Oxygen on the Moon

<u>Group 3</u>

Tyler Watt
Brian Pack
Ross Allen
Michelle Rose
Mariana Dionisio
Blair Apple

Presentation Outline

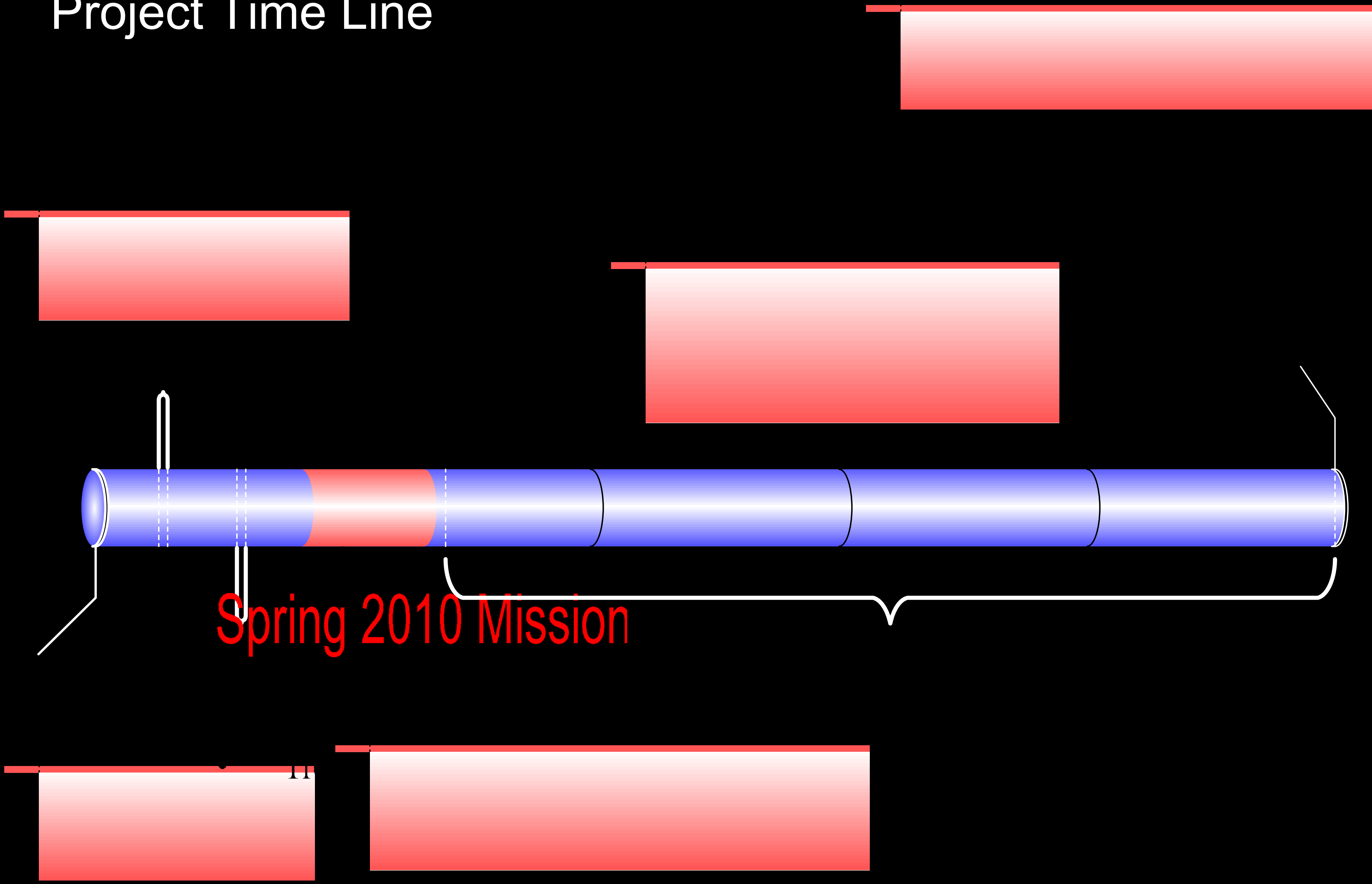
- Background
- Overview of logistics
- Process options
- General process information
- Reaction kinetics
  - Operating conditions optimization
- Diffusion model
- Equipment design
- Cost estimation
- Conclusions

- Mystery bonus material

Background

- President Bush announces plan for lunar exploration on January 15th, 2004
  - Stepping stone to future Mars exploration
  - Previously proposed by Bush, Sr.
- 2003 Senate hearing: lunar exploration for potential energy resources
  - Lunar Helium-3, Solar Power Satellites (SPS)
- President's Commission on Moon, Mars, and Beyond
  - Commissioned to implement new exploration strategy
  - Report findings in August 2004

Project Time Line



Biological Considerations

- Oxygen production requirements
  - Average human consumes 305 kg O_2/year
- Total oxygen production goals:
  - 8.4 kg/day or 20 moles/hr
- 6 month back-up oxygen supply for emergency use
  - Adequate for survival until rescue mission

Overview of Logistics

- Primary Concern
  - Each launch costs $200 million
  - Maximum lift per launch: 220,200 lbs
  - Minimize necessary launches
- Secondary Concerns
  - Minimize process energy requirements
  - Operate within budget (non-profit project)
  - NASA budget: $16 billion/yr
    - $12 billion/yr dedicated to lunar exploration

Process Options

- Process rankings
  - Evaluated for very large scale O_2 production
    - 1000 tons per year

Process	Technology	No. of Steps	Process Conditions
Ilmenite Red. with H_2	8	9	7
Ilmenitre Red with CH_4	7	8	7
Glass reduction with H_2	7	9	7
Reduction with H_2S	7	8	7
Vapor Pyrolysis	6	8	6
Molten silicon Electrolysis	6	8	5
HF acid dissolution	5	1	2

(Taylor, Carrier 1992)

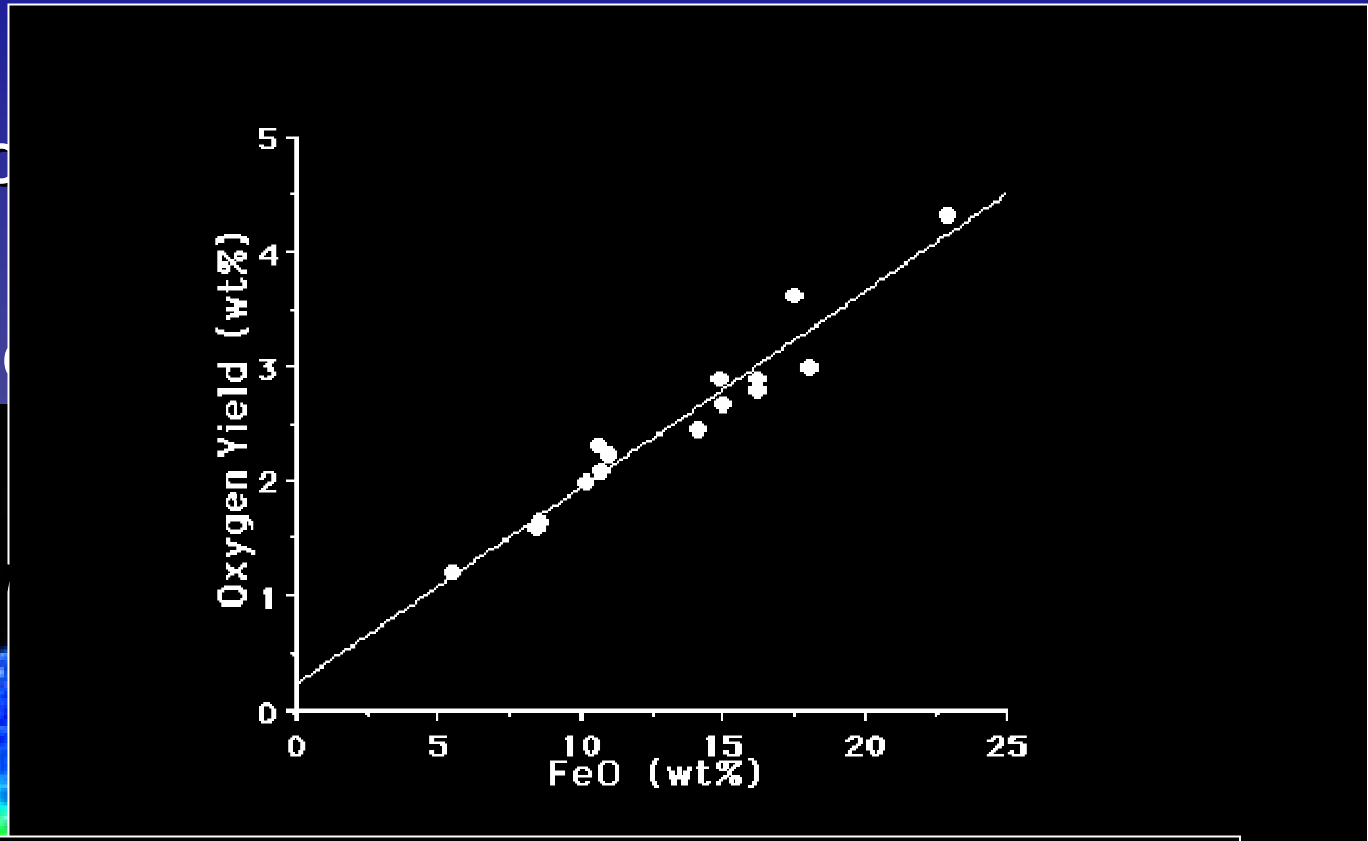
H_2 Reduction of Ilmenite Reaction

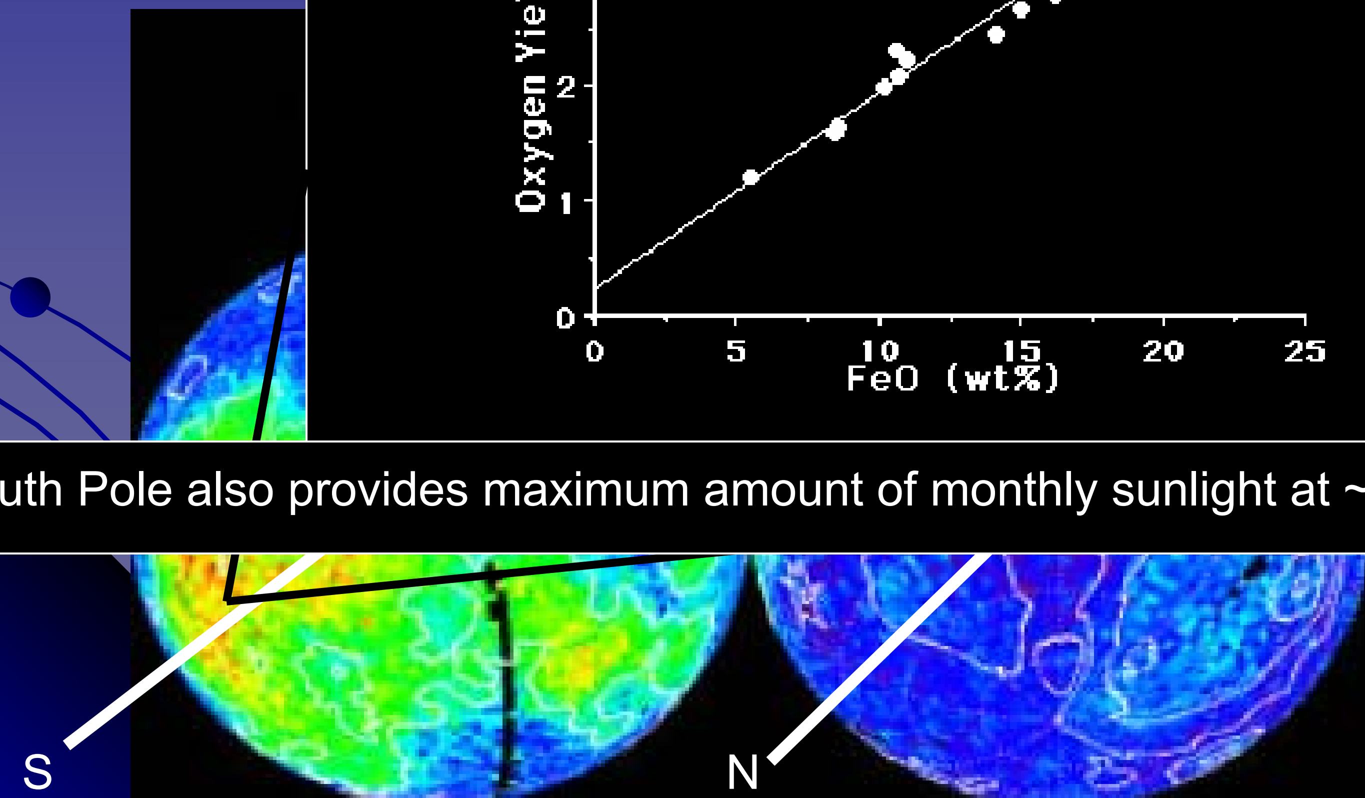
$$FeOTiO_2(s) + H_2(g) \longrightarrow Fe(s) + TiO_2(s) + H_2O(g)$$

- Previous experimentation has shown:
  - Iron oxide in ilmenite is completely reduced
  - Reaction temperature <1000°C
  - At these conditions, **3.2-4.6%** O_2 yields by mass
  - 35 kg of lunar soil per hour must be processed

