Moon Rocks into Spacecraft LOX: Modernizing a Study and Comparing Reactions

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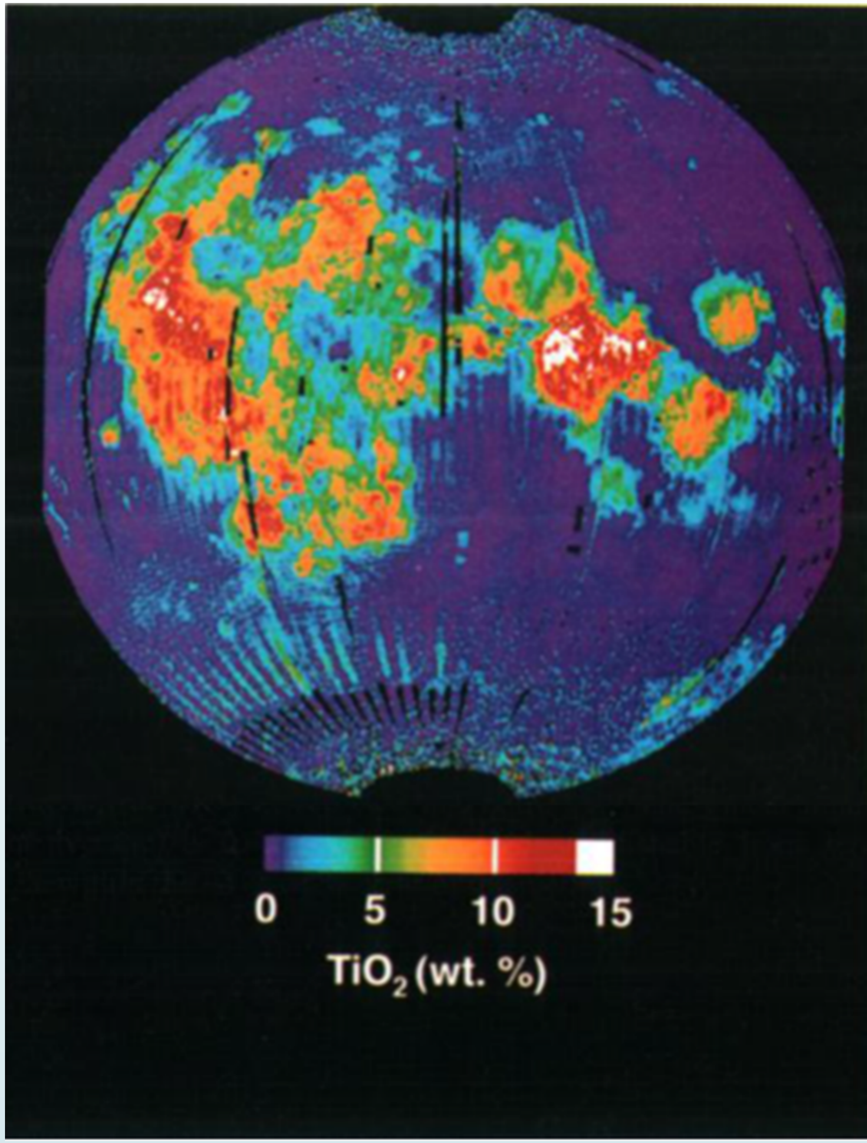
Space Resources Roundtable 2016

Introduction

- Why return to the Moon?
  - Stepping stone for deep space missions
  - Science!
  - Resources: fuel
    - Rocks -> O_2 -> LOX

Background – O_2 Source

- O_2 Sources:
  - Ice in permanently shadowed craters
  - Minerals in regolith
- Lunar Minerals Distribution
  - Highlands - silicates
  - Mare - oxide metals
    - $FeTiO_3$: 15 – 20 vol %
    - $[TiO_2] \propto [FeTiO_3]$



1994 Clementine lunar map
Lucey et al. (1998)

Eagle Engineering, Inc. Study

- Contract with JSC (1988)
- Lunar LOX pilot plant
  - 2 mt/month
- Ilmenite best feedstock
- One big plant > many small
  - Less mass redundancies
- Pilot plant stats
  - 24.7 mt [mass]
  - 146 kW [power needed]
  - H_2 reduction

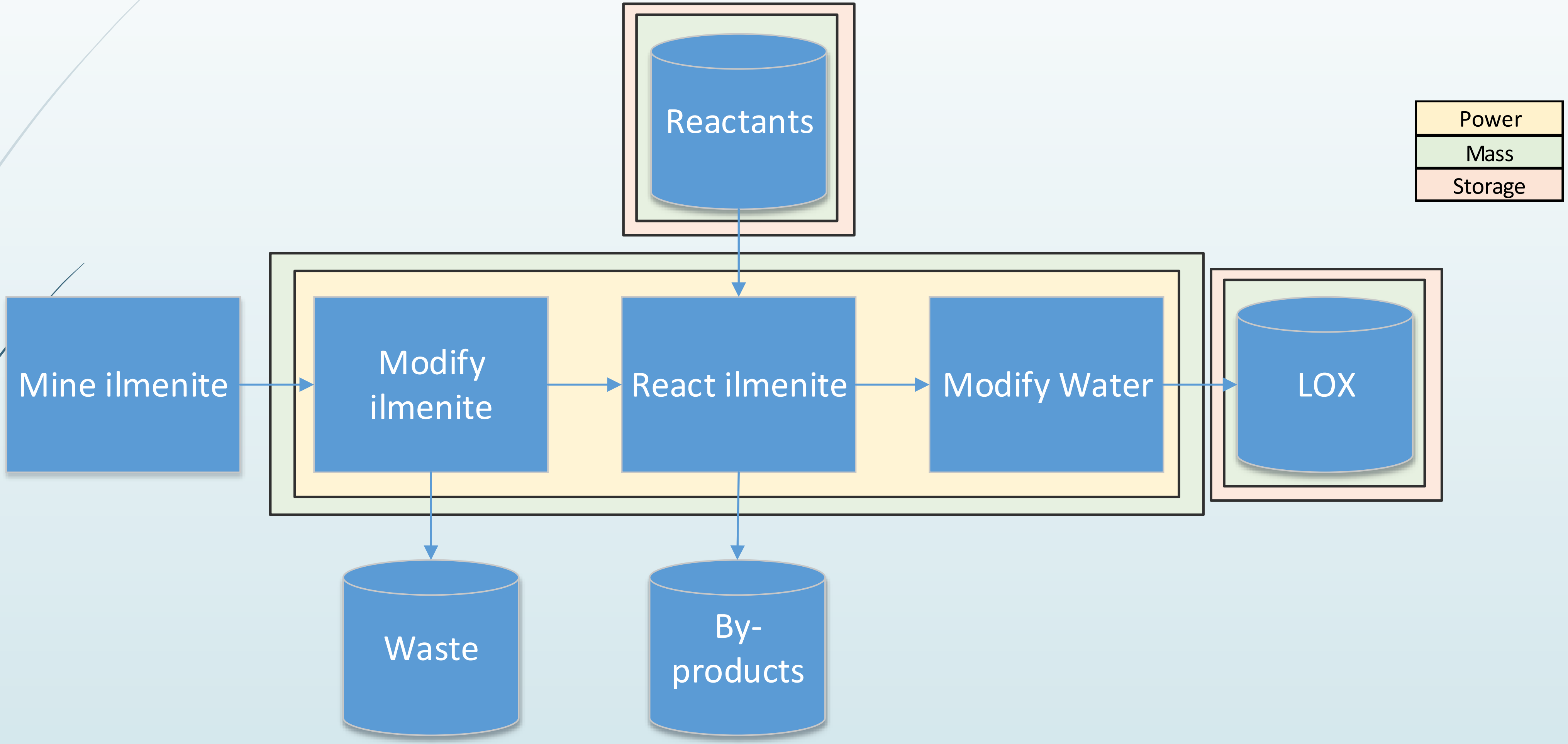
Problem Statement

- The Eagle Engineering, Inc. (EEI) report provides a detailed procedure to harvest LOX from the Moon, but it is outdated and could benefit from the modernization of its hardware as well as a cross-analysis of other potential extraction reactions.

