H2 in Reject (slpm)	0.00006	0.00007	0.00013	0.00358	0.00212	0.00008	
CO in Reject (slpm)	1.35638	1.15943	0.83380	0.47623	0.15234	0.01543	
Reactor H2 Conversion	37.59	44.60	56.81	72.97	89.87	98.21	
Overall H2 Conversion	37.44	65.28	84.92	95.90	99.50	99.84	