Powdered Metal Reactor

April 6, 2024

Capstone Final Design Presentation

Supervised by Dr. Reza Kholghy

PMR | Carleton University

GM1

Agenda

- Project Abstract
- Meet the Team
- Project Timeline
- Subgroup Progress
- Future Goals
- Q&A Period

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Slide 2

GM1 Agenda should probably go before abstract if we mention the abstract in it

Gaelan Moffat, 2024-03-22T04:07:20.086

Abstract

Carleton University's Powder Metal Reactor (PMR) team comprises nine students from three different disciplines, working collaboratively to engineer an innovative, student-made carbon dioxide-free metal fuel burner. The primary objective is to conceptualize, design, and construct a 5 kW thermal reactor capable of efficiently harnessing heat generated through the high-temperature oxidation of powdered metals, with a particular emphasis on the promising recyclable iron-air reactions. The long-term goal is to build a 20 kW model system to explore the viability of retrofitting coal power plants, offering a tangible solution towards achieving modern environmental goals using existing infrastructure. This project will provide comprehensive thermodynamic, techno-economic, lifecycle, and energy density analyses on iron and aluminum. Practical design challenges include developing a powder delivery mechanism capable of consistently delivering 50-micrometer diameter iron particles from a reservoir to the reaction chamber, optimizing thermodynamic processes to maximize energy potential, ensuring visibility of the reaction process while maintaining stringent safety standards, and managing fluid flow dynamics across multiple interfacing sub-assemblies.

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Abstract

- Carleton University's PMR team designed and built a 20kW carbon dioxide-free metal fuel burner capable of efficiently harnessing heat generated through the high-temperature oxidation of powdered metals.
- The long-term goal is to explore the viability of retrofitting coal power plants, offering a tangible solution towards achieving modern environmental goals using existing infrastructure.

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Abstract

- 20kW CO_2 free metal fuel reactor
- Future goals of retrofitting coal power plants

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AR1

Abstract in Numbers

Challenges

- Consistent and reliable powder delivery
- Optimizing thermodynamics and fluid flow
- Thorough safety systems and management

Goal

- Design and build Carleton's first powdered metal reactor.
- 50 um iron or aluminum powder, air or steam oxidizer
- Progress to 20 kW within the framework of coal power plant retrofitting
- Thorough Thermodynamic, TEA, LCA analyses

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Slide 6

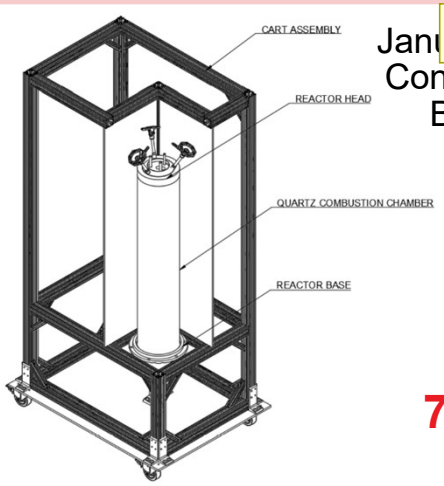
AR1 winnow it down, too wordy maybe get rid of who we are since we have a whole slide for it

Alexander Rusch, 2024-03-22T14:10:05.234

Project Timeline

April 2023
Project Announcement

September 2023
Project Begins



December 2023
Initial Design Complete

January 2024
Construction Begins

February 2024
Individual Subteam Testing Begins

March 2024
First Successful Test With Iron Powder

Slide 7

MW1 Do we want photo landmarks?
Mieke Wilkinson, 2024-03-18T21:48:24.707

MM1 0 Do we have one for each?
Maria McKiel, 2024-03-22T01:51:57.869

MW1 1 Done. Annimations make sure only one photo is shown at a time. View in slide show .
Mieke Wilkinson, 2024-03-22T03:54:06.018

GM

GM3

Meet the Team

Calculations

- Thermodynamic Calculations
  - 
  - J. Parent
  - 
  - M. Wilkinson
- Techno-Economic Analysis (TEA)
  - 
  - M. Mckiel
- Life Cycle Analysis (LCA)
  - 
  - Z. Meunier

Prototype System

- Reactor Design
  - 
  - A. Rusch
  - 
  - M. Wilkinson
- Off-Gas Handling
  - 
  - G. Moffat
- Powder Delivery
  - 
  - C. Rogerson
  - 
  - U. Okafor
  - 
  - E. St-Jacques
- Steam Generation
  - 
  - M. Mckiel
  - 
  - E. St-Jacques
- Safety
  - 
  - C. Rogerson

Project Engineer

Dr Reza Kholghy

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Slide 8

GM1 Dafety separate category, combine TEA and LCA
Gaelan Moffat, 2024-03-22T14:08:07.765