Scope of Study

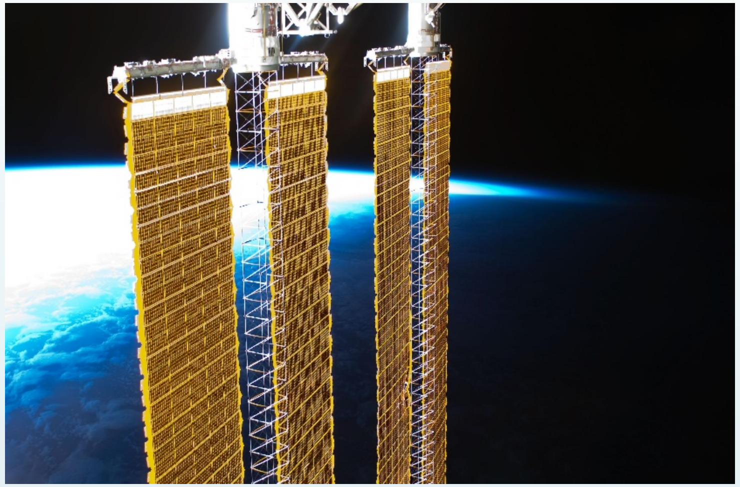
- Objective 1: Modernization of facility components
  - Power
  - Mass
  - Storage
- Objective 2: Compare reactions for optimal output
  - H_2 reduction
  - CO reduction
  - Carbochlorination

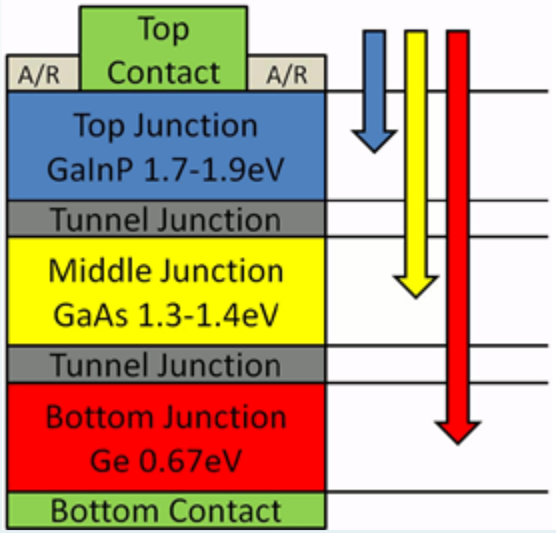
Eagle Engineering Process Schematic – Lite



Modernization – Power: PV Cells

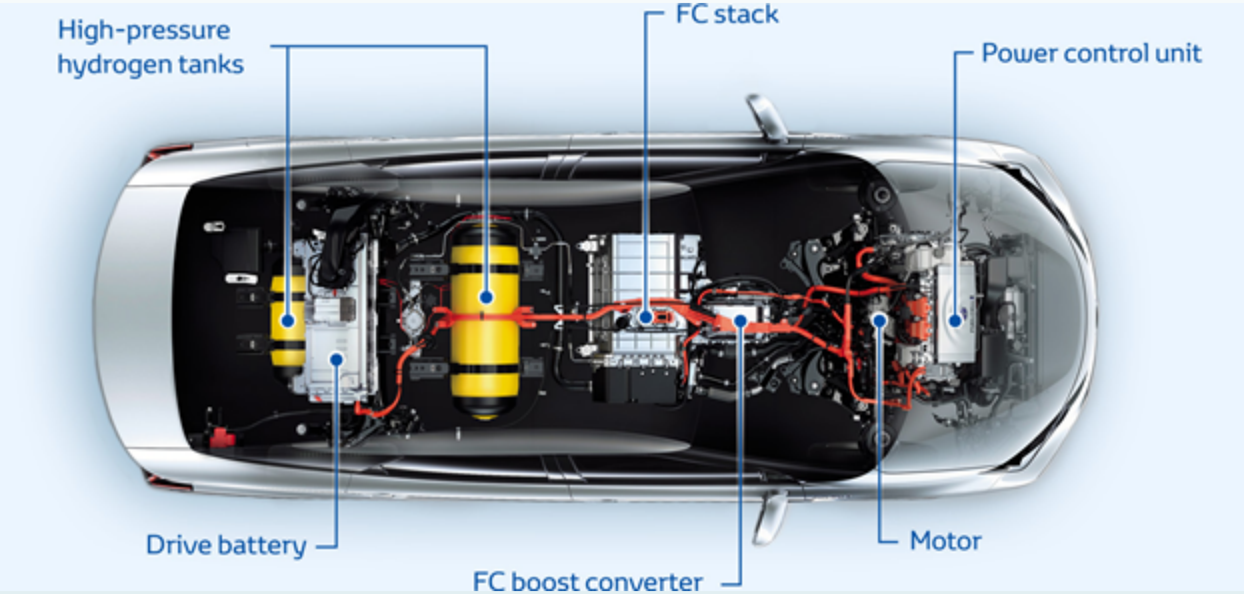
- Photovoltaic (PV) Cells
- 146 kW needed
  - 131 kW = operations
  - 15 kW = charge fuel cell
- ISS Panels
  - 8.74 m x 29.1 m
  - 7 panels, 86 W/m^2
  - 1368 W/m^2 (lunar surface)
- Eff. ~ 6.3%





PV System	Efficiency (%)
Eagle Engineering	6.3
Modern Consumer-grade	15
Modern Commercial-grade	23
Multi-junction Cell	44

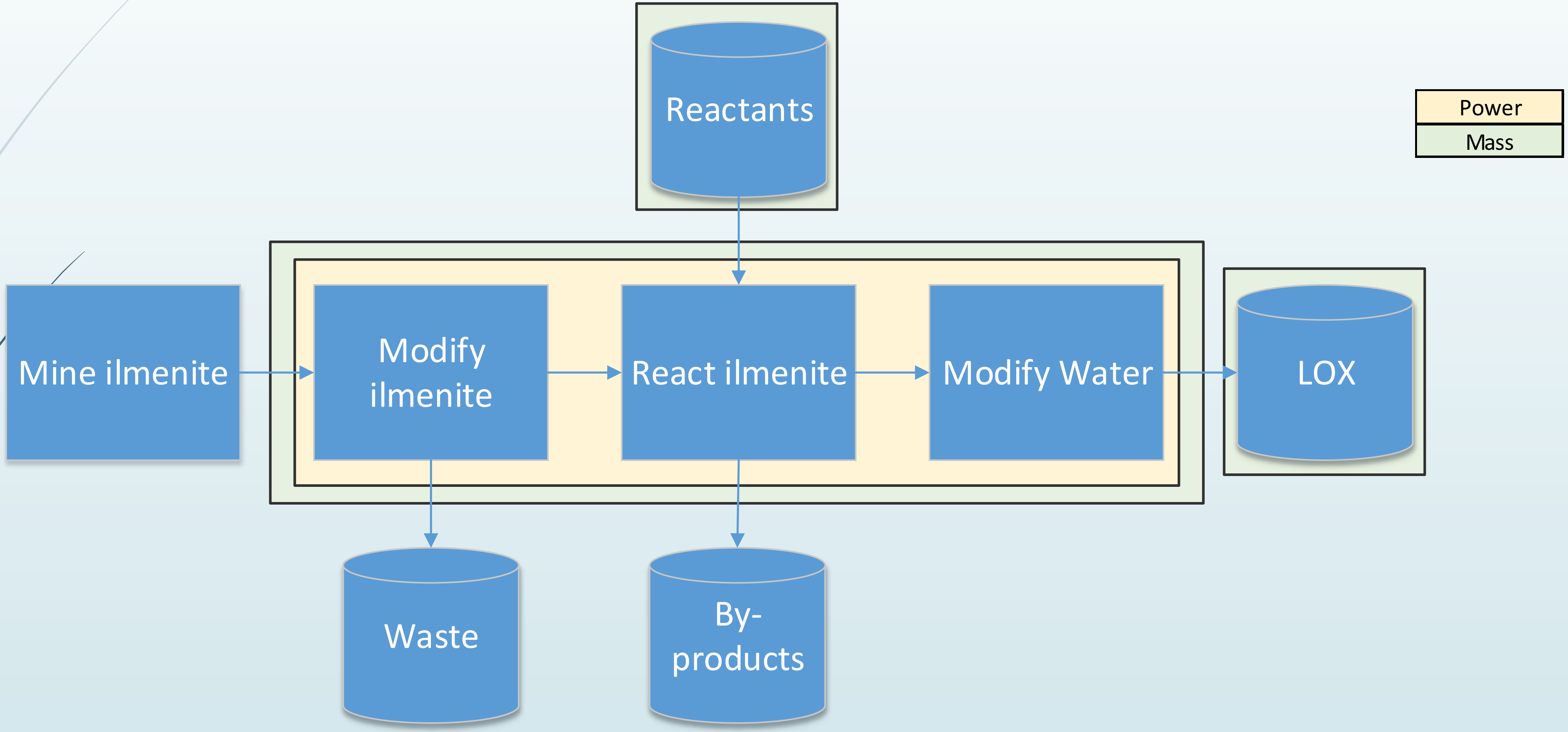
Modernization – Power: Fuel Cells



- 3200 kW-hr capacity
  - 9.6 kW needed
  - 336 hours (14 days)
  - "Hot-standby"
- Adjusted Operating Time
  - 114 kW → 9.6 kW
  - 2.9 hours → 34.4 hours