Process Location

- Oxygen pro
  lunar soil
- Plant locati

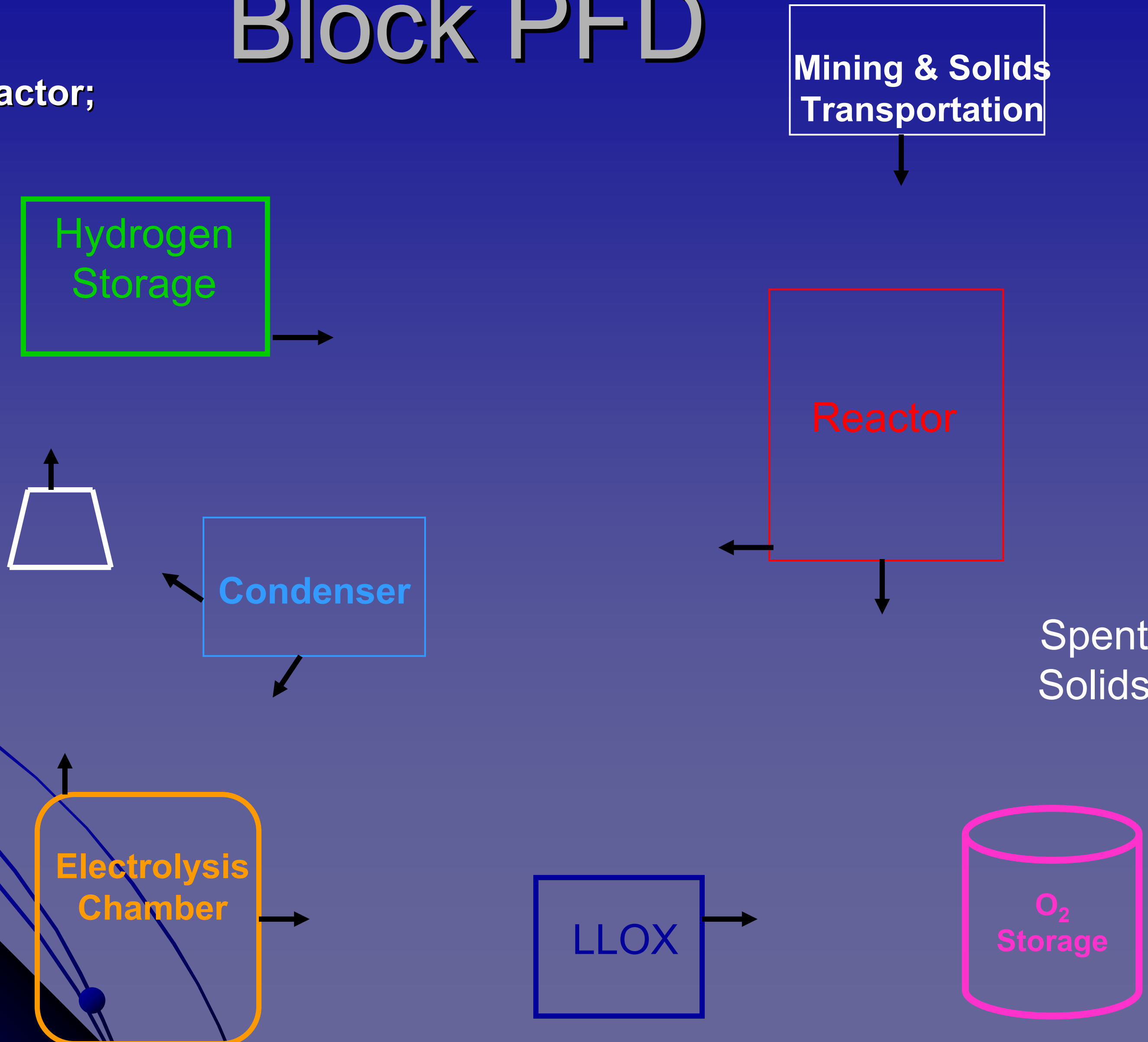




South Pole also provides maximum amount of monthly sunlight at ~90%

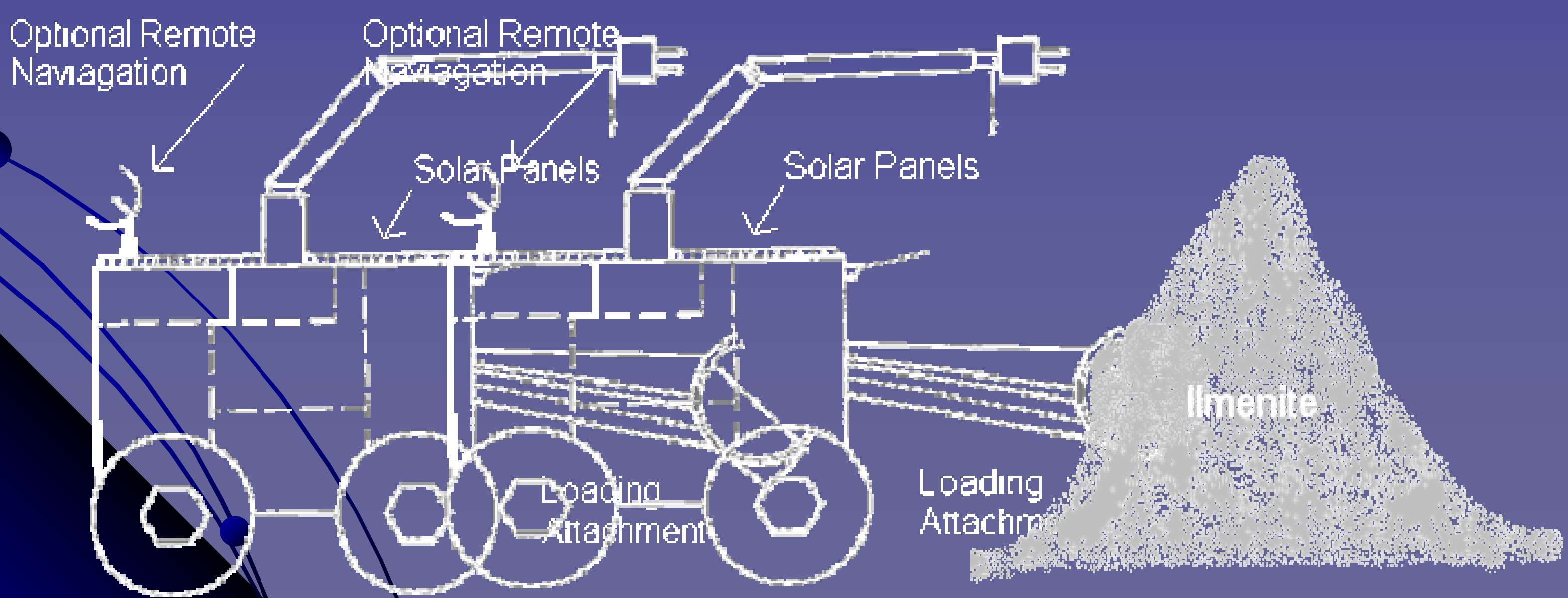
Block PFD

- Solids added to reactor; then H2 gas
- After reaction, H_2/H_2O goes to condenser; spent solids removed
- From condenser, H_2O liquid to electrolysis; H_2 gas to storage
- From electrolysis, O_2 is liquefied and stored; H_2 gas to storage for recycle



Obtaining Raw Materials

- Automatic miner provides lunar soil to process
  - Miner must provide 840 kg / day
  - Annual area mined 4000 m^2 (2.54 cm mining depth)
  - Initial hydrogen charge delivered as liquid water



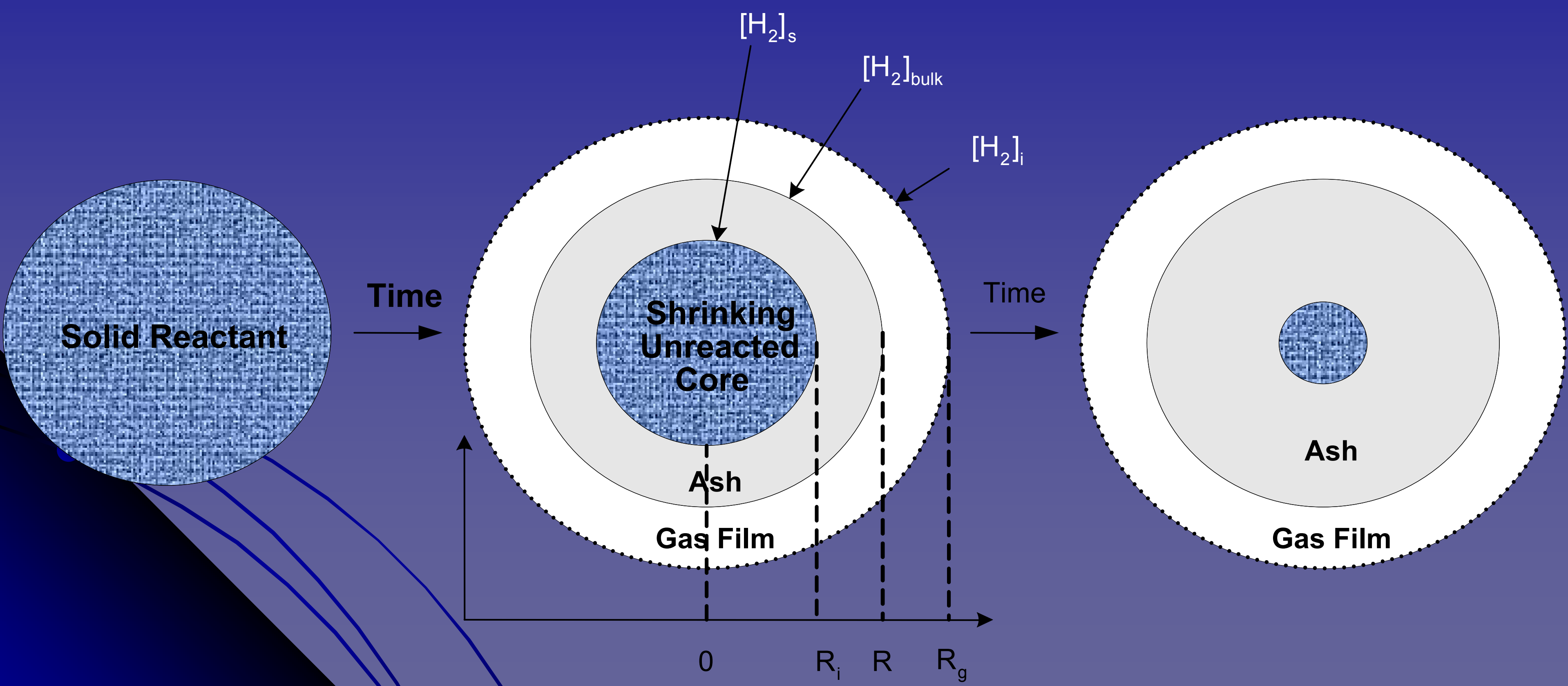
Reduction of Ilmenite Reaction

$$FeOTiO_2(s) + H_2(g) \longrightarrow Fe(s) + TiO_2(s) + H_2O(g)$$

- Previous experimentation has shown:
  - Rxn is **0.15** order in H_2
  - ΔH_{rxn}=9.7 kcal/g-mol
  - Particle radius is 0.012 cm (240 microns)
  - Complete reduction of ilmenite in 20-25 min.
  - T=900 °C, P =150 psia
  - At these conditions, **3.2-4.6%** O_2 yields by mass
  - **Reaction neither diffusion controlled nor reaction control: combination of both resistances accounted for in reaction model**

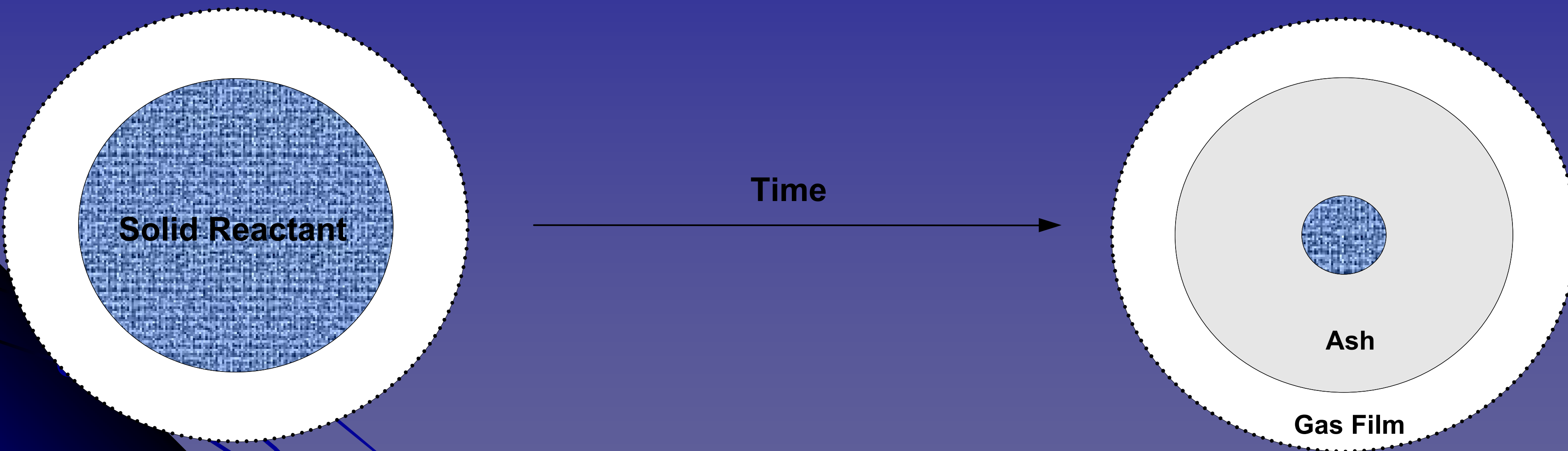
Unreacted Shrinking Core Model

- **Diffusion Limited**



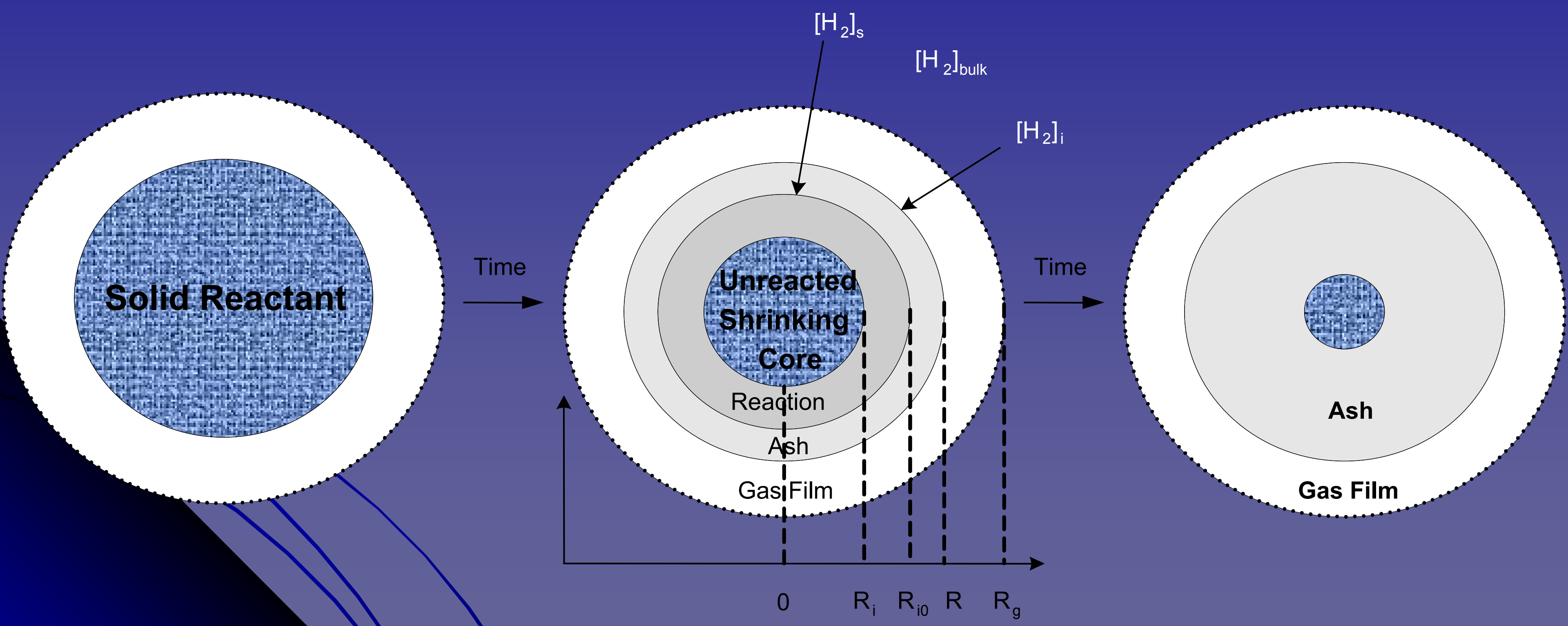
Homogenous Model

- Reaction Limited



Intermediate Model

•Reaction-Diffusion Control Combined



Reaction Model

$$\frac{d\eta_c}{dt} + \left[1 - 6\sigma_s^2(\eta_c^2 - \eta_c)\frac{d\eta_c}{dt}\right]^n = 0$$

where: B.C. η_c =1 @ **t =0**

σ_s^2 = reaction modulus
= $kC^{n-1}H^2$ (particle radius)/[6(effective diffusivity)]