AR2 put reza here
Alexander Rusch, 2024-03-22T14:09:22.171

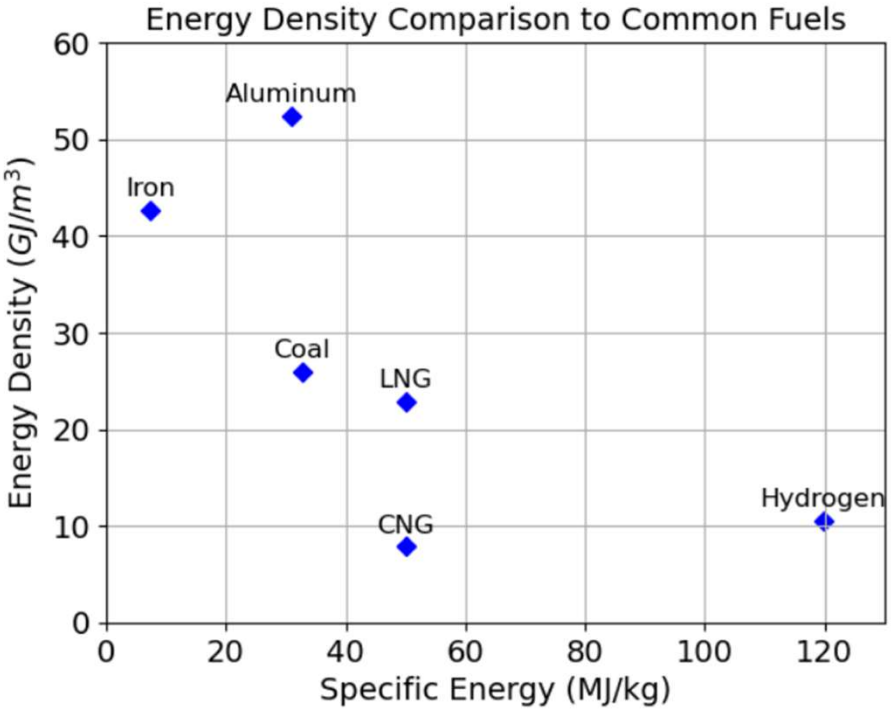
GM3 Animations need to be fixed
Gaelan Moffat, 2024-03-22T19:01:40.973

GM1

Thermodynamic Calculations

- Why Utilize Metal Fuels?

1. Energy Dense



2. Zero CO_2 Emitted (*At point of combustion)

Fuel	$KgCO_2$ /kWh
Natural Gas	0.197
Bituminous Coal	0.411
Iron	**0**
Aluminum	**0**

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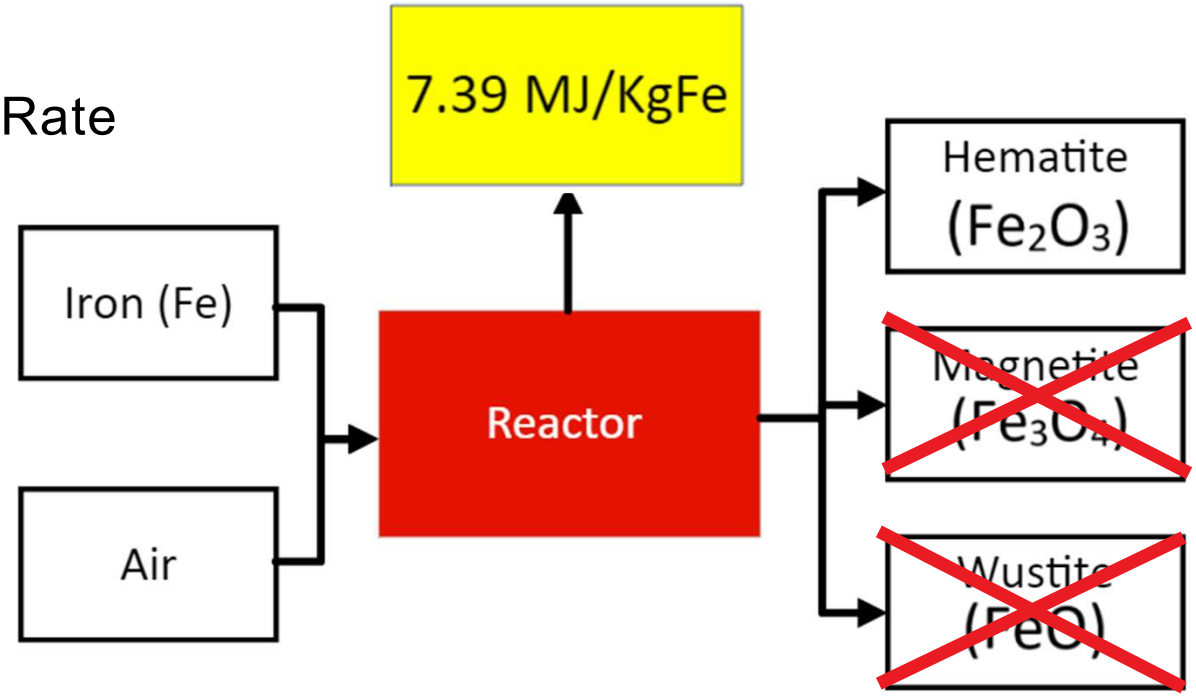
Slide 9