Fuel Cell	Op. Time (hr)	Output (kW)	Op. Time @ 9.6 kW (hr)
Eagle Engineering	336	9.6	336
Honda Clarity	2.31	100	24.1
Hyundai Tucson	2.65	100	27.6
Toyota Mirai	2.9	114	34.4

Eagle Engineering Process Schematic – Lite



Modernization – Mass: PV System

- For 146 kW output
- At least >50% mass savings
  - Assuming linear efficiency vs. mass

PV System	Efficiency (%)	Mass (kg)	kg / kW
Eagle Engineering	6.3	5721	39.2
Modern Consumer-grade	15	2452	16.8
Modern Commercial-grade	23	1635	11.2
Multi-junction Cell	44	817	6

Modernization – Mass: Fuel Cell

- Given 3200 kW-hr capacity
- 10 fuel cells required
  - 144.5 kg each

Fuel Cell	Eagle Engineering	Totoya Mirai
Output (kW)	9.6	114
Mass (kg)	3285	144.5
Adjusted Operating Time (hr)	336	34.4
Quantity for 3200 kW-hr	1	10
Total Mass (kg)	3285	1445

Modernization – Mass: Storage Tanks

- Eagle Engineering
  - High leak rate
  - "Maximum 93.36 kg/day boil-off of LOX"
- Chai et al. (2014)
  - Orbital fuel depot
- Extremely low boil-off losses vs. Eagle Engineering
  - More massive

Storage Tank	LOX Boil-off (kg/day)	Tank Mass (kg)	Boil-off/Tank Mass
Eagle Engineering	93.4	109.5	0.853
Chai et al. (2014)	0.017	680	0.000025

Modernization – Storage Tanks

- Chai et al. (2014)
  - Multi-layer insulation (MLI)
  - Active cryogenic cooler

Boil-off Rates		
Storage	**LOX (kg/day)**	**LH_2 (kg/day)**
Eagle Engineering	93.40	0.071
Modern, passive	0.017	0.011
Modern, active	0.008	0.005
Modern, future	0.000	0.000
Power Required (W)	**LOX (W)**	**LH_2 (W)**
Eagle Engineering	0	0
Modern, passive	0	0
Modern, active	80	10
Modern, future	105	122

Modernization – Summary

- Almost all substantial improvements
- Achieved with equipment available today

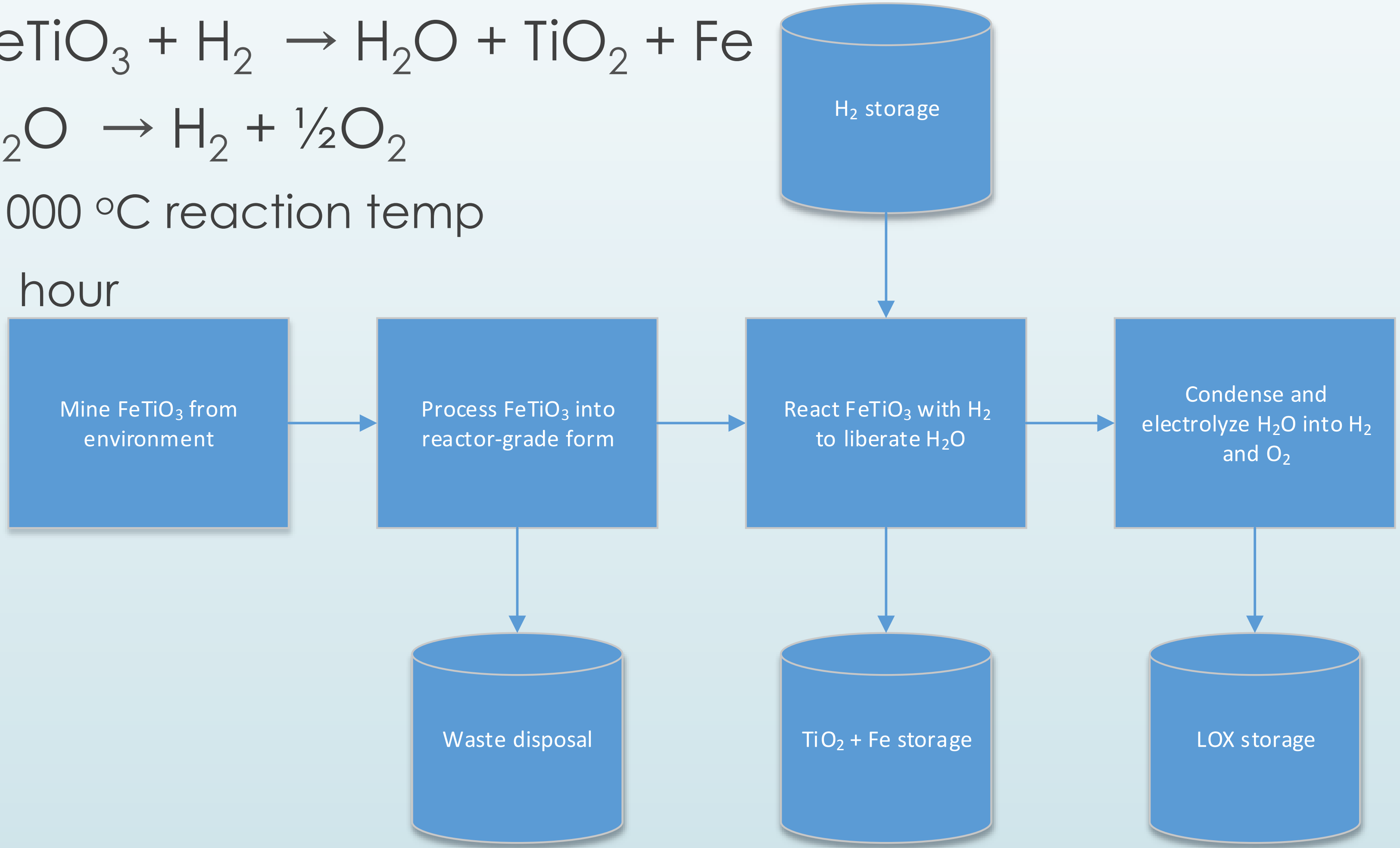
Eagle Engineering vs. Modernized Comparison Chart			
Power	**Eagle Engineering**	**Modernized**	**Savings**
PV System	Many panels at 6.3% eff.	Few panels at higher eff.	**8.7% / 16.7% / 37.7% eff.**
Fuel Cell	Few large tanks	Multiple small stacks	**Flexibility, small form factor**
Mass	**Eagle Engineering**	**Modernized**	**Savings**
PV System	5721 kg	817 - 2451 kg	**3270 - 4904 kg (57% - 86%)**
Fuel Cell	3285 kg	1445 kg	**1840 kg (56%)**
Storage Tanks	109.5 kg	680 kg	**-570.5 kg (-84%)**
Storage	**Eagle Engineering**	**Modernized (passive)**	**Savings**
LOX	93.4 kg/day	0.017 kg/day	**93.383 kg/day (99%)**
LH2	0.071 kg/day	0.011 kg/day	**0.06 kg/day (84%)**

Objective 2: Process Comparison

- Extraction Reactions
  - H_2 Reduction
  - CO Reduction
  - Carbochlorination
- Pros and Cons: “What do you want?”
  - Product(s)?
  - Versatility?
  - Complexity?