η_c = dimensionless radial coordinate of shrinking core
= core radius/particle radius

t = dimensionless time
=(time)(kC^n_{H2})/[(solid molar density)(particle radius)]

n = reaction order, found to be 0.15

CH_2 = constant H_2 concentration, gm-mol/cm^3

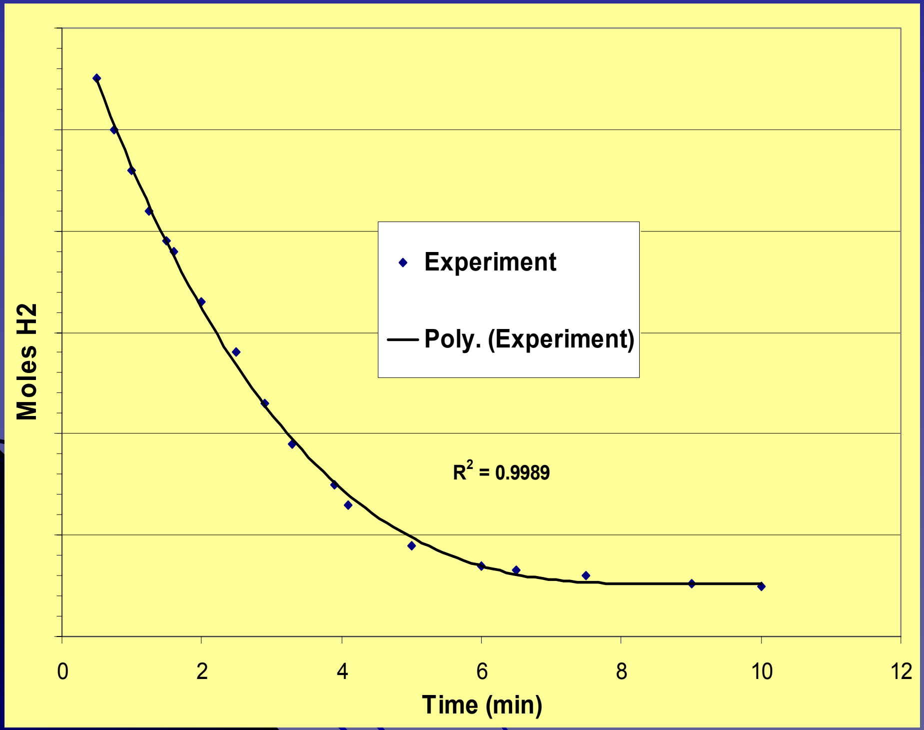
kC^nH_2 = rate expression, 0.15 order in CH_2
= reaction rate, mole H_2/sec-cm^2, k= rate constant

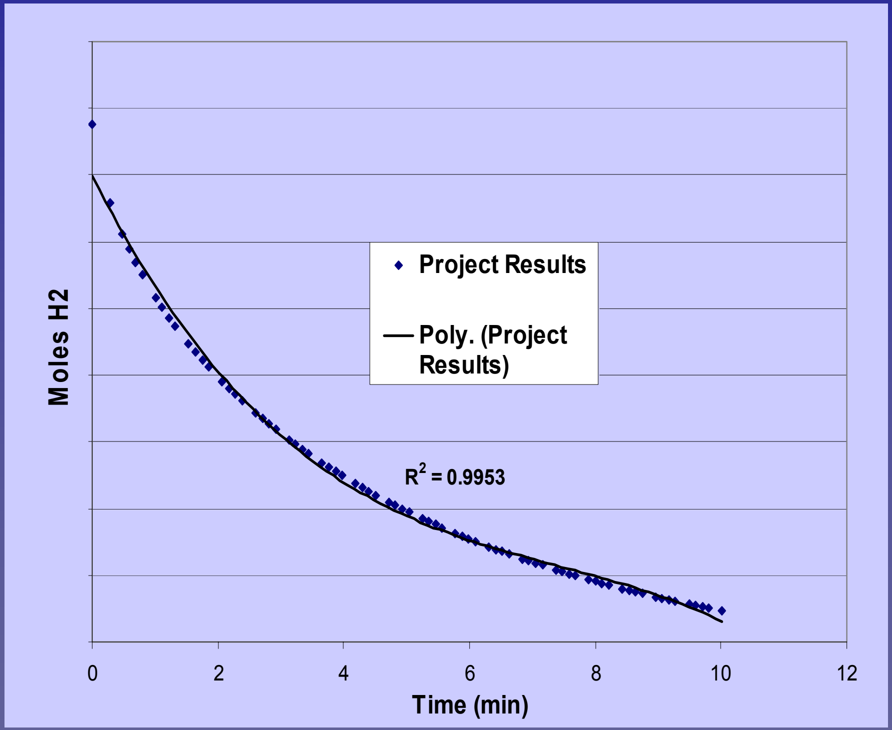
(Gibson et. al, 1994)

Solution Method

- DE numerically solved for rate change of shrinking core **(dn_c/dt)**
- Reaction modulus, σ_s, used as parameter
- σ_s varied until project results compared respectably with prior experimental results
- Reaction rate constant, *k*, then was determined from the value of σ_s
  - **RECALL:**
    - σ_s **= (kC^{n-1}H^2 (particle radius)/[6(effective diffusivity)])$^{0.5}$**

Result Comparison





Project Results

- Reaction modulus

  σ = 3.52

  NOTE: $\sigma < 10$ – Intermediate (reaction and diffusion control)

- Rate constant

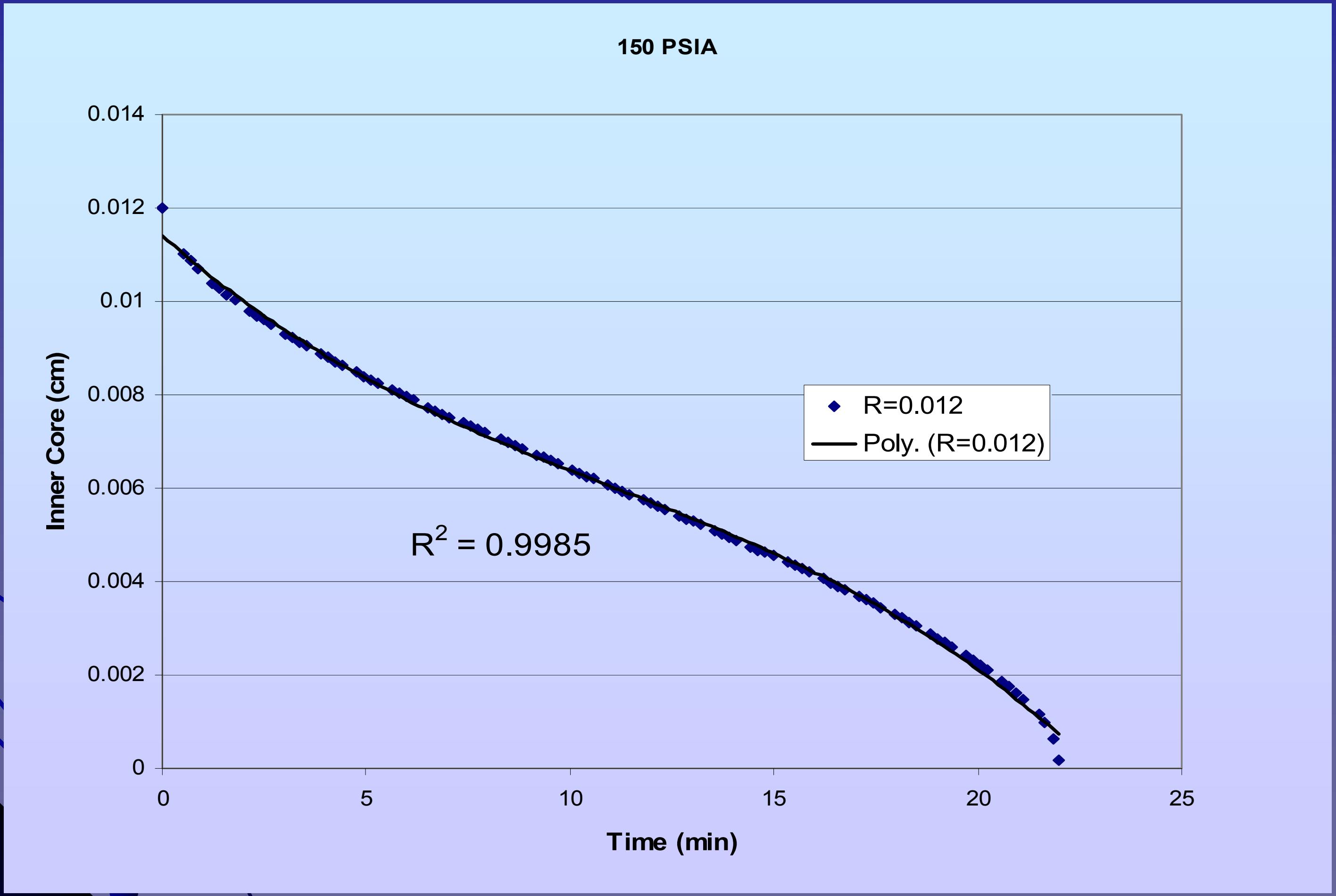
  ***k* = 4.57 x 10^{-4} $M^{0.85}$/min**