GM1 update this graphic
Gaelan Moffat, 2024-03-22T14:13:15.143

Thermodynamic Calculations

- Mass Flow Rate



Available Energy = Chemical Energy of the Reactants – Chemical Energy of the Products

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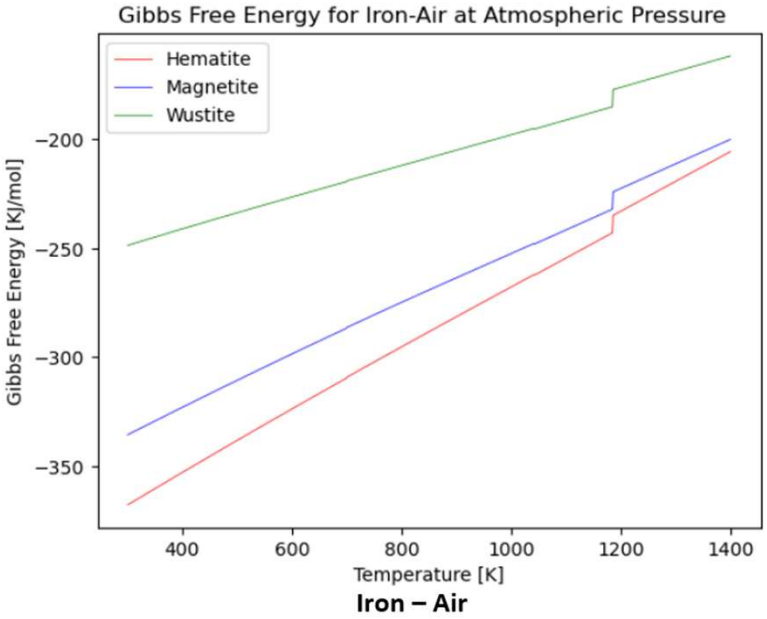
Thermodynamic Calculations

- In what conditions will the reactions occur?

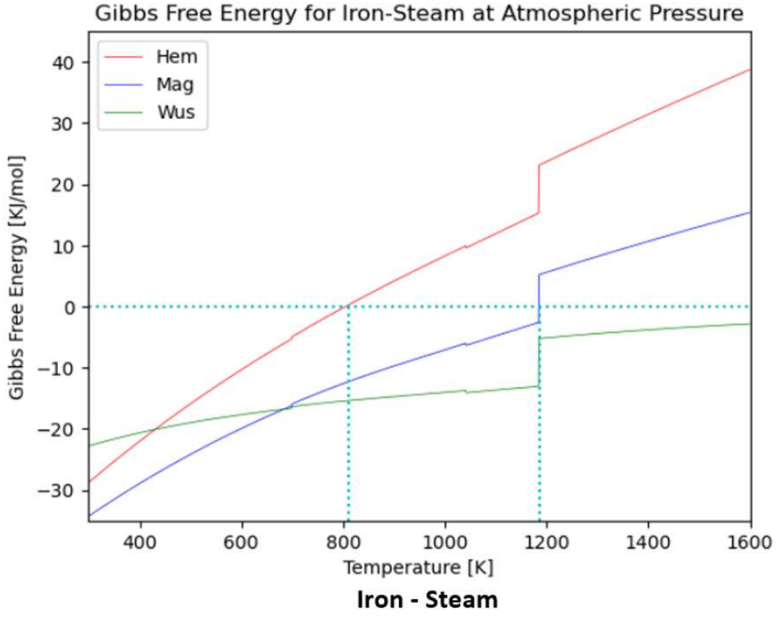


Iron – Air

$$Fe_{(s)} + 0.5\,(O_2 + 3.76N_2)_{(g)} \rightarrow FeO_{(s)} + 1.88\,N_{2(g)}$$

$$Fe_{(s)} + {}^{2}/_{3}\,(O_2 + 3.76N_2)_{(g)} \rightarrow {}^{1}/_{3}\,Fe_3O_{4(s)} + 2.51N_{2(g)}$$

$$Fe_{(s)} + {}^{3}/_{4}\,(O_2 + 3.76N_2)_{(g)} \rightarrow {}^{1}/_{2}\,Fe_2O_{3(s)} + 2.82N_{2(g)}$$