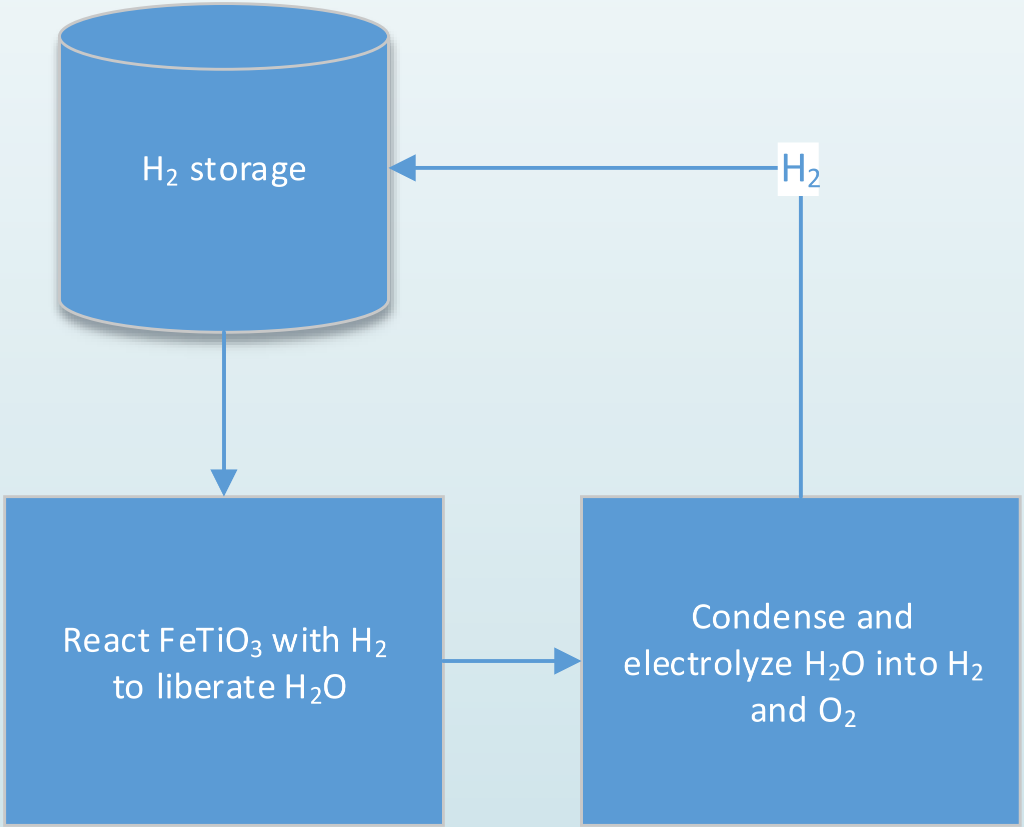
Process Comparison - H_2 Reduction

- 1) $FeTiO_3 + H_2 \rightarrow H_2O + TiO_2 + Fe$
- 2) $H_2O \rightarrow H_2 + ½O_2$
  - 1000 °C reaction temp
  - 1 hour



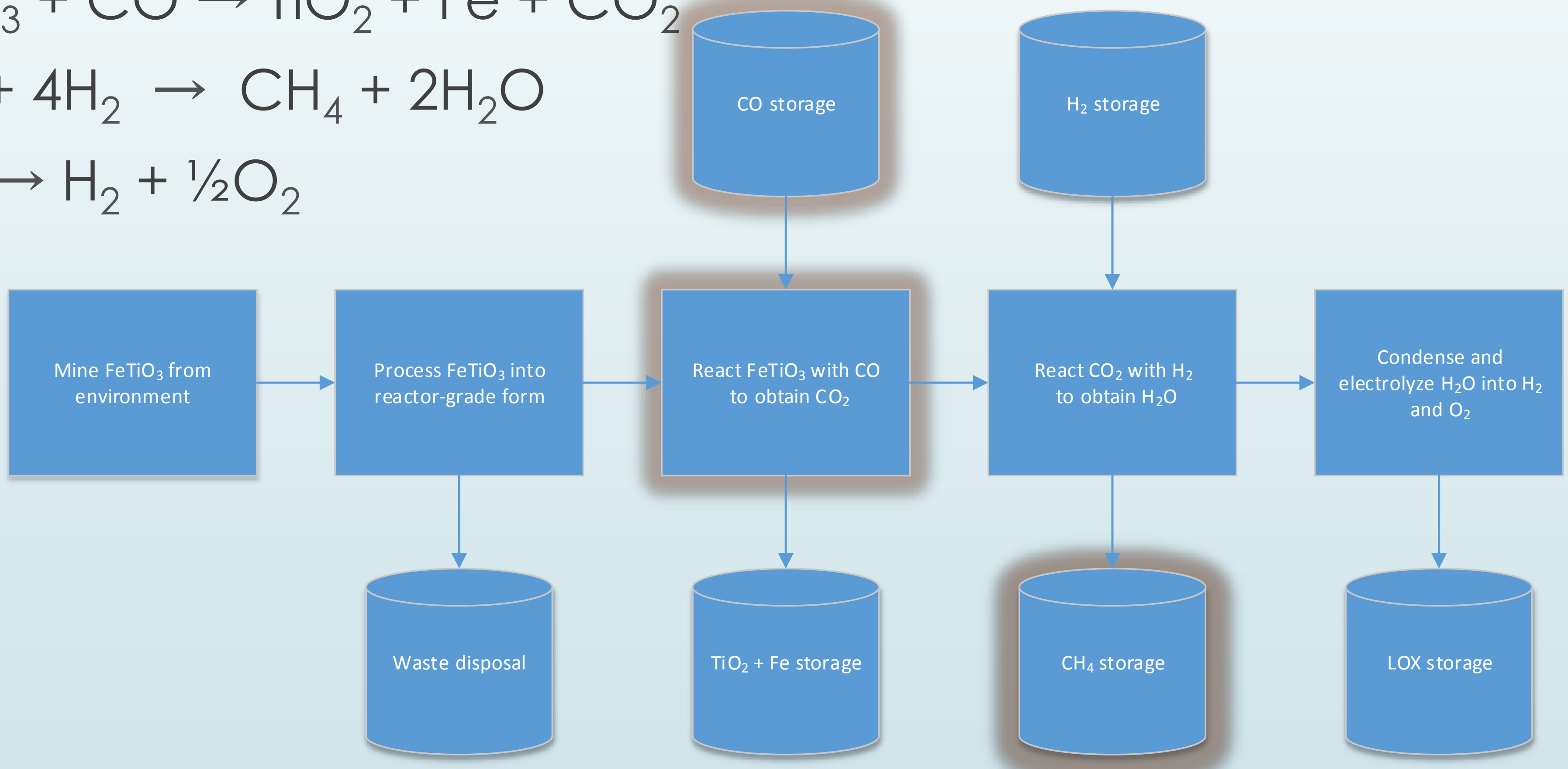
H_2 Reduction – Recycling Reactant

- Integrated into process



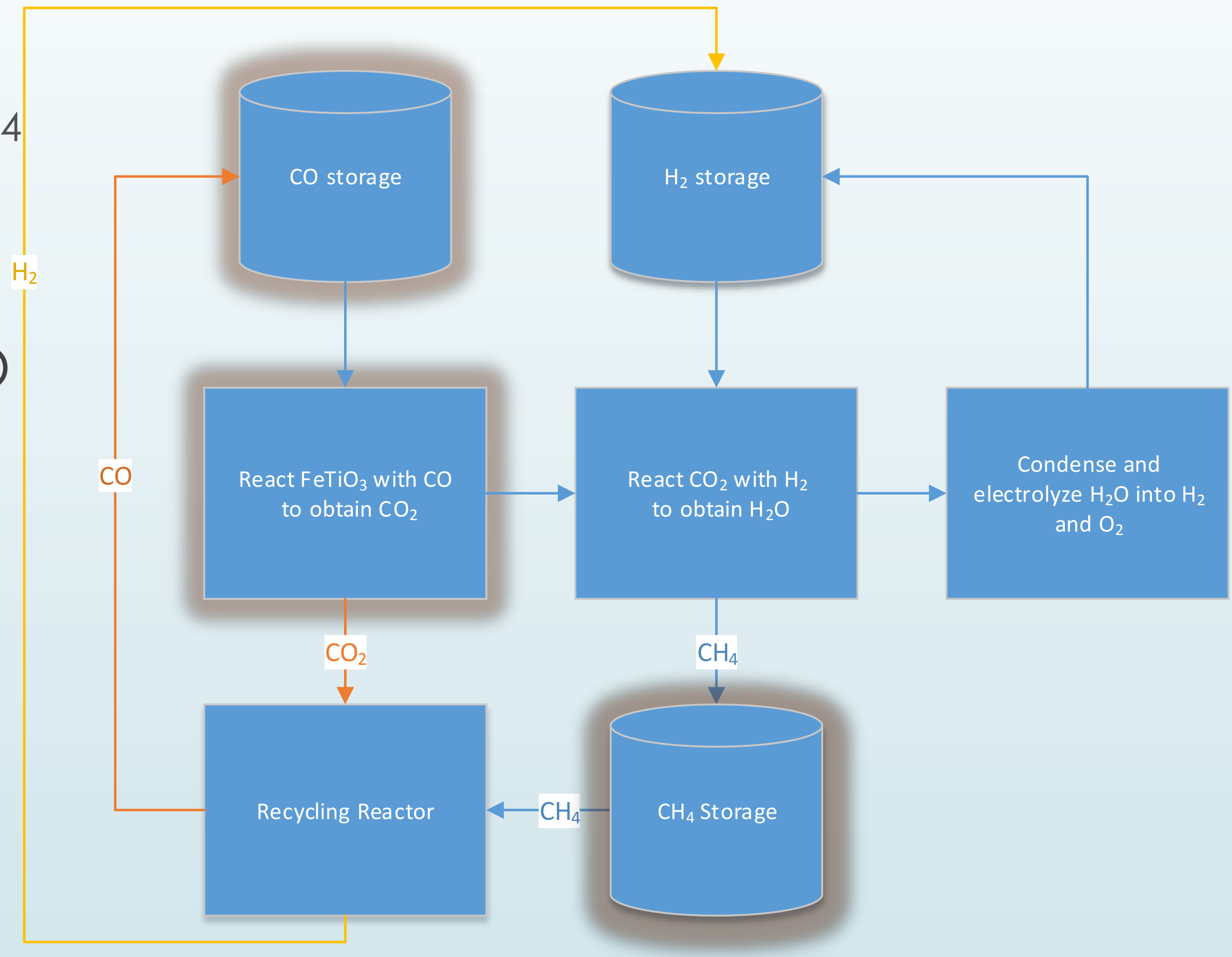
Process Comparison - CO Reduction

- Similar to H_2 Reduction
  - 1 hour, 1000 °C
- 1) $FeTiO_3 + CO \rightarrow TiO_2 + Fe + CO_2$
- 2) $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
- 3) $H_2O \rightarrow H_2 + ½O_2$