- Reaction time of experimental model

  ***t* = 22 min for a particle radius of 0.012 cm (d_p=240 microns)**

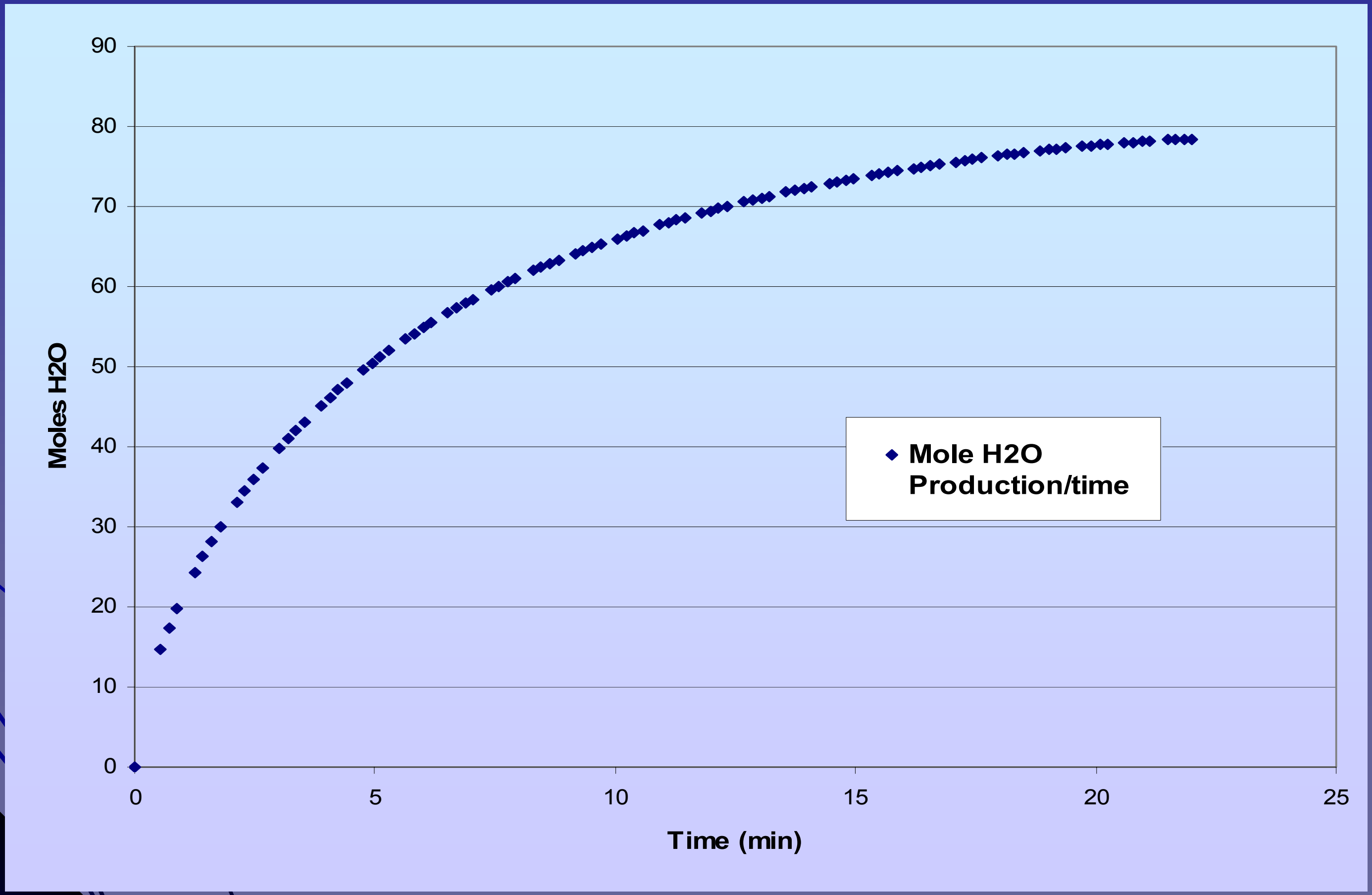
Shrinking Core

- **Radius of particle 0.012 cm**



Water Production

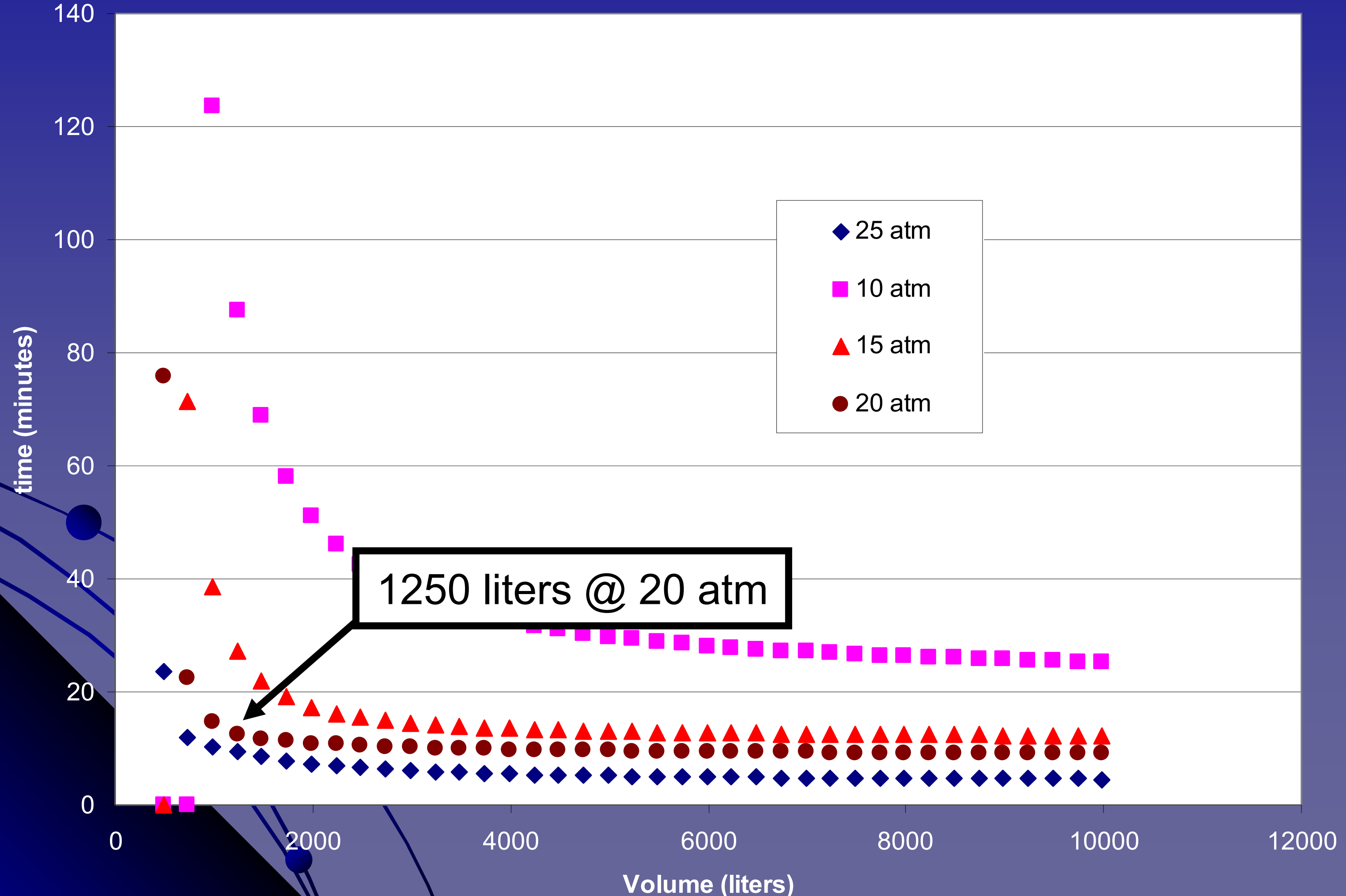
- 78 moles produced in 22 minutes



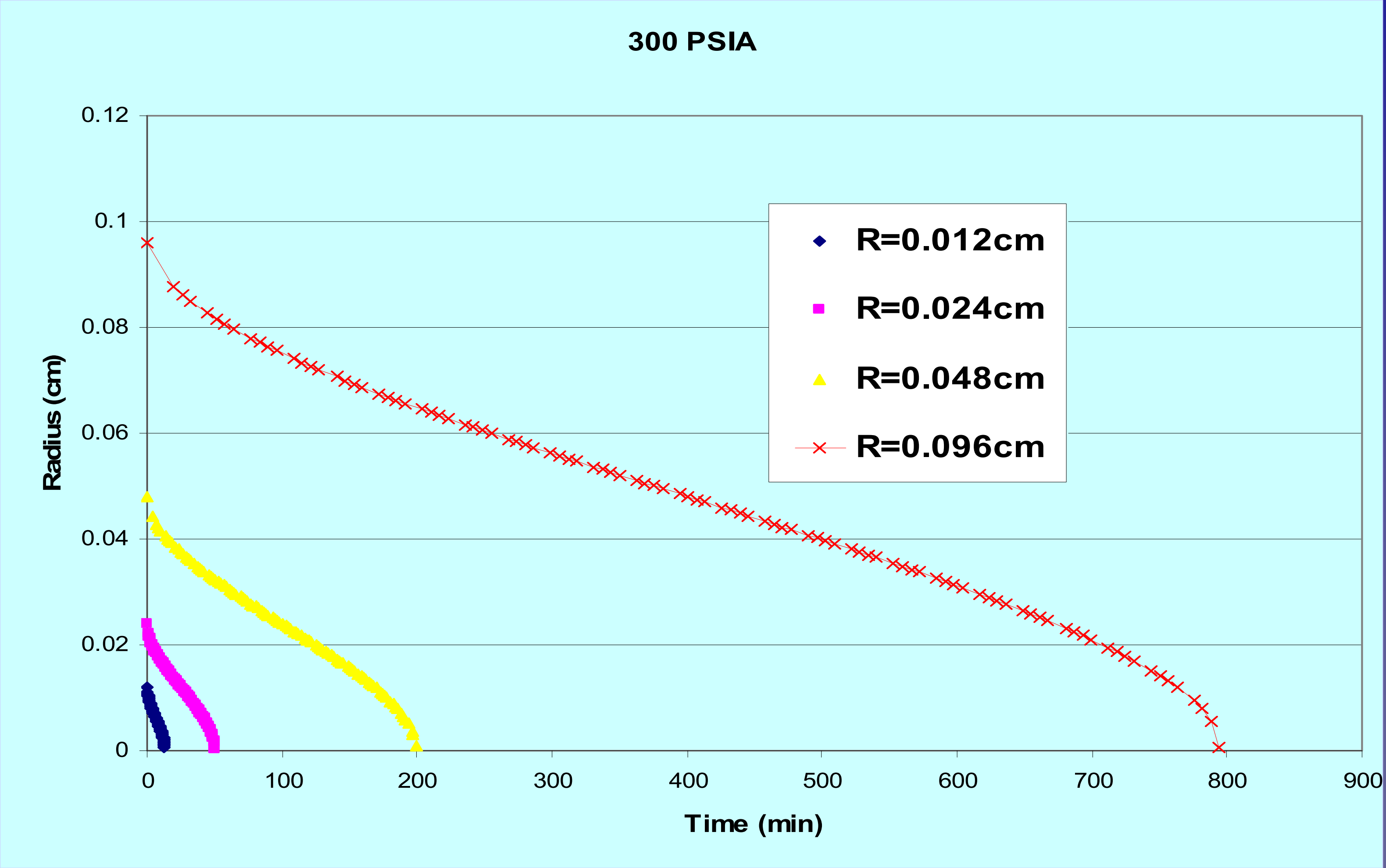
Using the Model

- Reactor Design
  - Pressure optimization
  - Volume optimization
  - Usable particle size

Operating Conditions Optimization



Effect of Particle Diameter



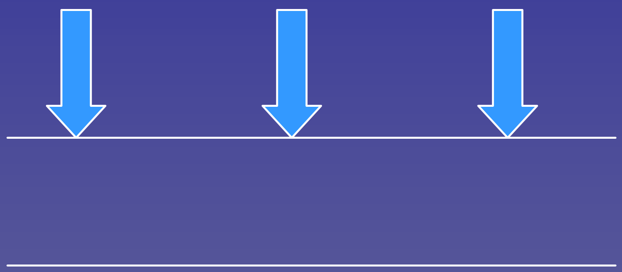
Optimal Operating Conditions

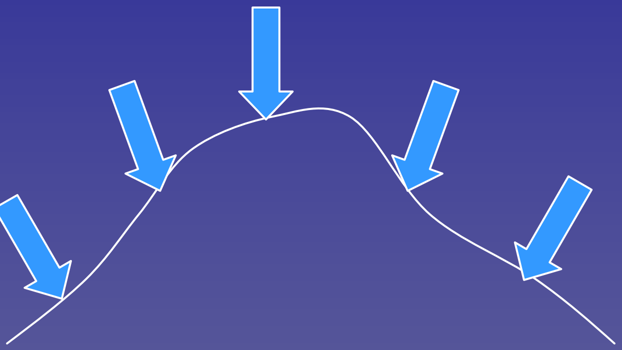
- Pressure of reactor: 300 psi
- Volume of reactor: 1250 liters
- Number of batches per day: 12
- Mean particle diameter: 240 μm
  - 80% of lunar soil less than 960 μm
- Reaction complete in <15 minutes

Reactor Diffusion Model

- Must use fixed bed reactor
  - Fluidized particles highly erosive
- Analyze diffusion to determine bed depth, reactor dimensions and possible effect on batch time
  - Bed Depth
    - Thin if diffusion is slow
    - Thick if diffusion is fast
  - Reactor Dimensions
    - Volume fixed
    - Affects diameter and height
  - Batch Time
    - May need to factor in time for diffusion

Reactor Design Considerations





- Complicates reactor design
- Facilitates diffusion

- Simpler reactor design
- Possible diffusion complications

Diffusion in Reactor

- Model using simplified continuity equation
  - General Continuity Equation

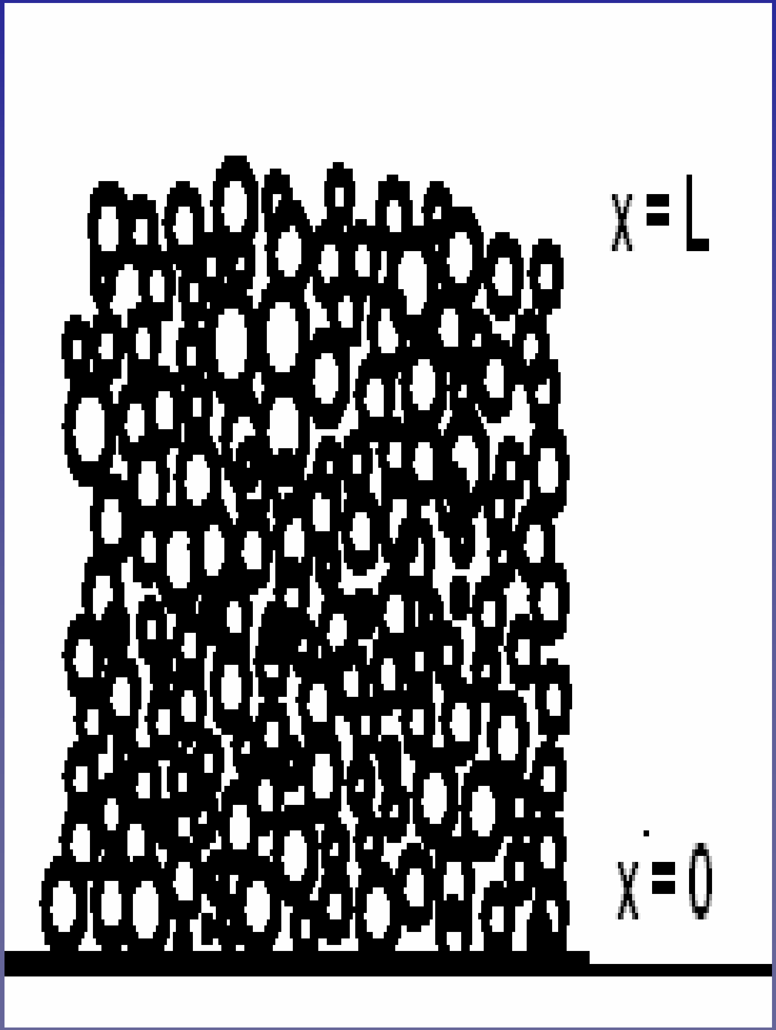
$$\frac{\partial C_{H2}}{\partial t} + \nabla N_{H2} - R_{H2} = 0$$

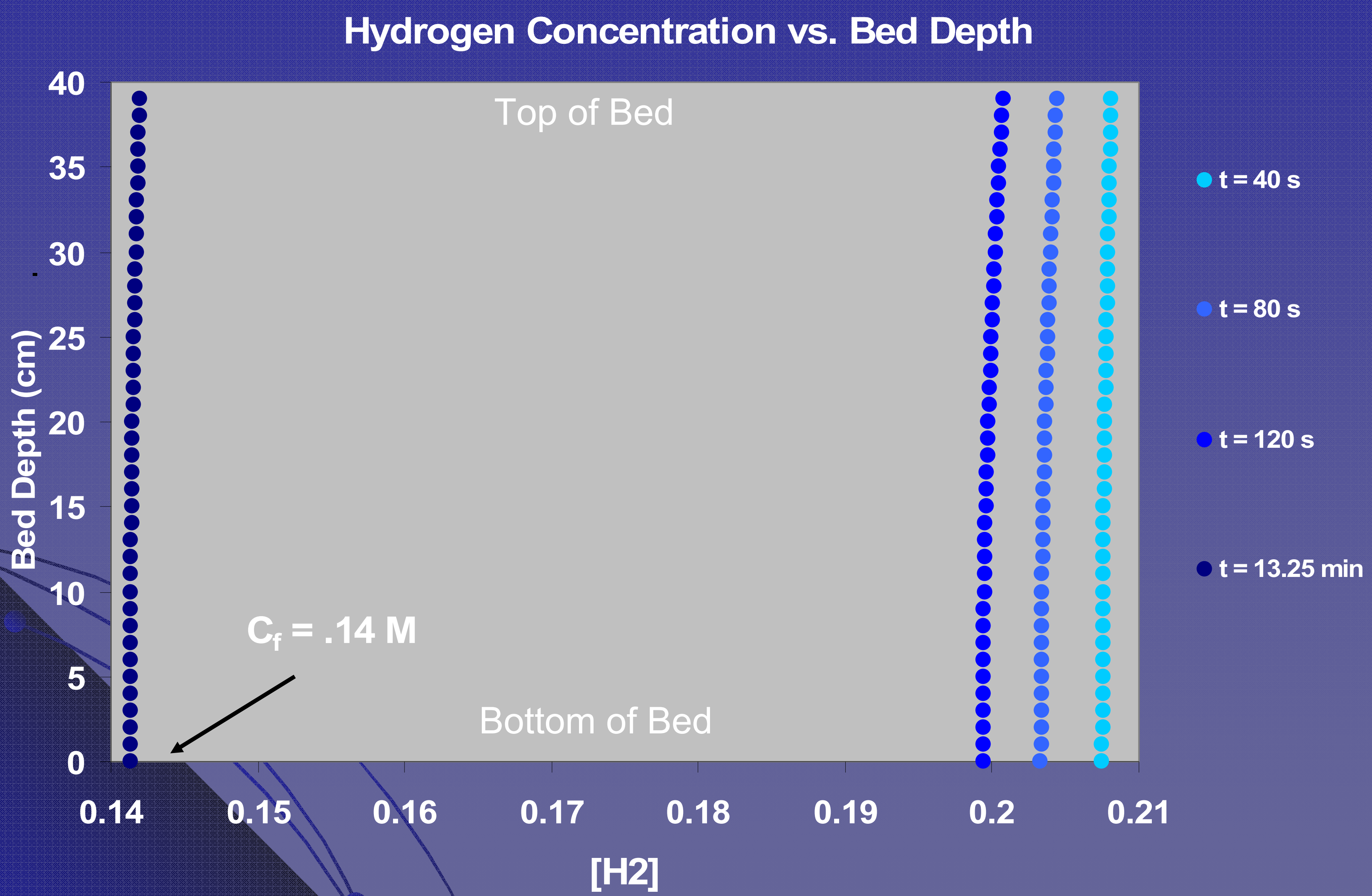
  - For a one dimensional system

$$\frac{\partial C_{H_2}}{\partial t} + D_{H_2,H_2O} \frac{\partial^2 C_{H_2}}{\partial x^2} - R_{H_2} = 0$$

Conditions and Assumptions

- Assume R_{H2} is constant
- Initial Condition
  - $C(x,0) = C_{H2,o} = 0.21$ M
- Boundary Conditions
  - $$\left.\frac{\partial C}{\partial x}\right|_{x=0} = 0$$
  - $C(l,t) = C^* = C_{H2,o} - R_{H2}t$