Iron - Steam

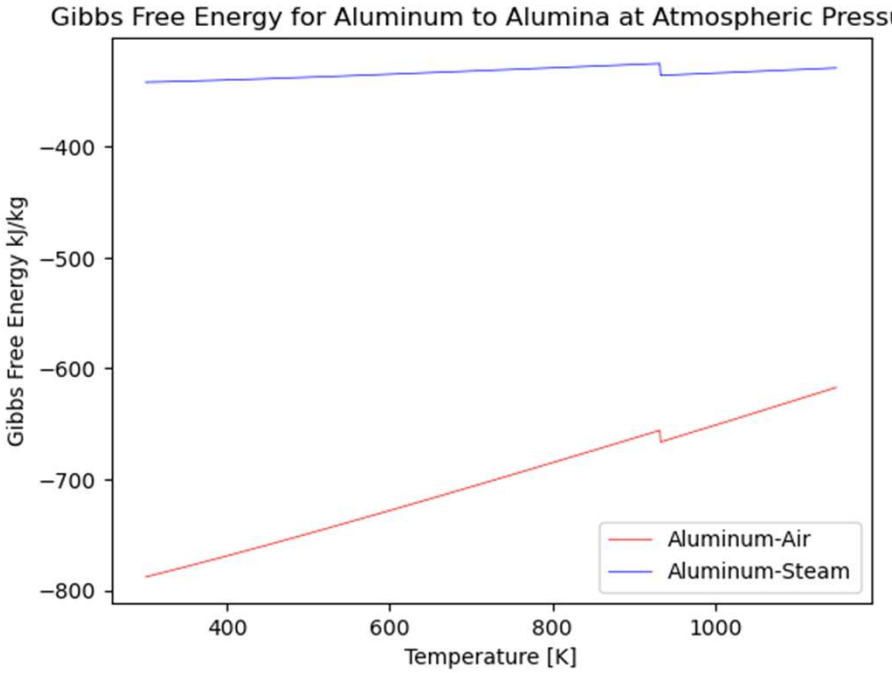
$$Fe_{(s)} + H_2O_{(g)} \rightarrow FeO_{(s)} + H_{2(g)}$$

$$Fe_{(s)} + {}^{4}/_{3}\,H_2O_{(g)} \rightarrow {}^{1}/_{3}\,Fe_3O_{4(s)} + {}^{4}/_{3}\,H_{2(g)}$$

$$Fe_{(s)} + {}^{3}/_{2}\,H_2O_{(g)} \rightarrow {}^{1}/_{2}\,Fe_2O_{3(s)} + {}^{3}/_{2}\,H_{2(g)}$$

Thermodynamic Calculations

- In what conditions will the reactions occur?



Aluminum - Water

$$AL_{(s)} + 1.5\ H_2O_{(l)} \rightarrow\ 0.5\ Al_2O_{3(s)} + 1.5\ H_{2(g)}$$

Aluminum -Steam

$$AL_{(s)} + 1.5\ H_2O_{(g)} \rightarrow\ 0.5\ Al_2O_{3(s)} + 1.5\ H_{2(g)}$$

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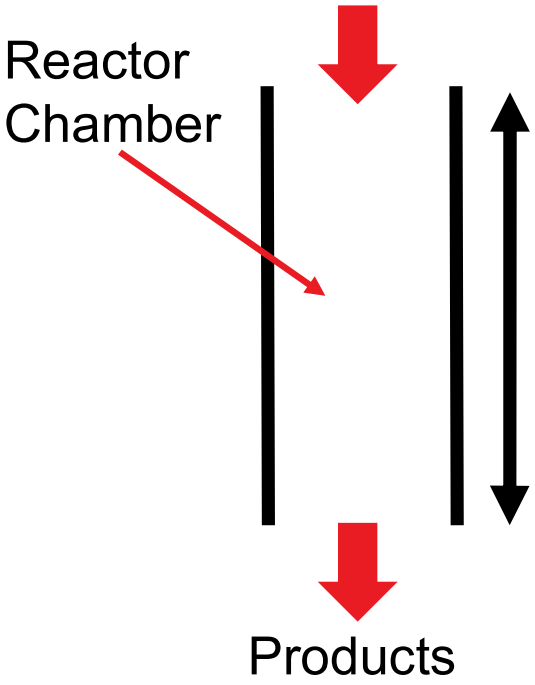
Thermodynamic Calculations