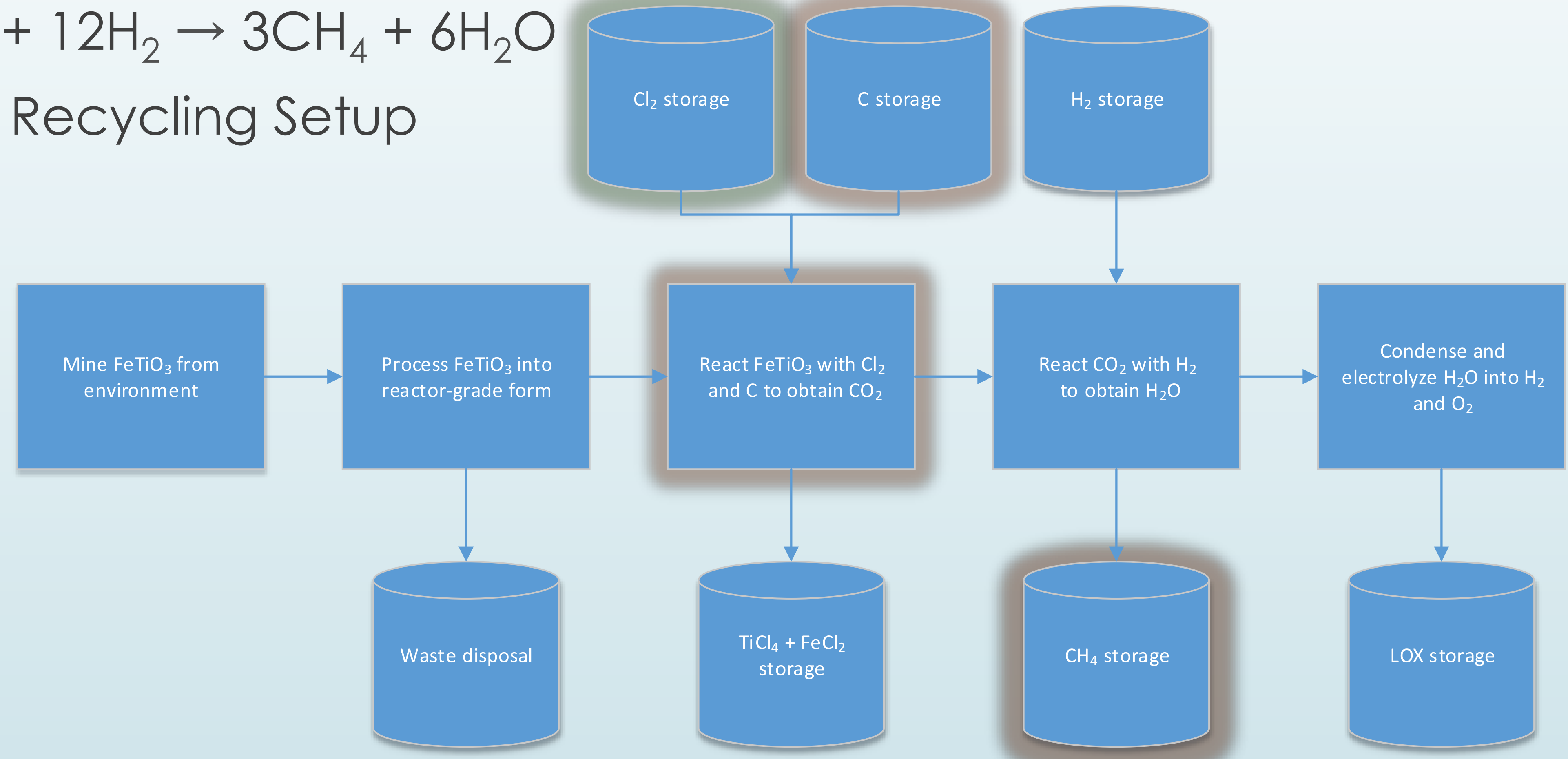
CO Reduction - Recycling Reactant

- Recycling Reactor: CH_4
  - $CH_4 \rightarrow C + 2H_2$
  - 1200 °C
- Recycling Reactor: CO
  - $C + CO_2 \rightarrow 2CO$
  - 1150 °C
- Separate reactions
- Separate times
- Uses ilmenite CO_2



Process Comparison - Carbochlorination

- Similar to CO Reduction
- $2FeTiO_3 + 6Cl_2 + 3C \rightarrow 2FeCl_2 + 2TiCl_4 + 3CO_2$
- $3CO_2 + 12H_2 \rightarrow 3CH_4 + 6H_2O$
- Same Recycling Setup



Processes – Pros and Cons

- Products and Versatility
  - By-products desired?
  - Future changes?
- Complexity
  - More is worse

Process	Products	Versatility	Complexity
H_2 Reduction	3	Low	Low
CO Reduction	4	Medium	Medium
Carbochlorination	4	Medium	High

Processes – Energy Needed

- H_2 Reduction least energy intensive
- CO Reduction/Carbochlorination similar

Process	H_2 Reduction	CO Reduction	Carbochlorination
Reaction 1	$FeTiO_3 + H_2 \rightarrow H_2O + TiO_2 + Fe$	$FeTiO_3 + CO \rightarrow CO_2 + TiO_2 + Fe$	$2FeTiO_3 + 6Cl_2 + 3C \rightarrow 3CO_2 + 2FeCl_2 + 2TiCl_4$
Reaction 1 Temp	1050 °C	1000 °C	1000 °C
Reaction 2	-	$CO_2 + 4H_2 \rightarrow + CH_4 + 2H_2O$	$3CO_2 + 12H_2 \rightarrow 3CH_4 + 6H_2O$
Reaction 2 Temp	-	1000 °C	1000 °C
Recycle 1	(electrolysis)	$CH_4 \rightarrow C + 2H_2$	$CH_4 \rightarrow C + 2H_2$
Recycle 1 Temp	-	1200 °C	1200 °C
Recycle 2	-	$C + CO_2 \rightarrow 2CO$	$C + CO_2 \rightarrow 2CO$
Recycle 2 Temp	-	1150 °C	1150 °C

Processes – Moles Reactant vs. Moles Product

- Carbochlorination is best extractor of O_2

Reactant	H_2 Reduction	CO Reduction	Carbochlorination
$FeTiO_3$	2	1	0.666
H_2	2	4	4
CO	-	1	-
C	-	-	1
Cl_2	-	-	2
Product	**H_2 Reduction**	**CO Reduction**	**Carbochlorination**
Fe	2	1	-
TiO_2	2	1	-
$TiCl_4$	-	-	0.666
$FeCl_2$	-	-	0.666
O_2	1	1	1

Processes – By-product Profit Calculator Lookup Table

Reactant	Molar Mass (kg/mol)	H_2 Red. Reactant kg/1 kg O_2	CO Red. Reactant kg/1 kg O_2	Carbochlor. Reactant kg/1 kg O_2
$FeTiO_3$	0.152	9.48	4.74	3.16
H_2	0.002	0.13	0.25	0.25
CO	0.028	-	0.88	-
C	0.012	-	-	0.38
Cl_2	0.071	-	-	4.43
Product	**Molar Mass (kg/mol)**	**H_2 Red. Product kg/1 kg O_2**	**CO Red. Product kg/1 kg O_2**	**Carbochlor. Product kg/1 kg O_2**
Fe	0.056	3.49	1.75	-
TiO_2	0.080	4.99	2.50	-
$TiCl_4$	0.190	-	-	3.95
$FeCl_2$	0.127	-	-	2.64

Processes – By-product Profit Calculator

Reactant	Cost ($/kg)	Product	Price ($/kg)
CO		TiO_2	
Cl_2		Fe	
H_2		$FeCl_2$	
C		$TiCl_4$	

Process	H_2 Reduction	CO Reduction	Carbochlorination
Reactant Cost ($/1 kg Oxygen)	$0.00	$0.00	$0.00
Product Price ($/1 kg Oxygen)	$0.00	$0.00	$0.00
Profit?	$0.00	$0.00	$0.00

Processes – Summary

- Score value
  - Red = 1, Orange = 2, Green = 3
- H_2 Reduction = 9
- CO Reduction = 7
- Carbochlorination = 7

Processes	H_2 Reduction	CO Reduction	Carbochlorination
Products	3	4	4
Versatility	Low	Medium	Medium
Complexity	Low	Medium	High
Energy Needed	Low	High	High
Ilmenite Needed	2	1	0.666
Profit	?	?	?