Hydrogen Concentration vs. Bed Depth
Bed Depth (cm)
40
35
30
25
20
15
10
5
0
Top of Bed
Bottom of Bed
C$_f$ = .14 M
0.14
0.15
0.16
0.17
0.18
0.19
0.2
0.21
[H2]
t = 40 s
t = 80 s
t = 120 s
t = 13.25 min

Diffusion Conclusions

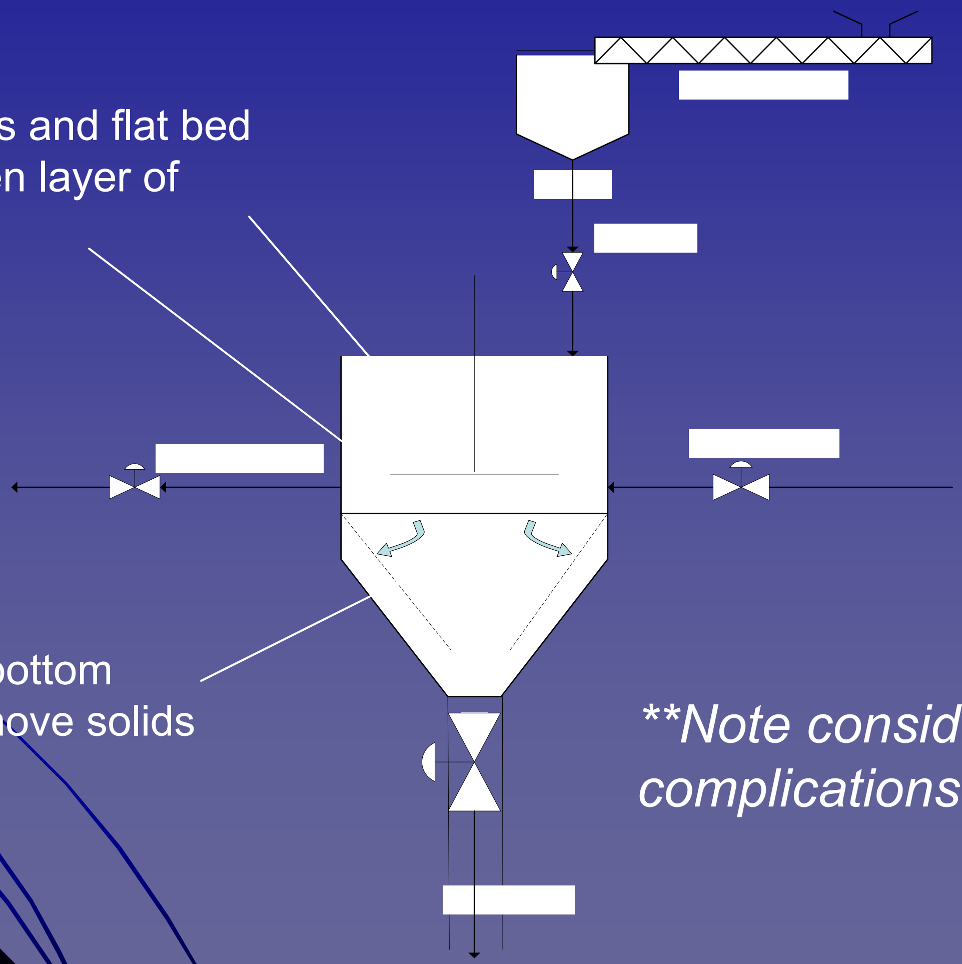
- Hydrogen diffuses very fast through the bed
- Water diffuses very fast through the hydrogen above the bed
- Diffusion is not a problem in the reactor

Reactor Design Considerations

- Fast diffusion facilitates design:
  - Not necessary to agitate H_2
  - Not necessary to have an even layer of ilmenite
    - Can use hopper bottom to facilitate discharge of solids
    - Smoothing mechanism unnecessary
- Must feed and remove reactants and products in an order that will minimize H_2 loss

Initial Reactor Design

•Smoothing blades and flat bed bottom create even layer of ilmenite

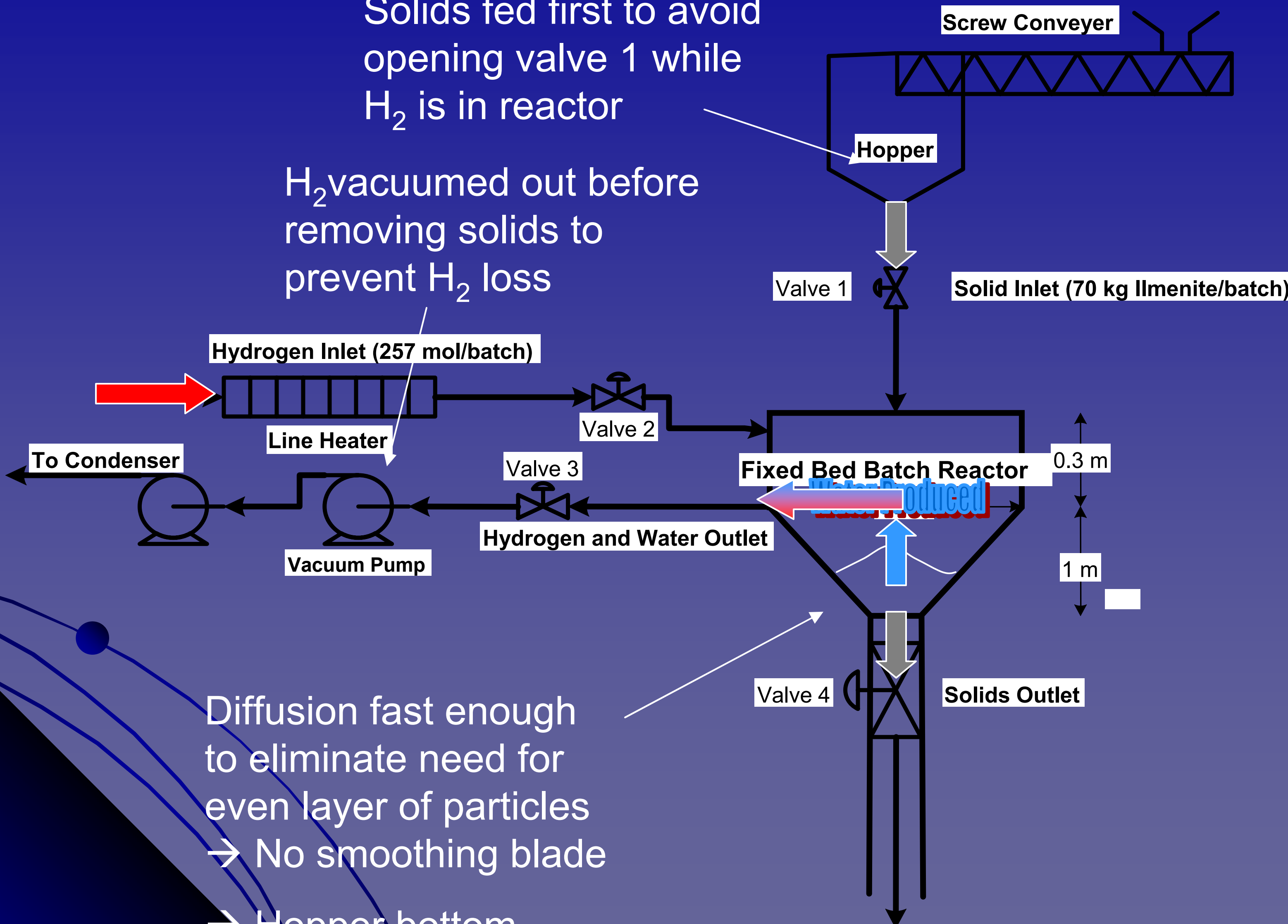


"Trap door" bottom opens to remove solids

***Note considerable complications with moving parts*

Solids fed first to avoid opening valve 1 while H_2 is in reactor

H_2 vacuumed out before removing solids to prevent H_2 loss



Diffusion fast enough to eliminate need for even layer of particles

→ No smoothing blade

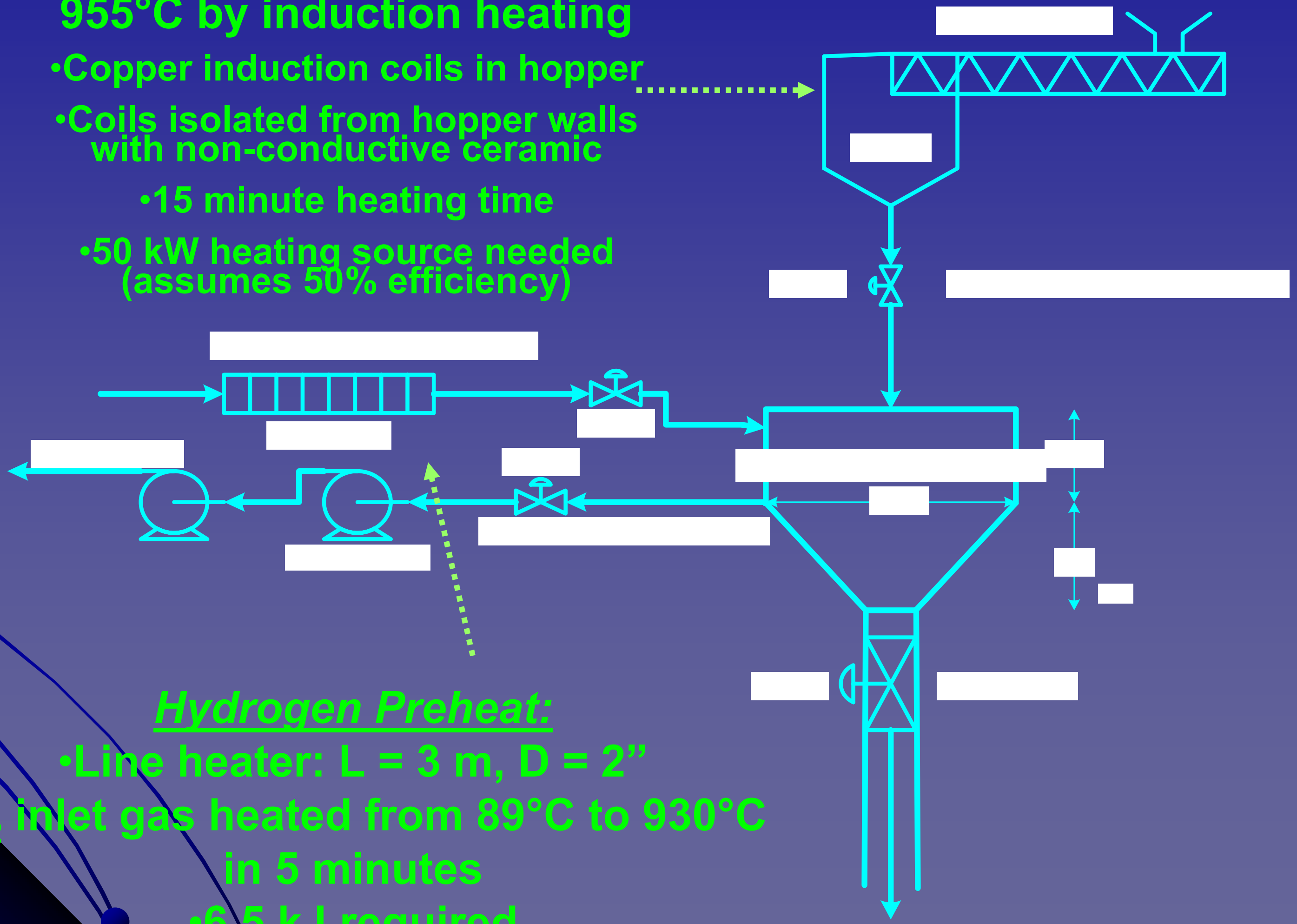
→ Hopper bottom

Reactant Preheat

- Reaction T=900°C
  - Ilmenite enters at -30°C
  - H_2 enters at 89°C
- Heating Options:
  - **Heat inside reactor (heating coils)**
    - Difficult to repair
    - Very slow heating due to low convection (stagnant H_2)
  - **Preheat H_2, heat ilmenite with H_2**
    - Complex solid-gas heat exchanger (rotating parts)
    - Flowing hot H_2 over ilmenite in the reactor causes dust levitation
  - **Preheat H_2 with a line heater; preheat ilmenite in hopper by induction heating**

Reactant Preheat

- Ilmenite heated from -30°C to 955°C by induction heating
- Copper induction coils in hopper
- Coils isolated from hopper walls with non-conductive ceramic
- 15 minute heating time
- 50 kW heating source needed (assumes 50% efficiency)

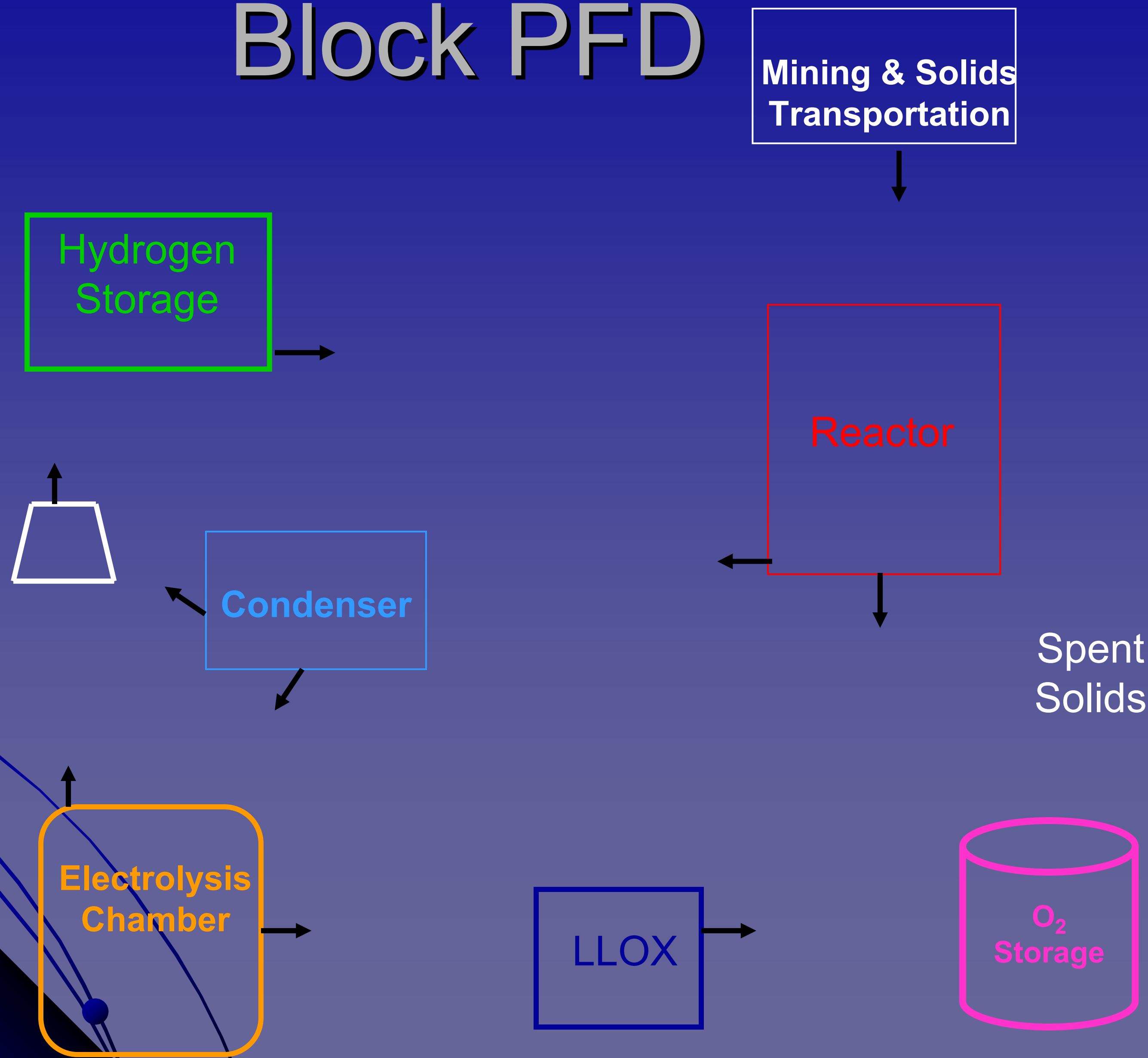


Hydrogen Preheat:

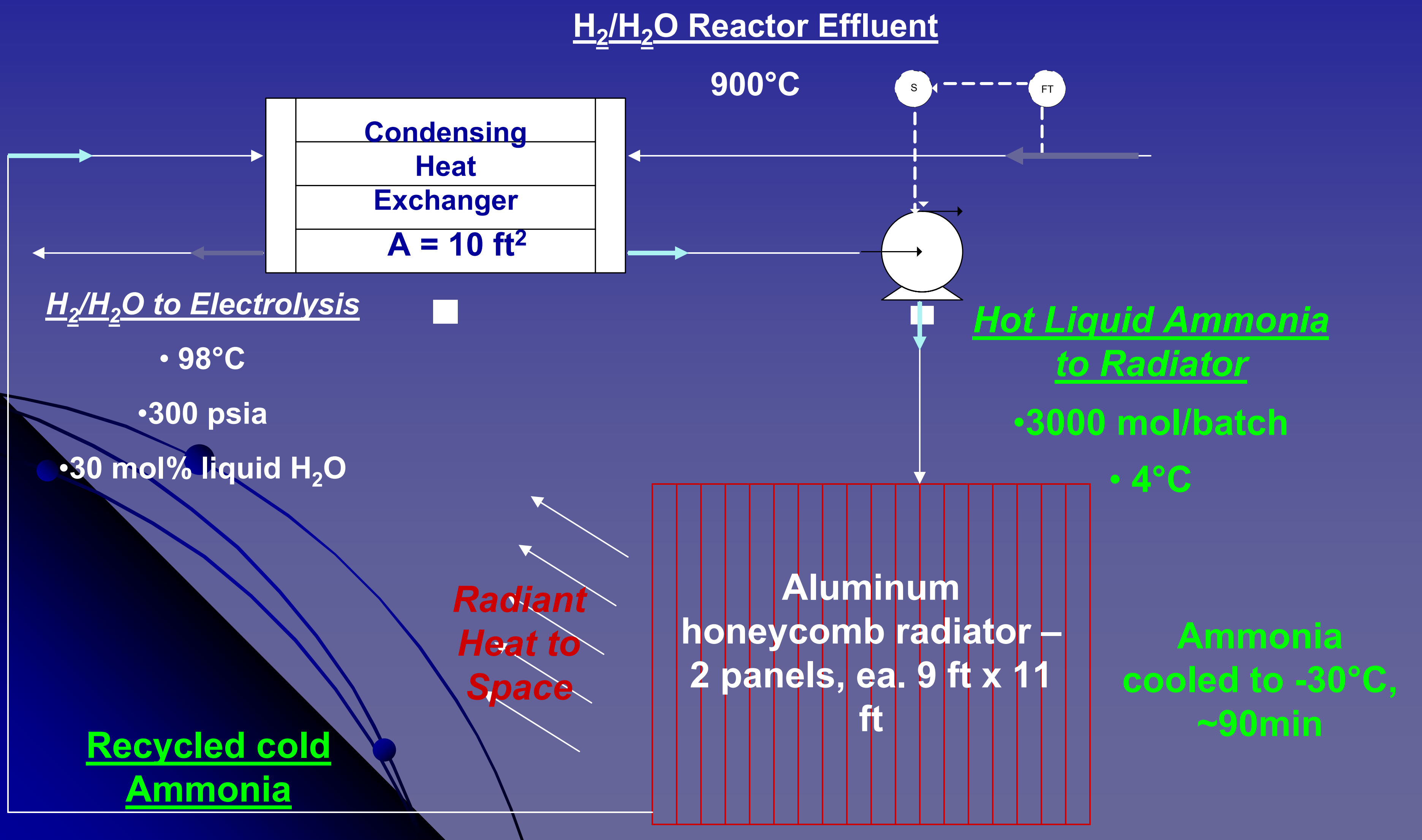
- Line heater: L = 3 m, D = 2”
- H_2 inlet gas heated from 89°C to 930°C in 5 minutes
- 6.5 kJ required

Block PFD

- **After reaction, H2/H2O goes to condenser; spent solids removed**



Condenser System

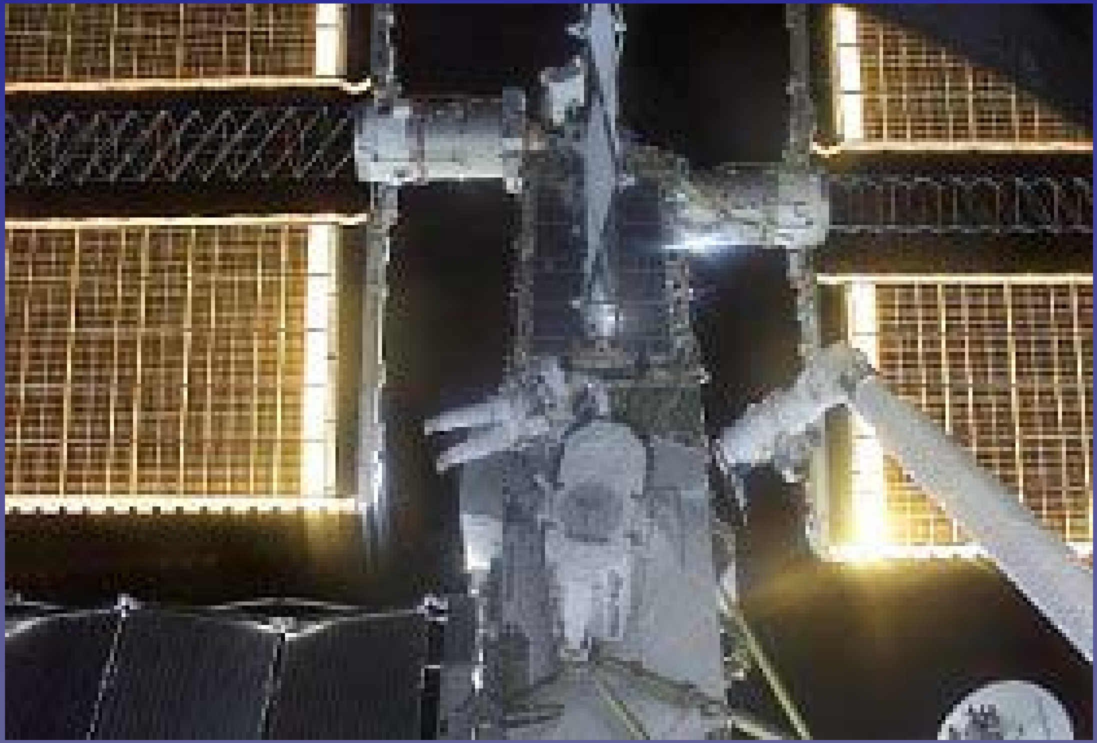


Why use Ammonia?

- Why not use something on site (i.e. H_2O or cold rock)?
- **Advantageous properties of Ammonia:**
  - **Very low freezing temperature (-77°C)**
  - **Lowest fouling rate (0.2286 J m K/s)**
  - **Most efficient of commonly used refrigerants (C.O.P. is ~3% better than R-22; 10% better than R-502)**
  - **High heat transfer characteristics (C_P, latent heat of vaporization, k)**

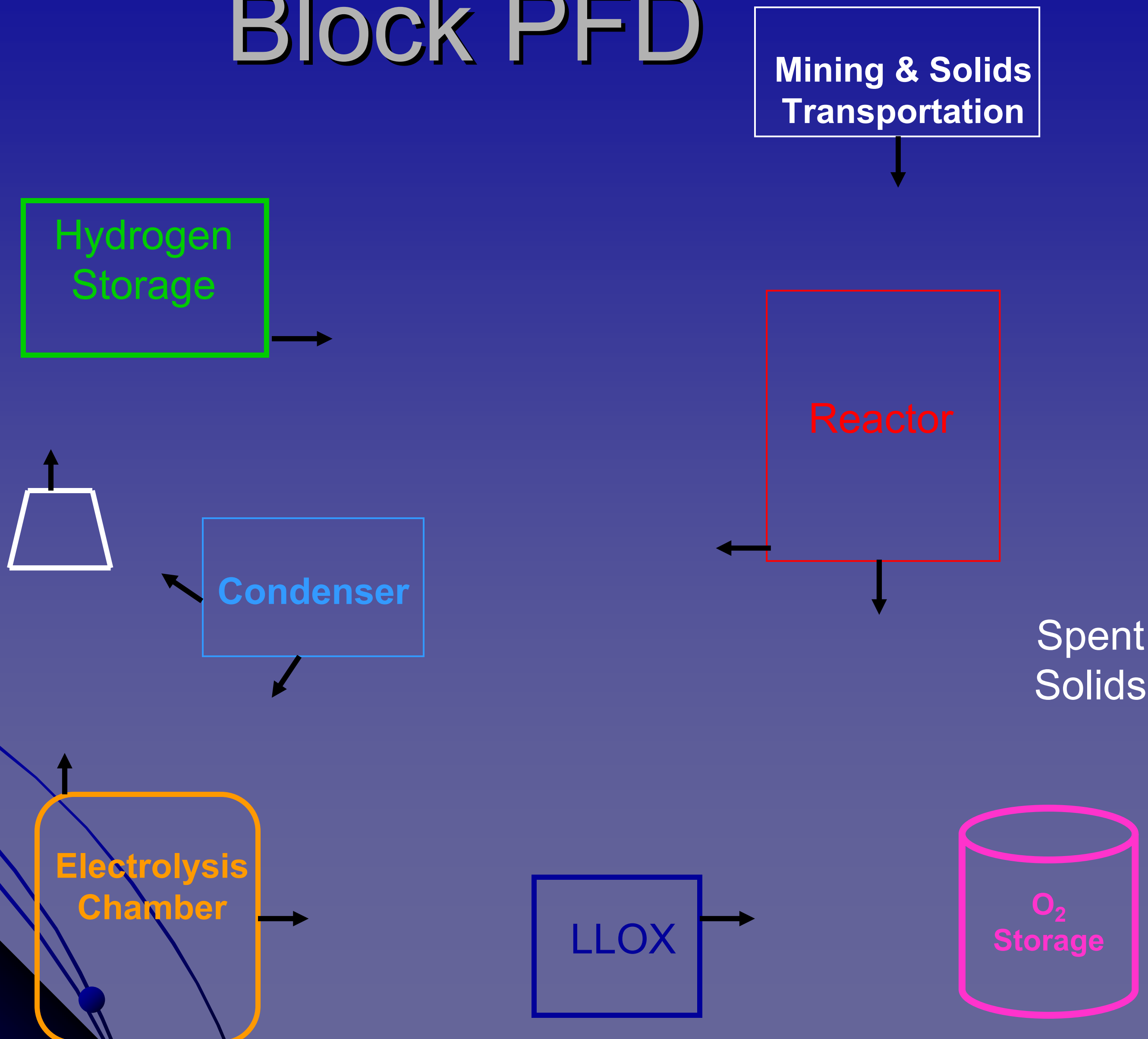
Condensing System

- Aluminum honeycomb radiator panels (ISS)
- Each panel 9 ft x11 ft and rejects 1.5 kW
- 2.3 kW must be rejected per batch
- Two panels used; one ammonia batch needs ~90 minutes
- Two panels hold nearly 5 batches of ammonia