- Reactor Length



Minimum Length

$$L_{MINIMUM} = 0.22m$$

1. Time Required for Reaction
2. Velocity of the Air Through the Reactor
3. Velocity of the Particle Relative to the Air

$$L_{MINIMUM} = t_{required} * (V_{Air} + V_{Particle,Relative})$$

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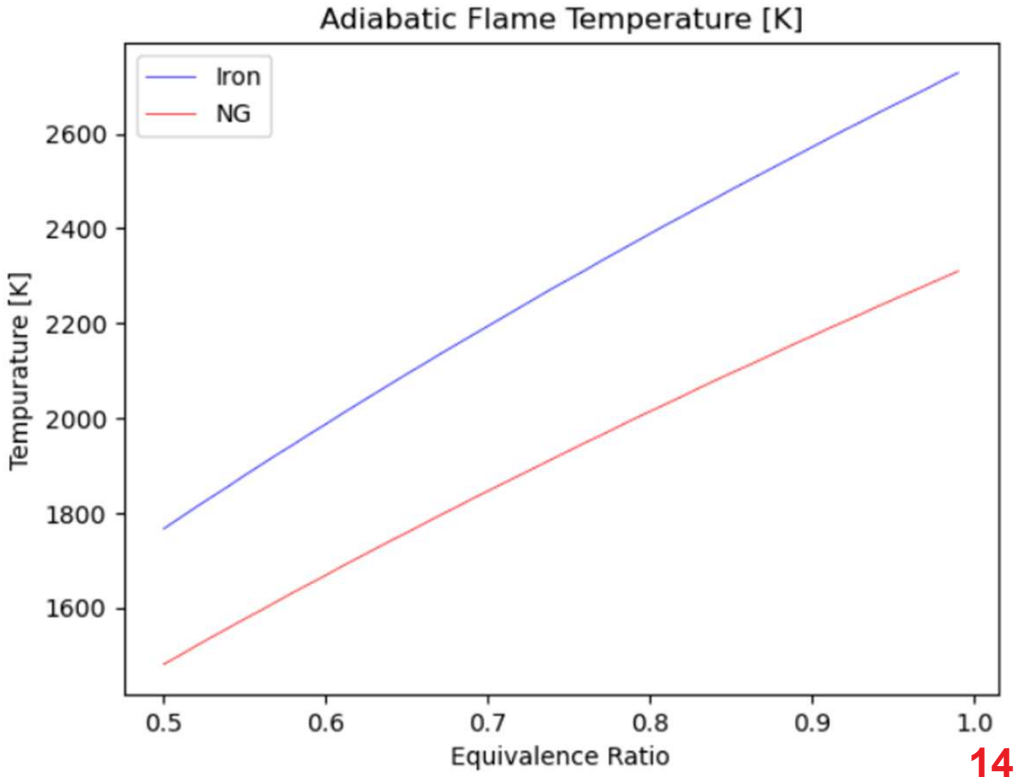
Thermodynamic Calculations

- How Can We Control the Temperature?

MW1



- Equivalence Ratio (Φ) = $\frac{Required\ Air}{Actual\ Air}$
- As the Amount of Air ↑ Temperature ↓

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Slide 14

MW1 Replace image, quality is bad

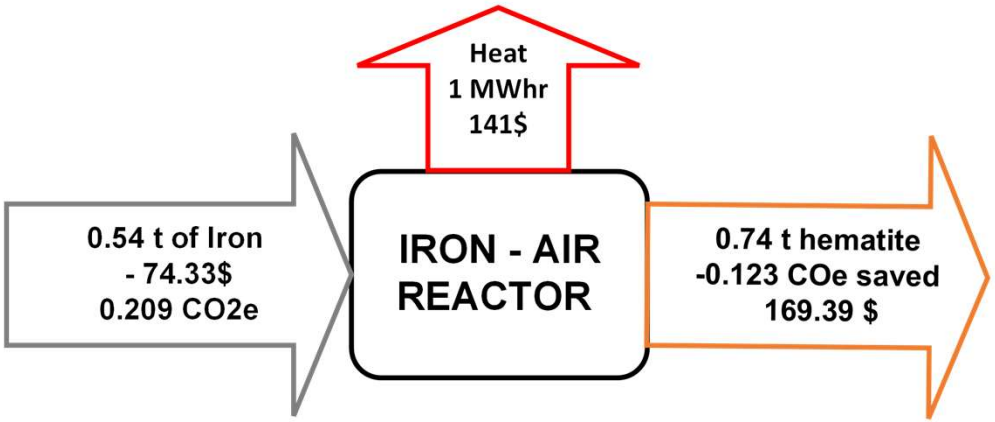
Mieke Wilkinson, 2024-03-26T18:02:40.476