Project Summary - Totals

- Objective 1
  - Power eff. increase
    - **9% - 38%** (143% - 603%)
  - Mass reduction
    - **3969 - 5603 kg** (43% - 61%)
  - LOX Boil-off reduction
    - **93.329 kg/day** (99%)
- Objective 2
  - H_2 reduction = 9
  - CO reduction = 7
  - Carbochlorination = 7

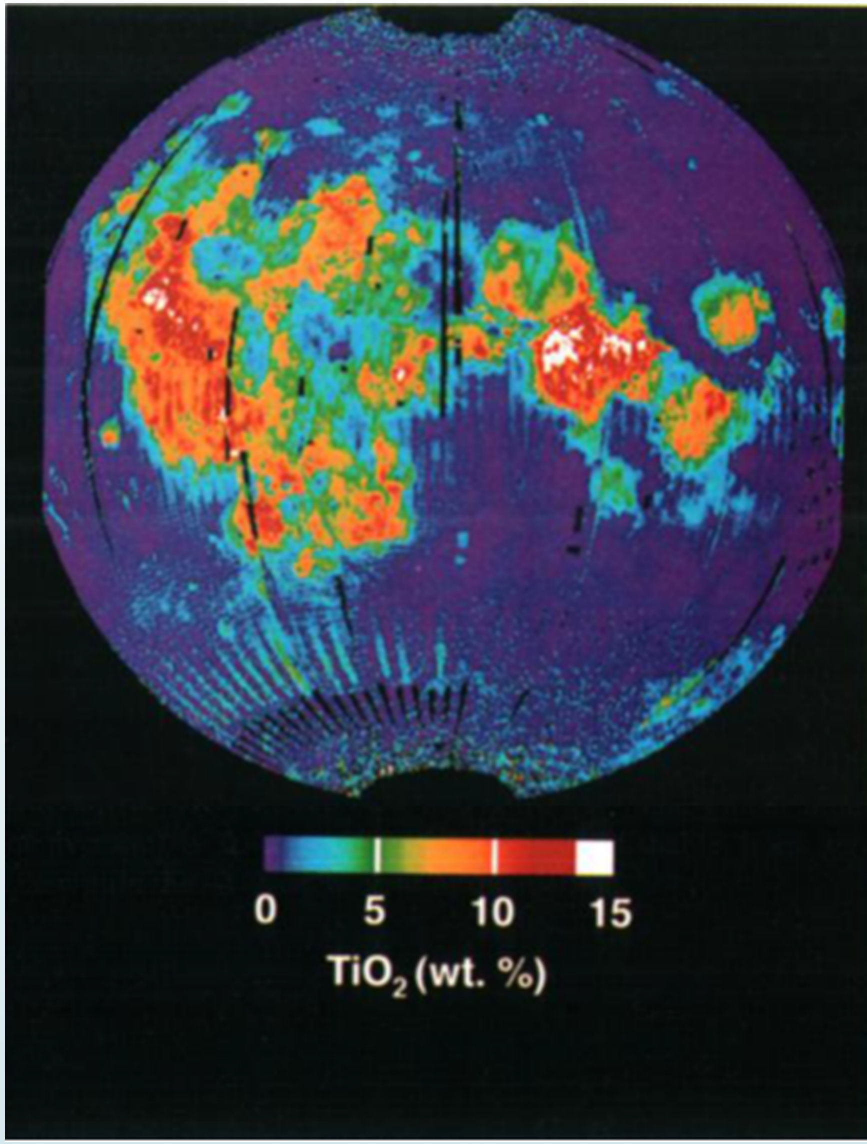
Conclusion

- Modernization of EEI's design is possible today
- Optimized design
  - Lowered mass = lowered launch costs
  - Less LOX lost

- Processes are goal dependent
- Profitability for by-products assumes terrestrial prices
  - Lunar "premium"

Future Work

- Base Design
  - Footprint
- Base Location
  - Which mare?
- Re-fueling options
  - Delivery to LEO?
  - “Lunar gas station”?

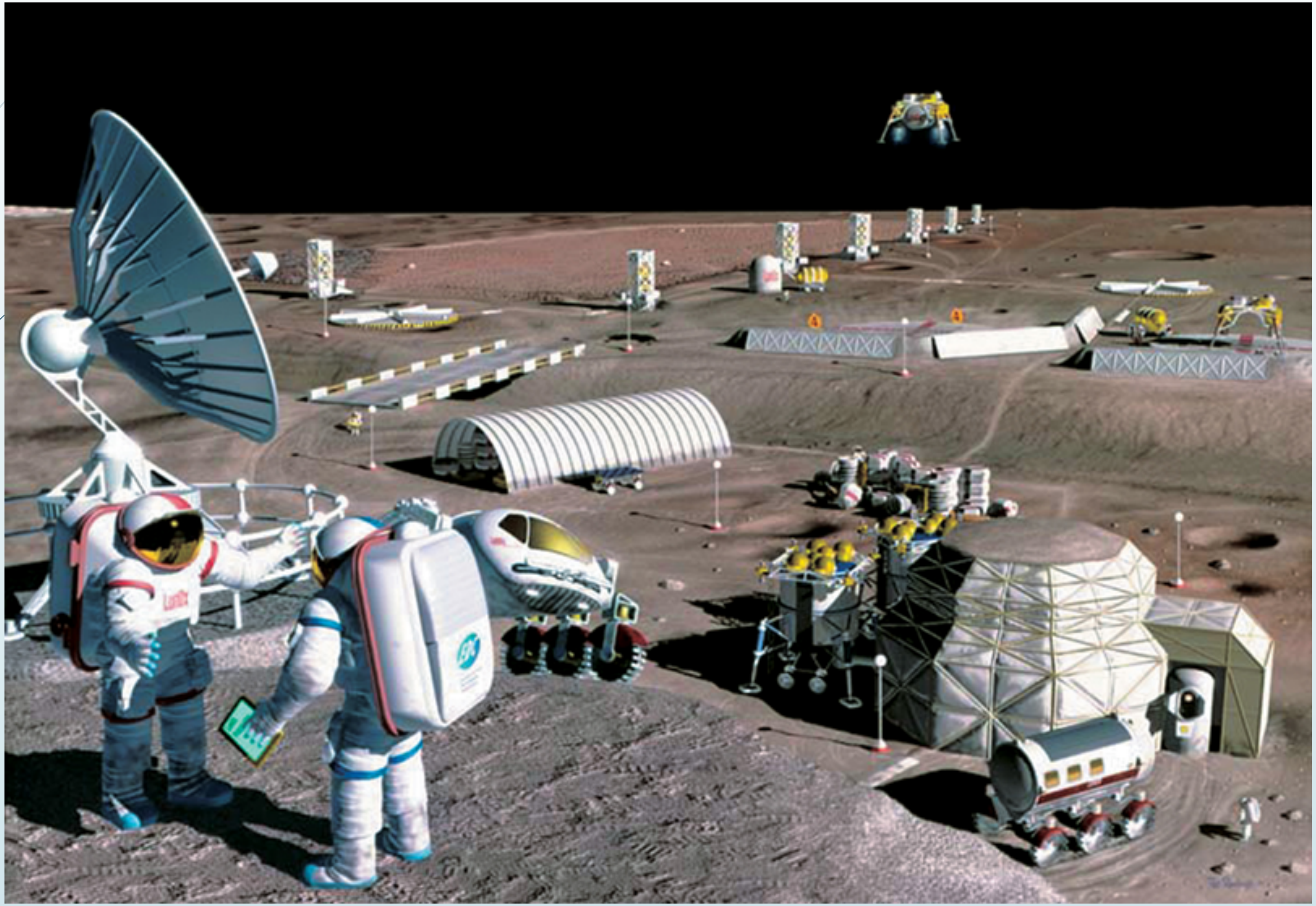


1994 Clementine lunar map
Lucey et al. (1998)

Acknowledgements

- North Dakota Space Grant Consortium (NDSGC)
- University of North Dakota
- Space Studies Department
  - Dr. James Casler
  - Marissa and Caitlin (Marlin)

Questions?