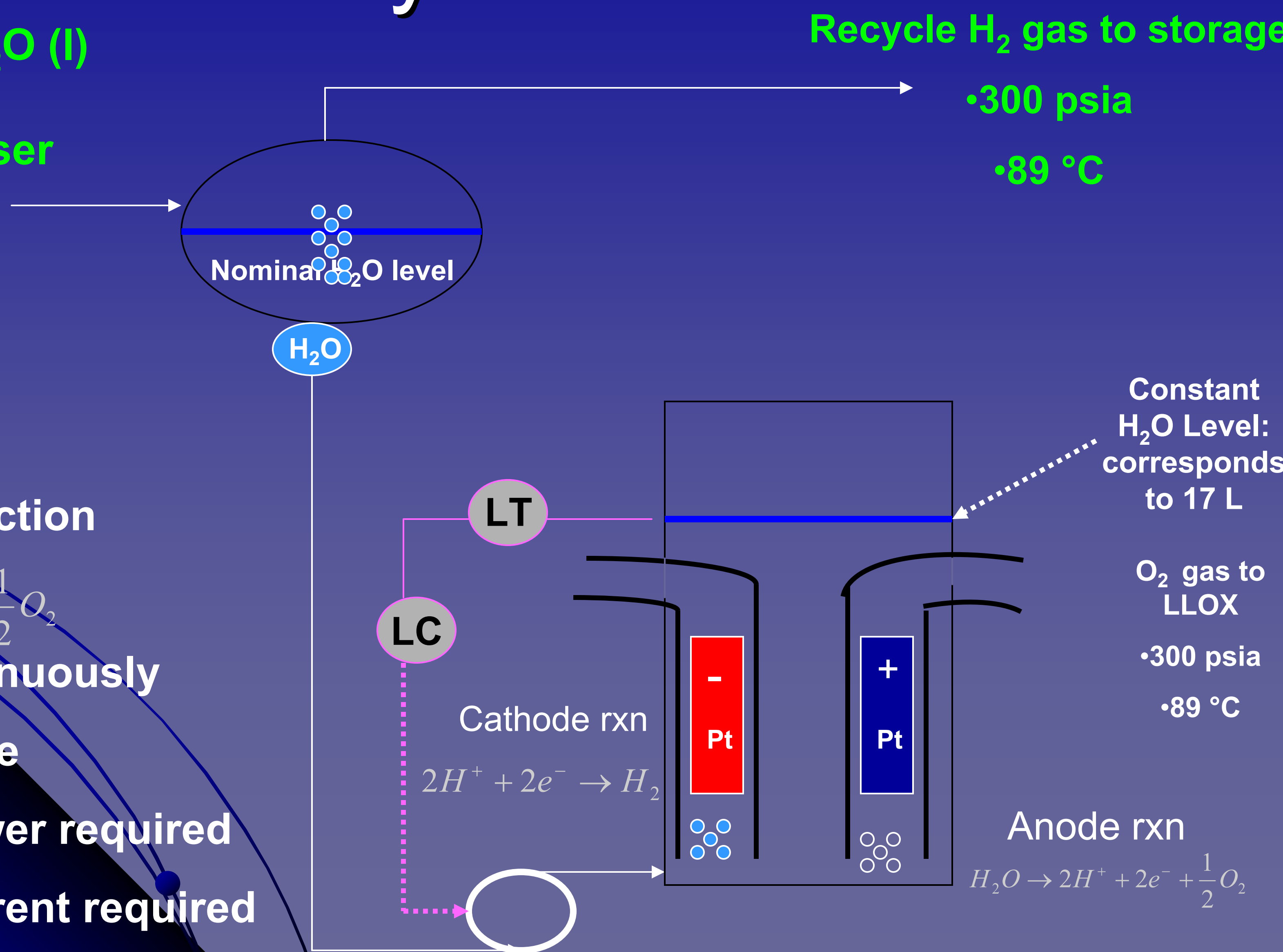


Block PFD

- From condenser, H2O liquid to electrolysis; H2 gas to storage



Electrolysis Chamber

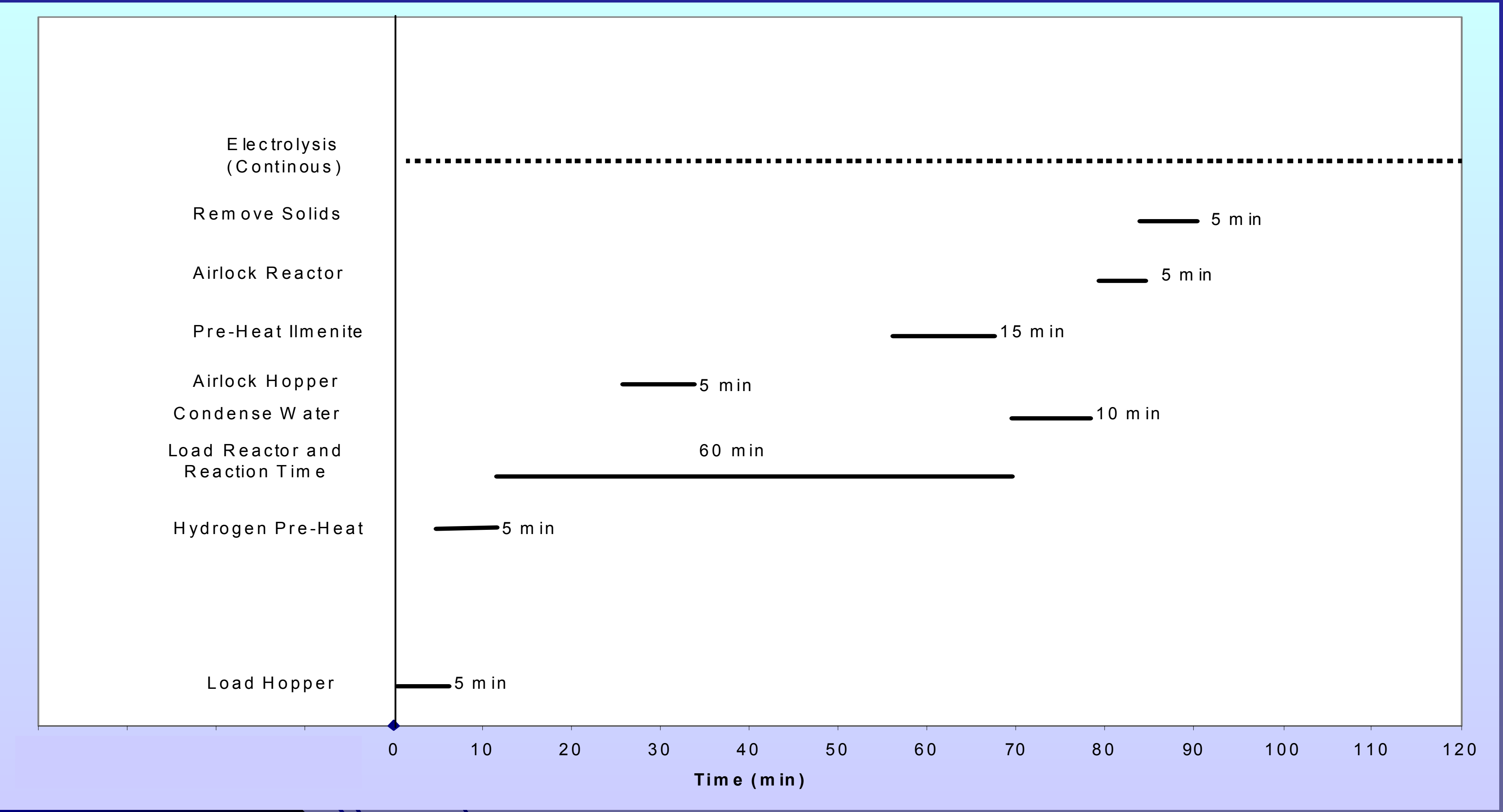


- Overall reaction

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

- Runs continuously
- 20 L volume
- 3.5 kW power required
- 2090 A current required

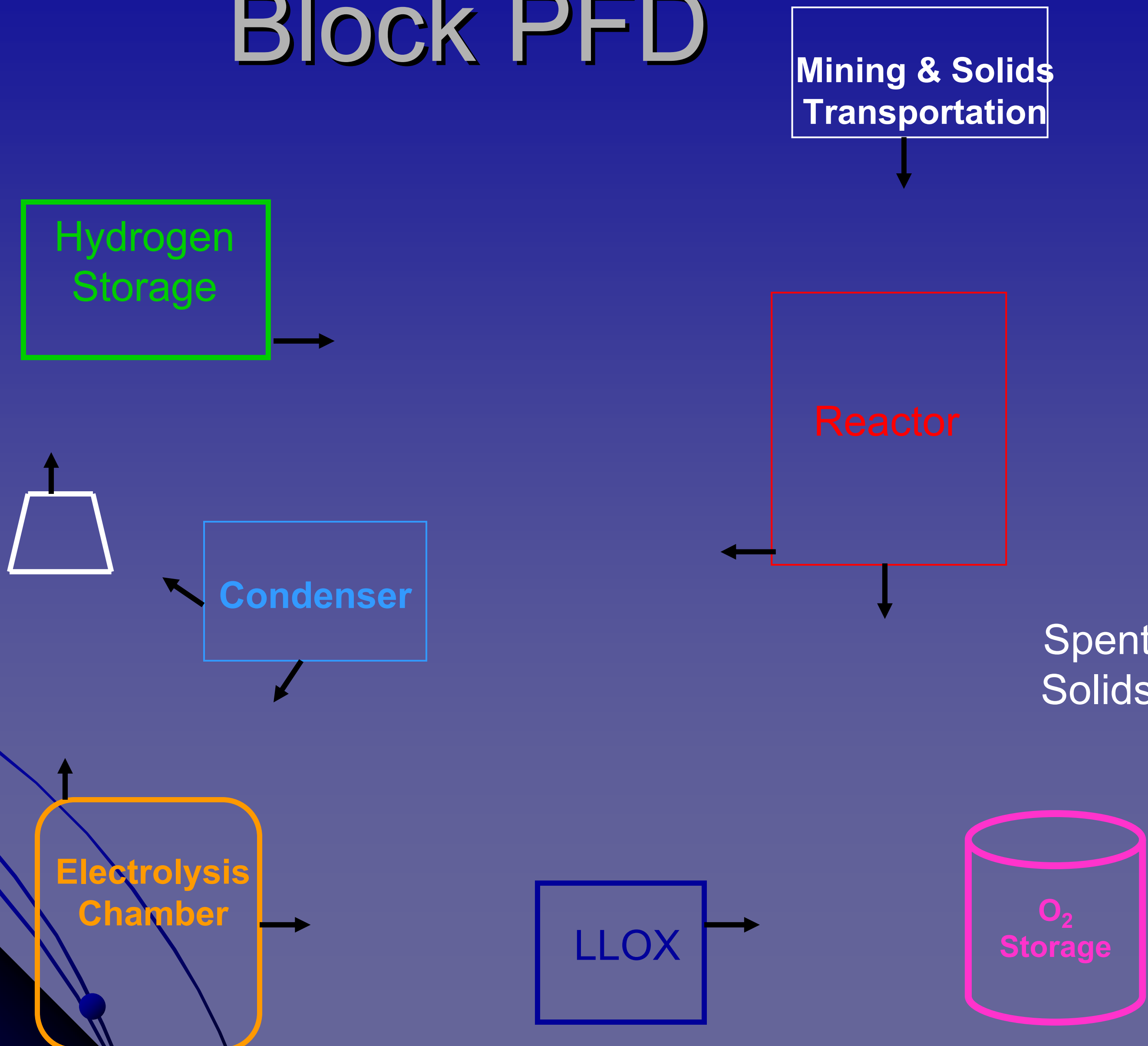
Overview: Process Timeline



TOTAL BATCH TIME: 90 minutes

Block PFD

- From electrolysis, O_2 gas is liquefied and stored

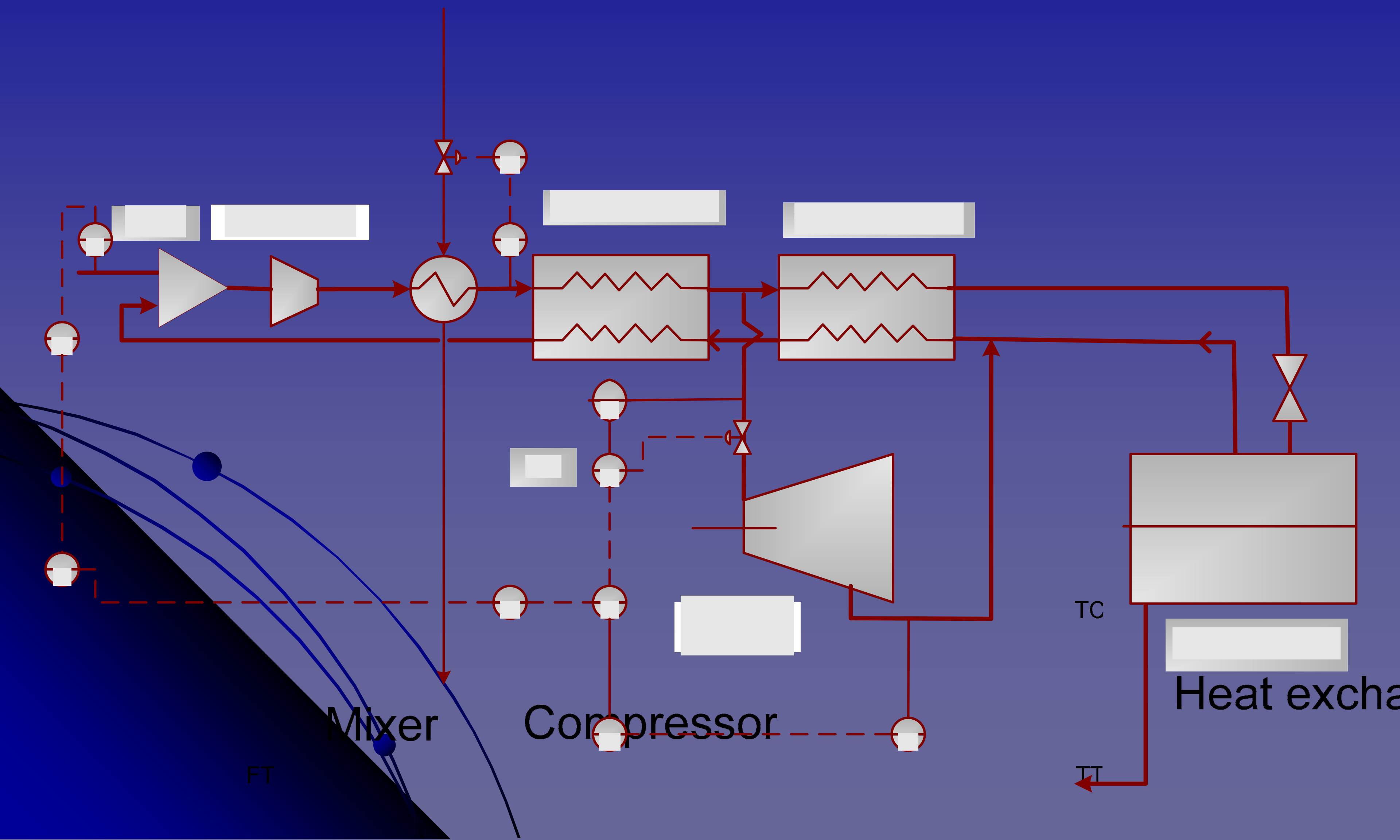


Oxygen Storage

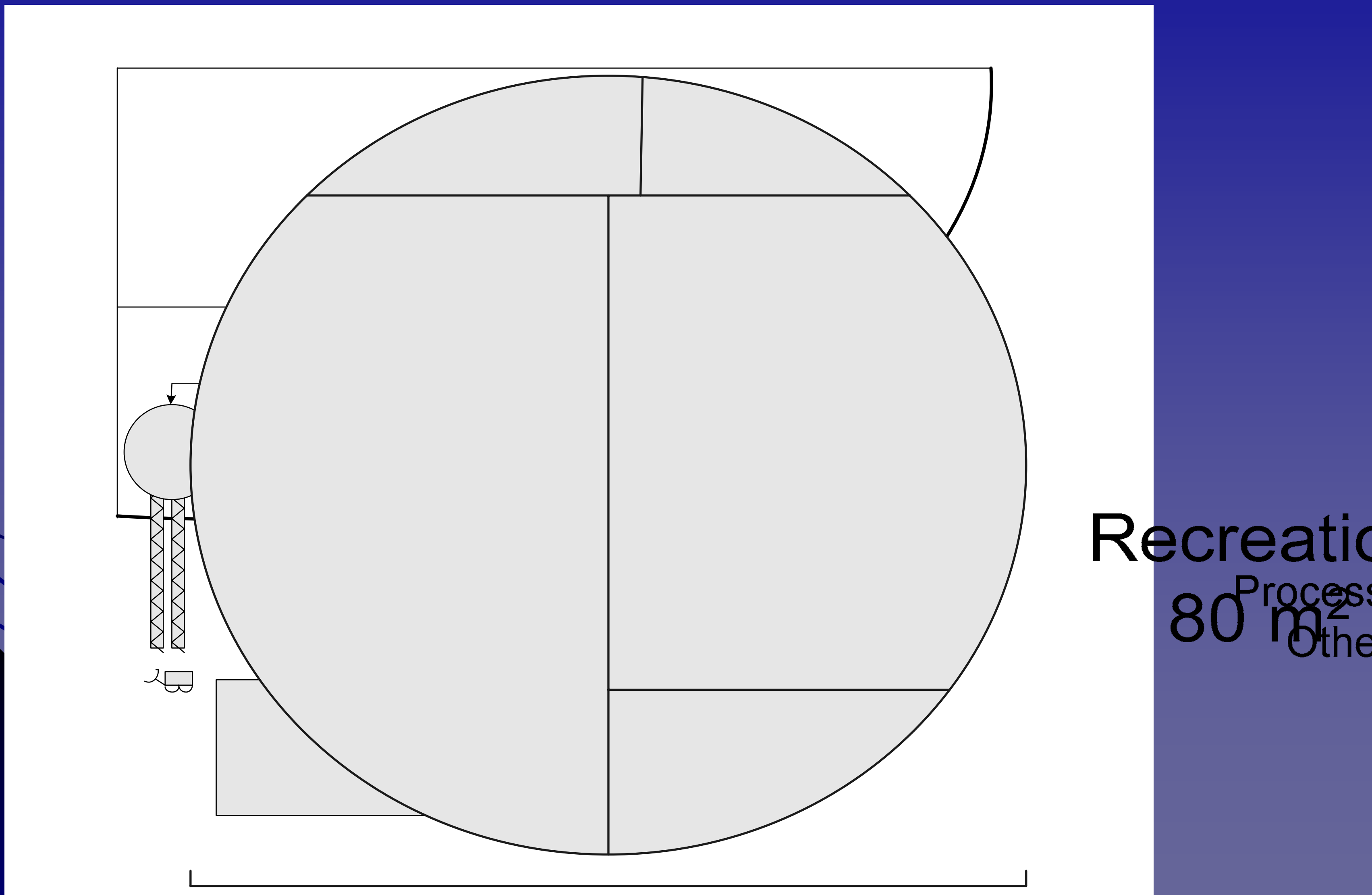
- **Necessary Capabilities**
  - Collection of six month emergency supply
  - Collection of occasional excess oxygen
  - Restore emergency supply
- **Options**
  - Compress and store as gas
  - Implement liquefaction process