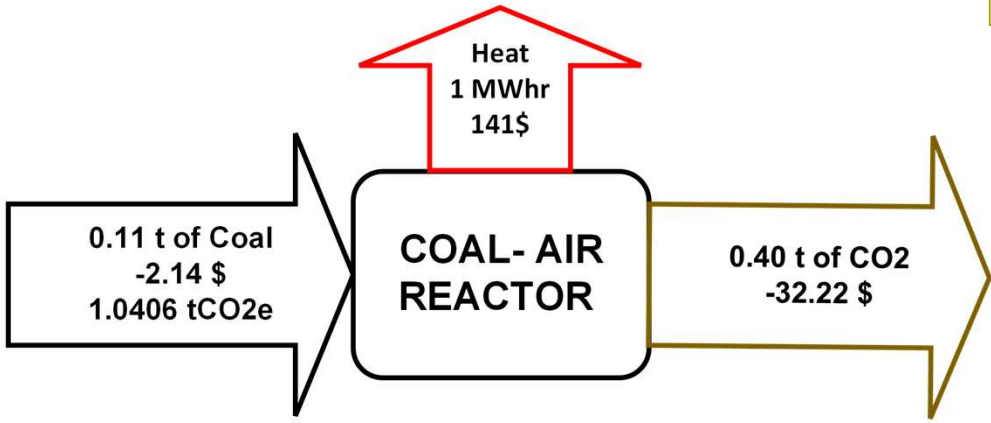
Techno-Economic & Life-Cycle Analysis

Value	Cost
Coal	131 USD$/tonne
Iron Ore	109.61 USD$/tonne
Secondary Iron	210.27 USD$/tonne
Electricity	141 CAD$/MWhr
Carbon Tax	80 CAD$/tonne of CO_2 emitted
Conversion Rate	1.36 CAD$/USD$

GM3

Techno-Economic & Life-Cycle Analysis





Reactor type	Net revenue ($CAD/MWhr)
Iron – Air	158.08
Coal - Air	89.23

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Slide 16

GM1 update to new graphic?
Gaelan Moffat, 2024-03-22T14:17:46.252

AR2 Update these pictures to the better font
Alexander Rusch, 2024-03-22T14:29:37.587

GM3 add net revenue
Gaelan Moffat, 2024-03-22T14:32:45.750

Techno-Economic & Life-Cycle Analysis

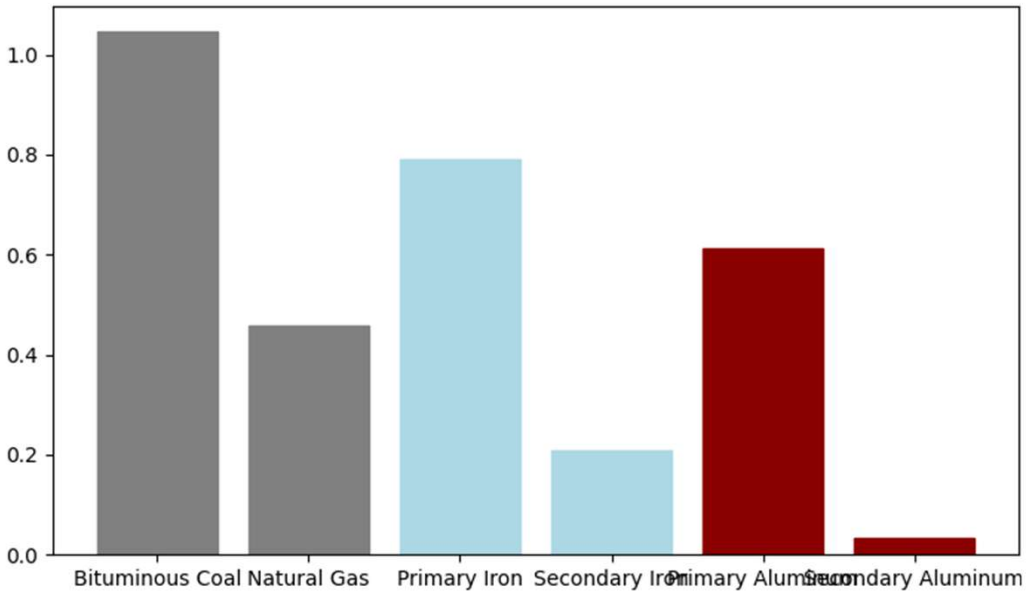
Material	GGI	Source	Notes
Primary Iron (Basic Oxygen Furnace)	1.62 MW1	WP_22-16_M6	Canada, natural gas energy
Secondary Iron (Electric Arc Furnace)	0.429	WP_22-16_M6	Canada, natural gas energy
Iron Oxide	0.142	WP_22-16_M6	
Bituminous Coal	2.68	WP_22-16_M5	
Natural Gas	3.06	WP_22-16_M5	
Unwrought Aluminum (primary)	5.30	WP_22-16_M7	North America (incl Canada), natural gas energy
Unwrought Aluminum (secondary)	0.29	WP_22-16_M7	North America (incl Canada), natural gas energy