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Modernization: CO Reduction Additional Mass

- Additional 224 kg to H_2 Reduction process
  - 1365 kg for modern components

Name	Eagle Engineering Mass (kg)	Modern Mass (kg)
Cyclone Separator (2)	2	2
Methane Storage Tank	109.5	680
CO Storage Tank	109.5	680
CO Heater	0.1	0.1
CO Blower	3	3
Fischer-Tropsch Reactor	0.1	0.1
Total Added	224.2	1365.2

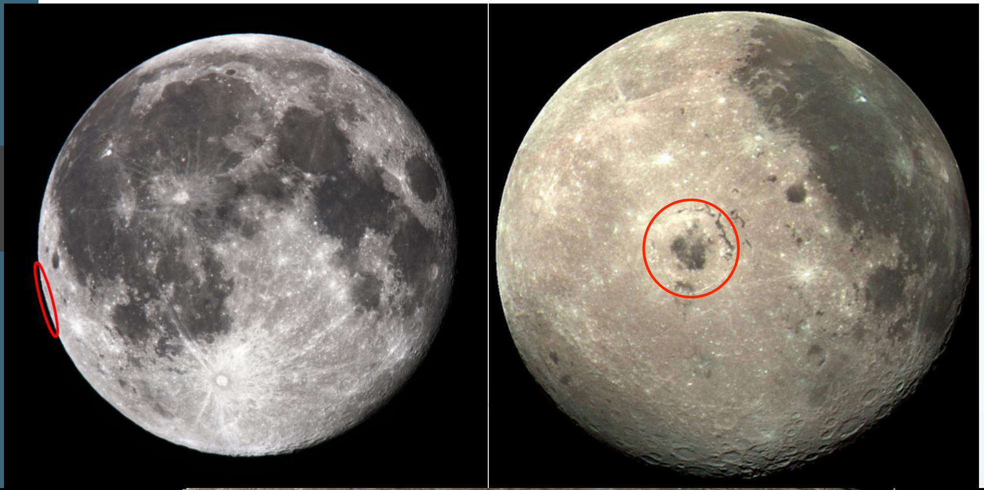
Modernization: Carbochlorination Mass and Power

- Additional 333.7 kg to H_2 Reduction process
  - One tank extra to CO Reduction process
  - 1475 kg for modern components

Name	Eagle Engineering Mass (kg)	Modern Mass (kg)
Cyclone Separator (2)	2	2
Methane Storage Tank	109.5	680
Cl Storage Tank	109.5	680
Cl Heater	0.1	0.1
Cl Blower	3	3
Fischer-Tropsch Reactor	0.1	0.1
C Storage Tank	109.5	109.5
Total Added	333.7	1474.7

Potential Markets

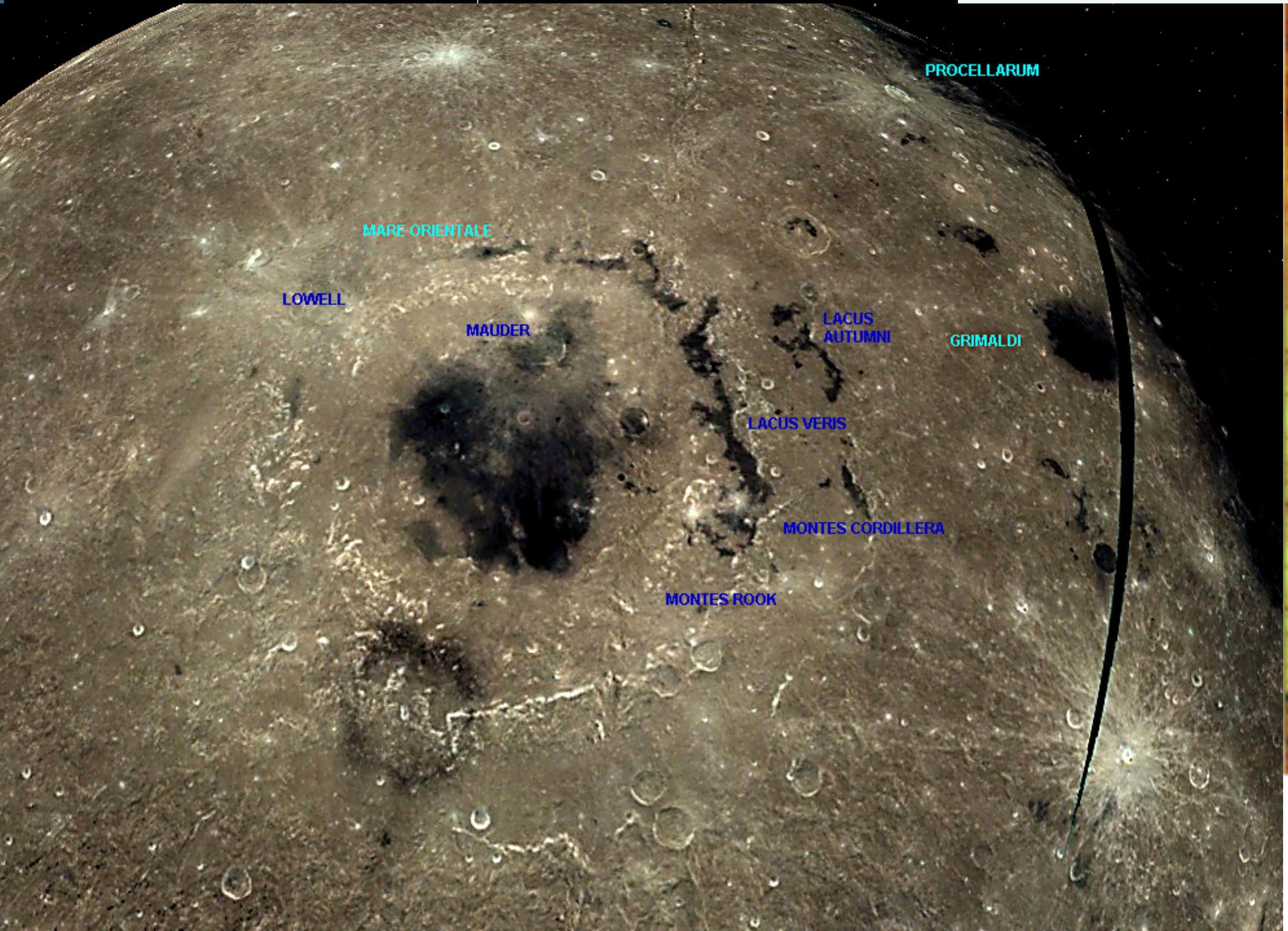
- LEO re-fuelling
  - Enable missions otherwise too difficult/expensive
- Satellite servicing
  - Extend lifetime of satellites
  - Expand satellite industry
- Inter-lunar base
  - Provide O_2 for base
- Intra-lunar base
  - Fuel a local economy