Liquefaction Process

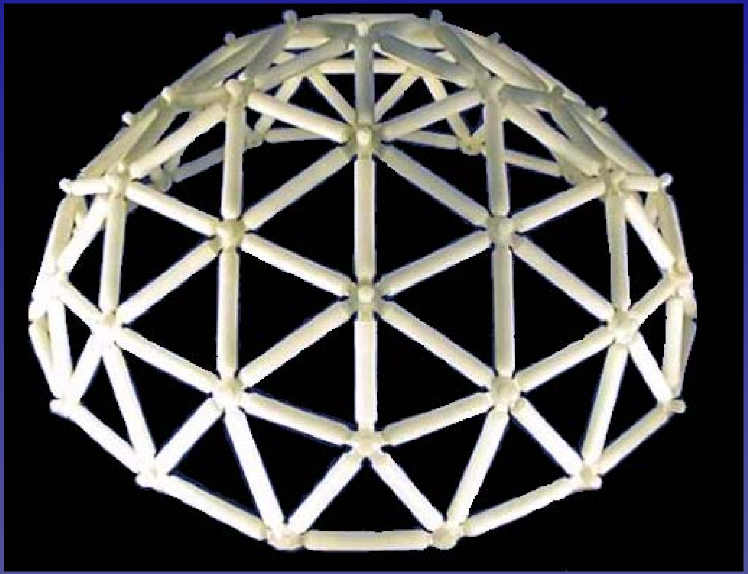
Modified Claude Cycle



Floor Plan



Habitat Structure



Geodesic Dome

- Maximum volume for a given surface area
- Structurally sound
- Easily constructed

Necessary layers

____

**Required for permanent habitation

____

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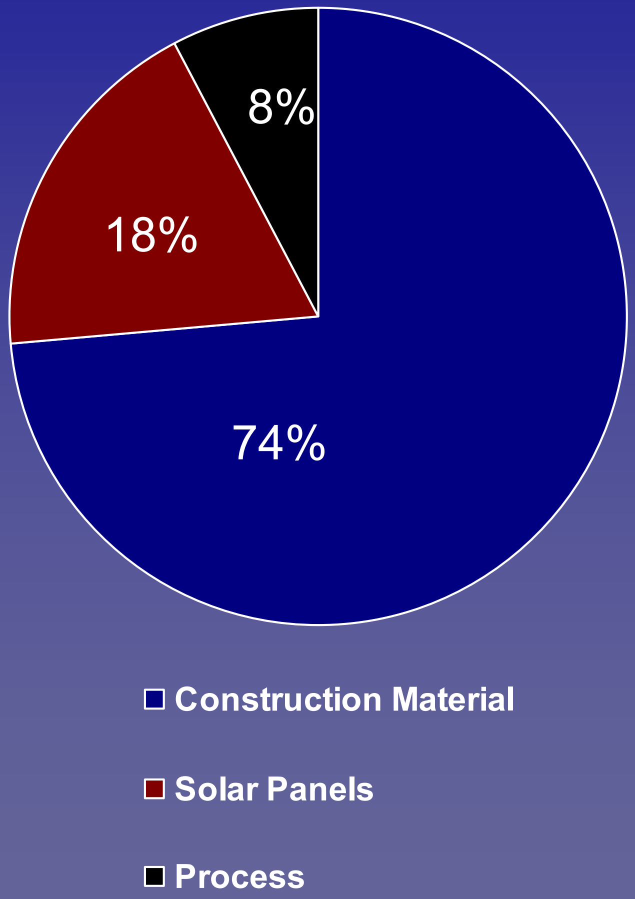
Habitat Energy Requirements

- Energy Needs (max. energy consumption)
  - 840 kW
- Energy will be input through electrical heating from solar panels
- Total solar panel area required
  - 5440 m^2 (based on 12% efficiency)
  - Less than 1 launch necessary

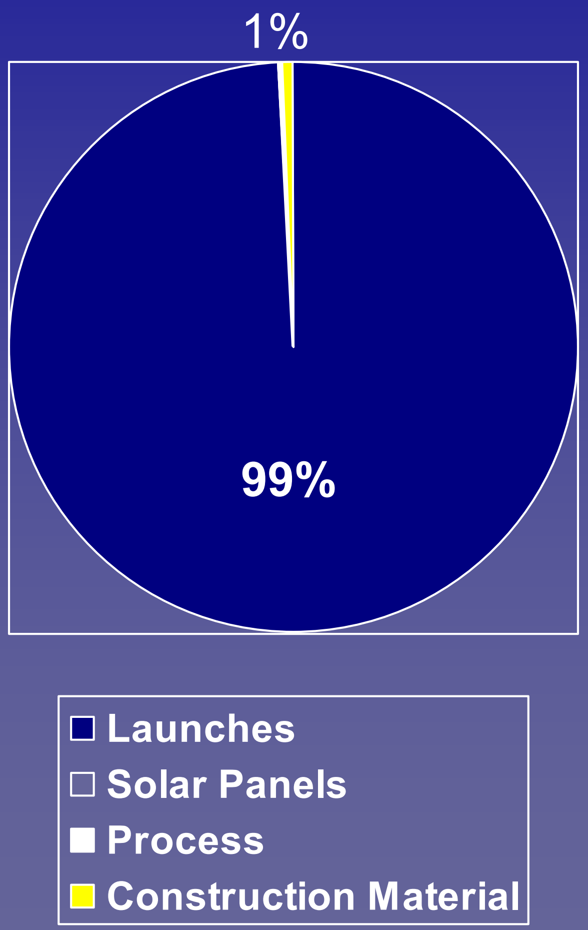
Cost Estimates

- Cost of project before delivery
  - Construction material: $32 million
  - Solar Panels: $8 million
  - Process: $3.4 million



Cost Estimates

- Cost of Shuttle Launches
  - 23 shuttle launches necessary
    - 13 Launches for habitat
    - 5 Exploratory launches
    - 3 Launches for astronauts
    - 1 Launch for solar panels
    - 1 Launch for process
  - Total cost of $4.6 billion



Conclusions

- Process
  - Design for simplicity and safety
    - Safety should be primary concern
    - Simplicity reduces unknowns with lunar enviornment
- Economics
  - Minimize shuttle launches to minimize cost
  - Habitat will be majority of shuttle launches

QUESTIONS?

Mystery Bonus Material

In Response To…

Email sent to Mr. Carlton Allen, head procurator of astro-materials at NASA's Johnson Space Center (shown at right at ilmenite testing facility?) inquiring about our final reactor design

"Your design looks reasonable to me."

Carlton Allen
Head Procurator of Astro-Materials

In Response To…

- <u>Email sent to kidsasknasa@nasa.gov:</u>

  "Hello NASA,

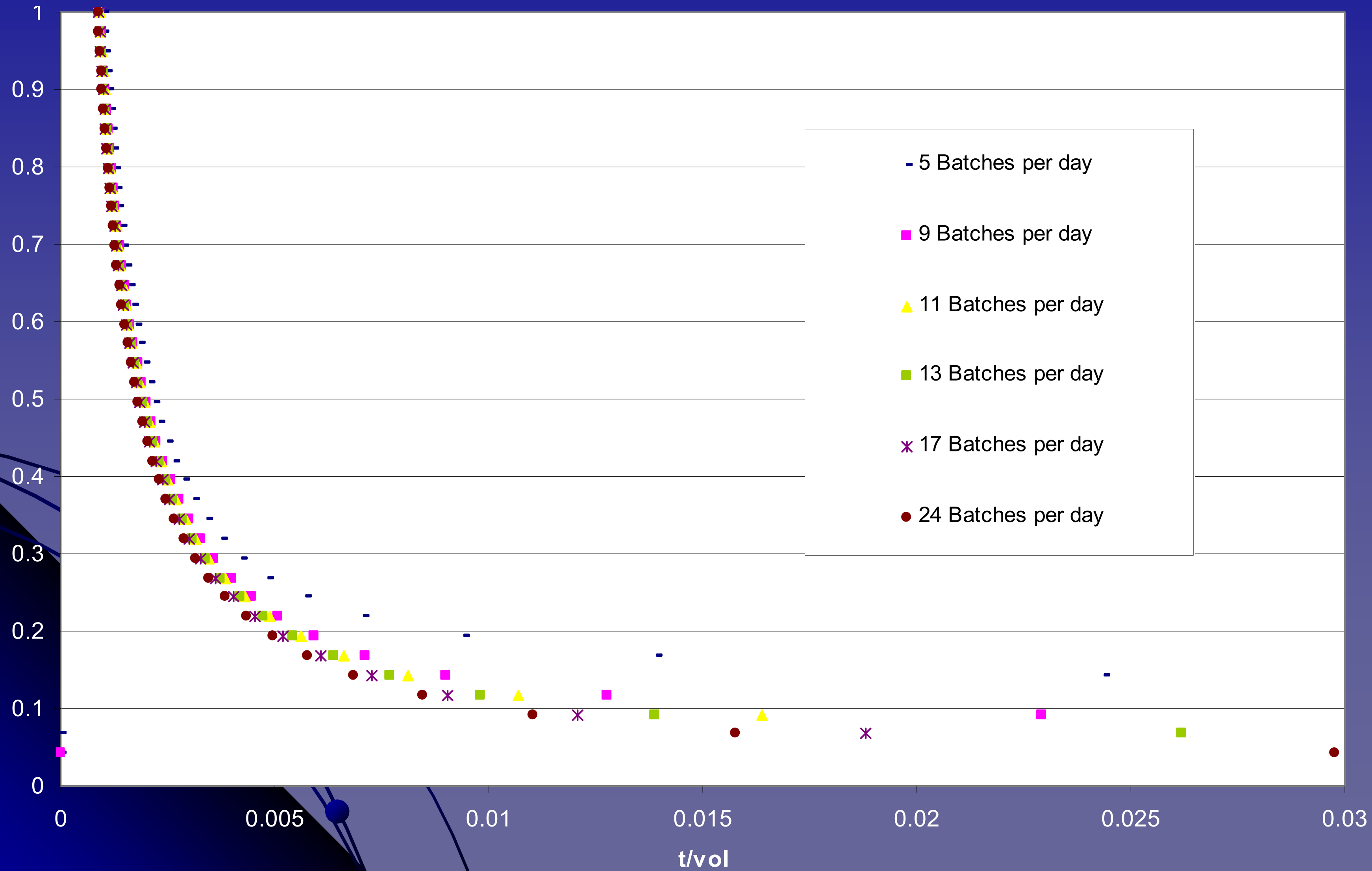
  I have heard a lot about President Bush's new plan for permanent colonies on the moon. It seems like it would be really hard to produce enough oxygen to support a reasonable number of people. I know a lot of research has been done on ilmenite. Is this the most likely way that NASA plans to produce oxygen? It seems like a good idea, but could you all fill me in on the physical properties of ilmenite.

  Thanks a lot,
  Stevie Hernandez
  Ms. Jagajewicz 4^{th} Grade Class President"

“Nasa is nowhere near making oxygen on the moon.”

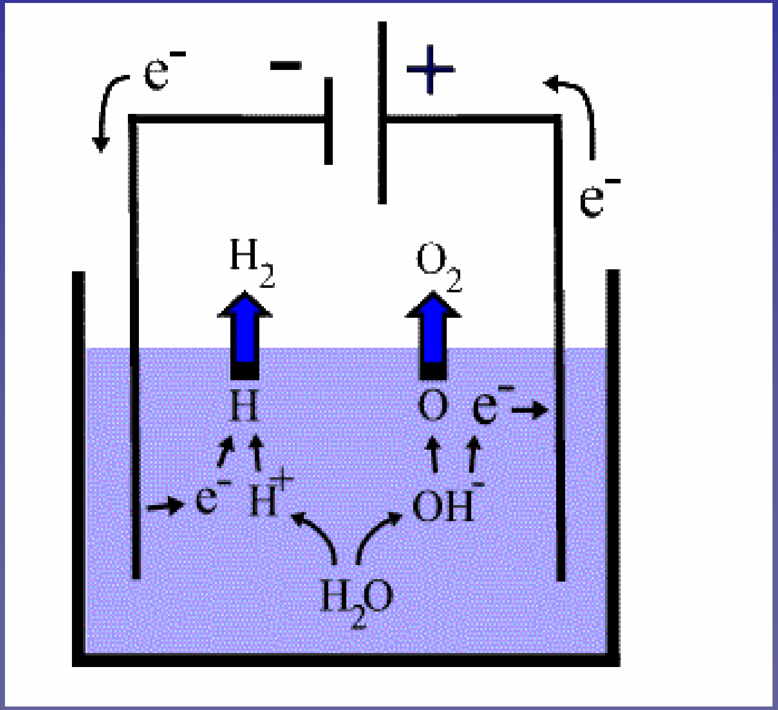
kidsasknasa@nasa.gov

Batch Number Optimization



Electrolysis Reactions (backup)

- $H_2O \longrightarrow H^+ + OH^-$
- H^+ picks up an electron from the cathode:
  - $H^+ + e^- \longrightarrow H$
  - $H + H \longrightarrow H_2$
- Anode removes the e^- that the OH^- ion "stole" from the hydrogen initially
  - OH^- combines with 3 others
  - $4OH^- \longrightarrow O_2 + 4H_2O + 4e^-$
- O_2 molecule is very stable-bubbles to the surface
- A closed circuit is created in a way, involving e^-'s in the wire, OH^- ions in the liquid
- Energy delivered by the battery is stored in the production of H_2



Back up – Calculations for Electrolysis

- Nernst Equation

$$E = E^{\circ} - \frac{RT}{n\Im}\ln\left(\frac{a_{H_2} a_{O_2}^{1/2}}{a_{H_2O}}\right)$$

- Gibbs electrochemical energy

$$\Delta G = -En\Im$$

- Work

$$W = -\Delta G$$

Equipment

- Compressor
  - 217 hp
- Heat Exchangers
  - E1 requires 100 ft^2
  - E2 requires 120 ft^2
- All equipment will be vacuum jacketed and a multilayer insulation systems will be implemented