Slide 17

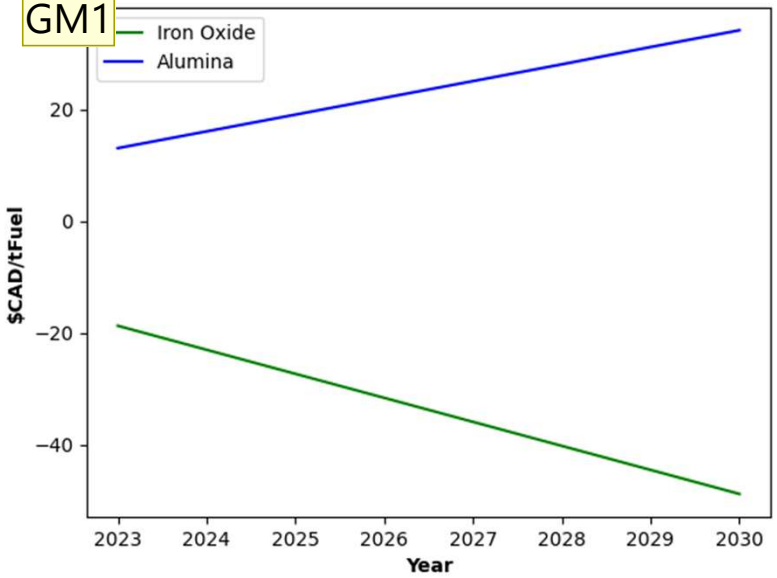
MW1 What does this mean?

Mieke Wilkinson, 2024-03-26T18:04:37.297

Techno-Economic & Life-Cycle Analysis



GM1



GM2

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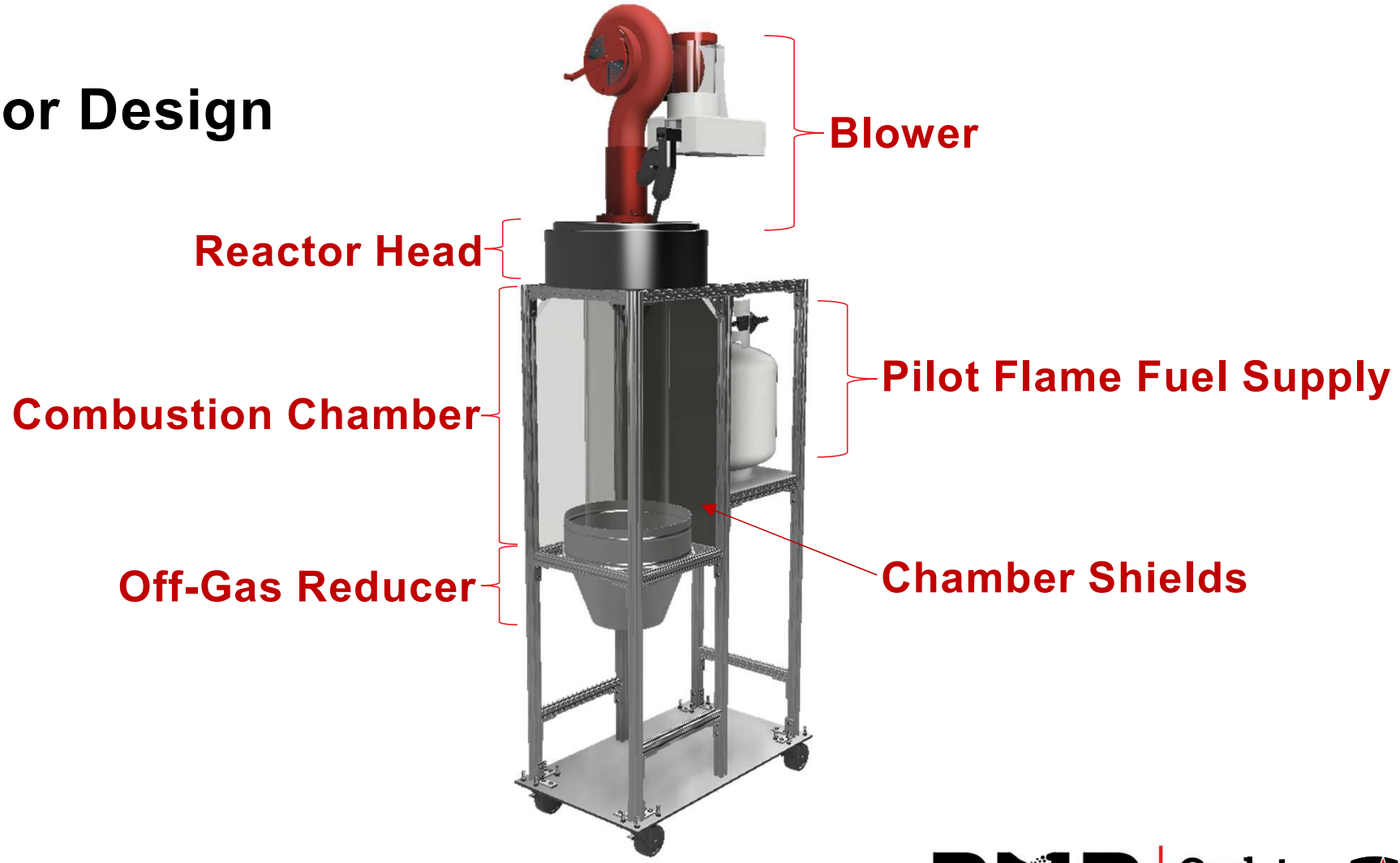
Slide 18