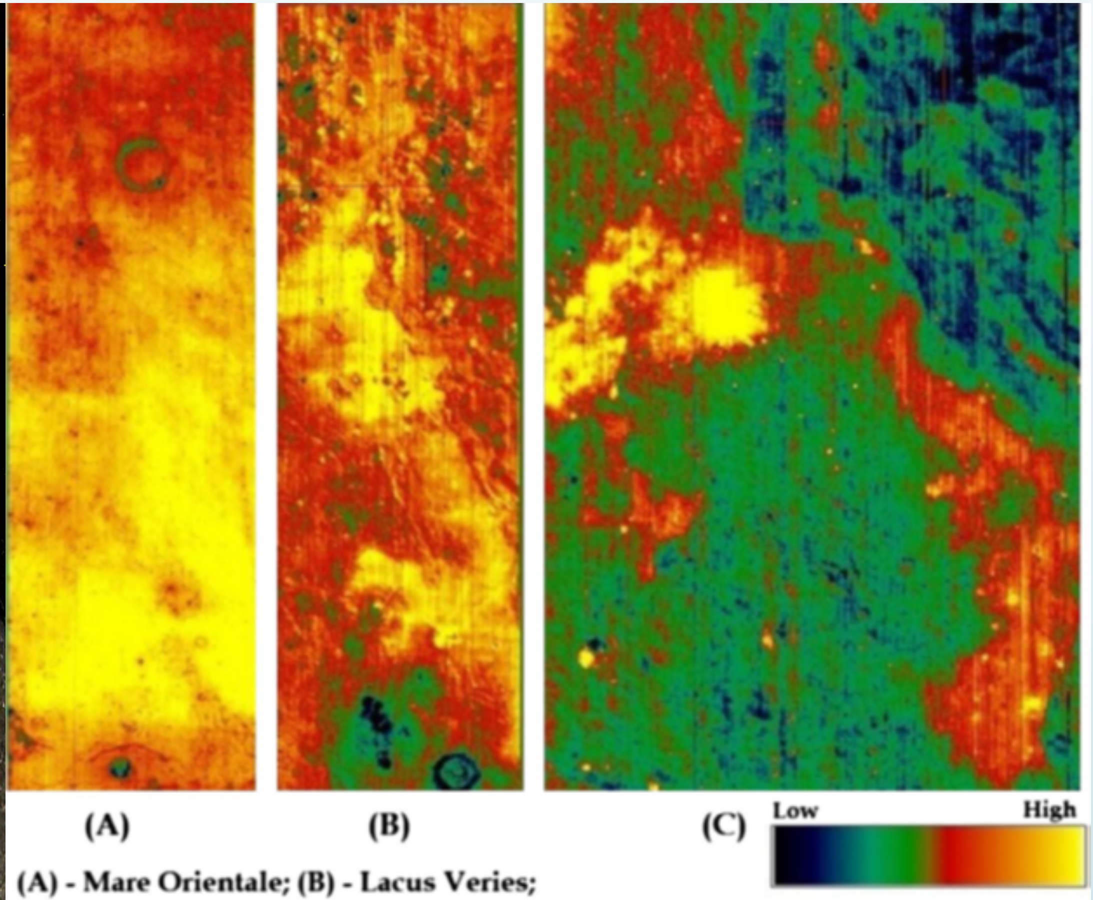


TiO_2 Mapping: SELENE Data

Japanese lunar surveyor, 2007

Low = 1-5%
High = 9-13%





(A) - Mare Orientale; (B) - Lacus Veries;
(C) - Lacus Autumni

Discussion: Comparing Processes

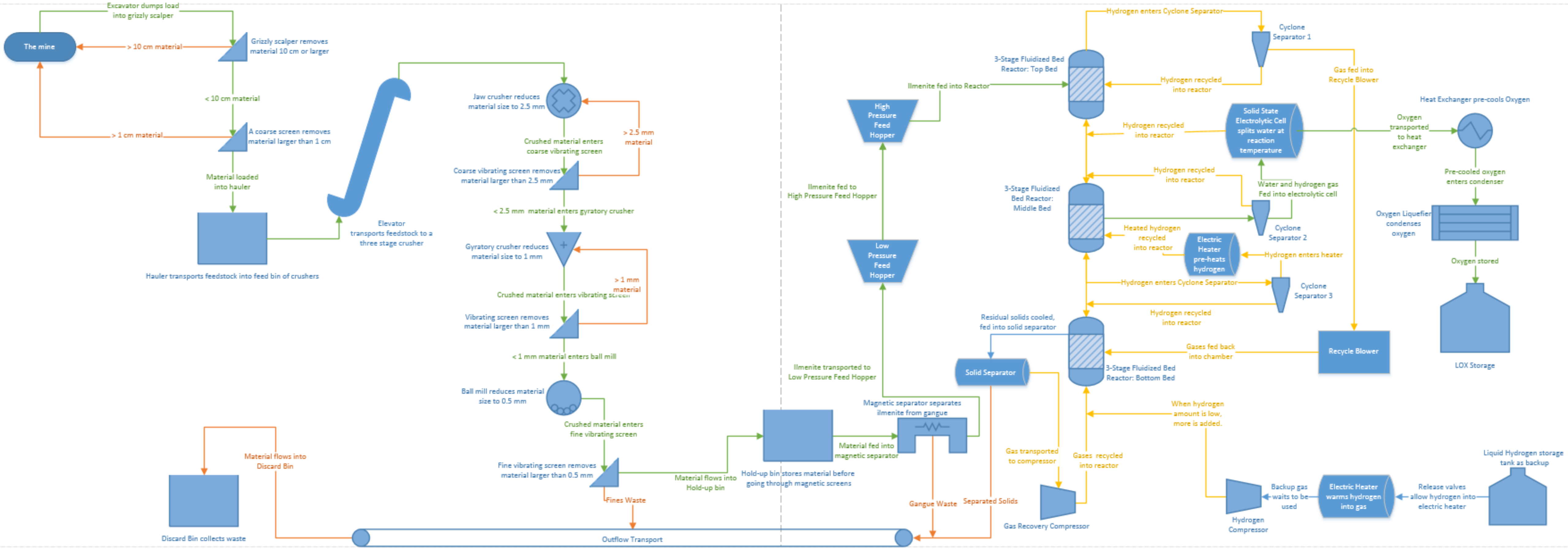
Carbotek Current	Mining	Beneficaion	Process	Power	Total
Mass (kg)	3363	3878	4816.1	9006	21063.1
Nominal Power (kW)	4.46	33.75	62.47	0	100.68
Volume (m^3)	75.589	44.813	19.421	115.2	255.023

Carbotek Updated	Mining	Beneficaion	Process	Power	Total
Mass (kg)	3363	3878	4816.1	4453	16510.1
Nominal Power (kW)	4.46	33.75	62.47	0	100.68
Volume (m^3)	75.589	44.813	19.421	102	241.823

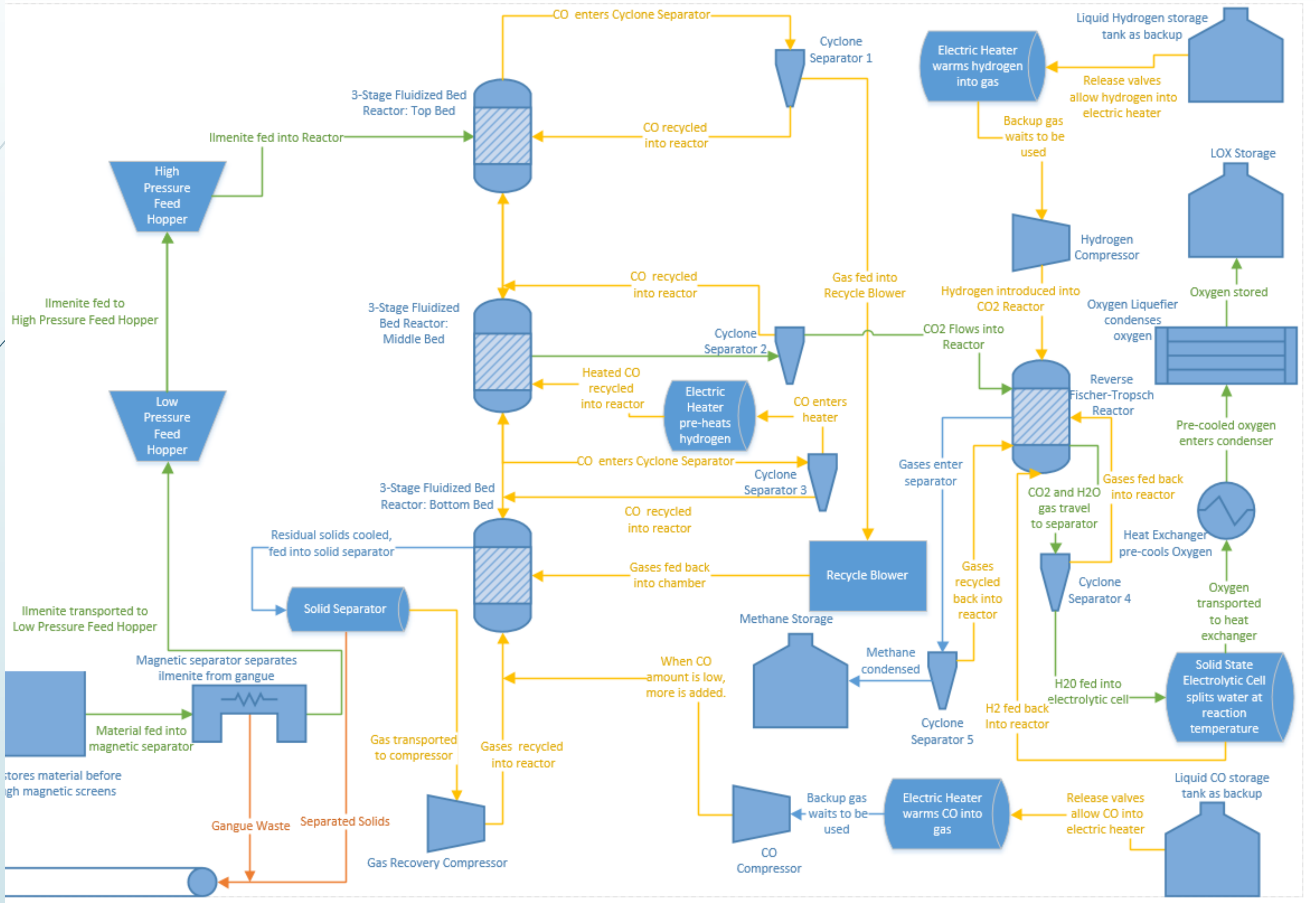
CO Reduction	Mining	Beneficaion	Process	Power	Total
Mass (kg)	3363	3878	5040.3	4453	16734.3
Nominal Power (kW)	4.46	33.75	62.56	0	100.77
Volume (m^3)	75.589	44.813	29.631	102	252.033

	Mining	Beneficaion	Process	Power	Total
Mass (kg)	3363	3878	5149.8	4453	16843.8
Nominal Power (kW)	4.46	33.75	62.56	0	100.77
Volume (m^3)	75.589	44.813	34.731	102	257.133

Eagle Engineering Process Schematic



CO Reduction Process Schematic



Carbochlorination Process Schematic