GM1 Bar titles overlapping
Gaelan Moffat, 2024-03-22T14:23:25.428

GM1 0 also RGB for colours
Gaelan Moffat, 2024-03-22T14:35:01.752

GM2 add with/without carbon tax
Gaelan Moffat, 2024-03-22T14:36:55.550

Reactor Design



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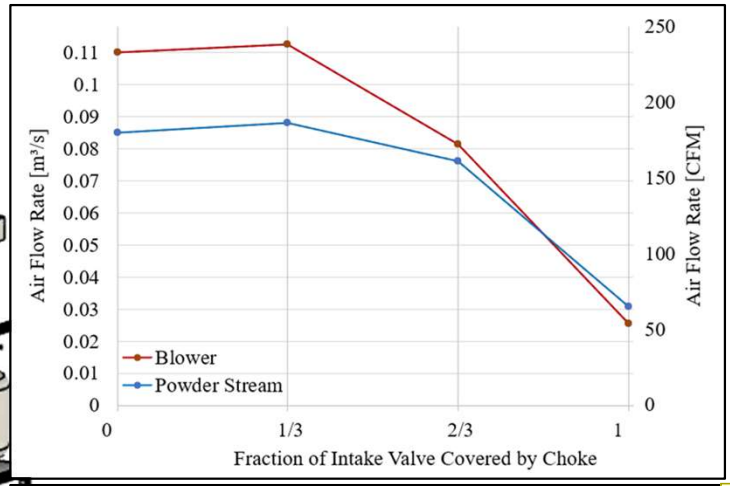
Reactor Design

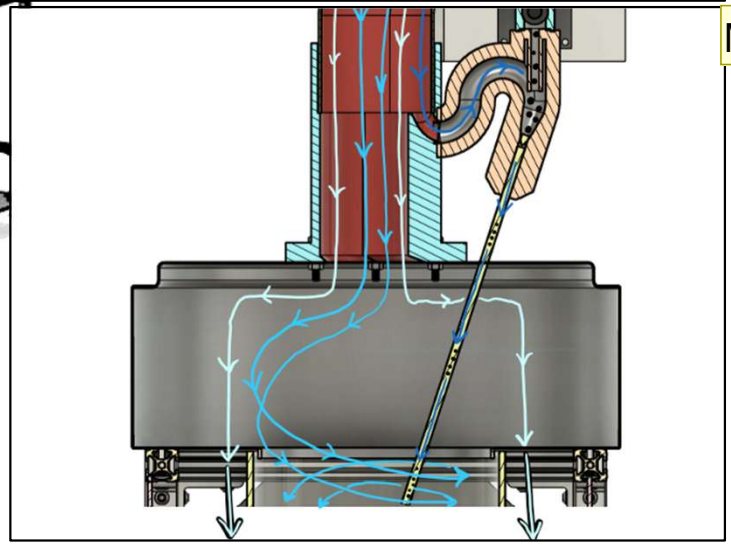
Blower

MW1

- Overcomes buoyancy of flame
- Provides cooling
- Creates swirl
- Supplies a propulsive gas for the powder
- Choke varies air from 240 - 50 CFM

MW3





MW2

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Slide 20

MW1 We should keep this the same as the label on the system overview. What about the other components, the 3D prints?
Mieke Wilkinson, 2024-03-21T12:45:00.644

MW2 update
Mieke Wilkinson, 2024-03-22T03:36:08.300

MW3 Par by par animate
Mieke Wilkinson, 2024-03-25T20:13:23.089

Reactor Design

Reactor Head

- Powder is delivered to pilot flame
- **1140°C**
- Reduced burner area for focal point control
- Internal geometry to form swirl
- Air curtain for cooling

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Reactor Design

Reaction Chamber

- Tempered glass tube
  - 200mm Diameter
  - 750mm Long

Thermal Gaskets

- Seals and Cushions Glass

Reducer

- Supports chamber
- Connection to Off-Gas subassembly

Chamber Shields

- Transparent for observation
- Operational safety

Combustion Chamber
&
Off-Gas Integration

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GM2

Reactor Design

Inverted, Reduced Fuel Area

- Central flame
- Stable swirl
- Blower overcomes buoyancy
- Choke modifies Air: Fuel ratio

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Slide 23

GM1 videos don't have transitions so currently block text
Gaelan Moffat, 2024-03-22T04:10:38.337

GM2 add flame not going down
Gaelan Moffat, 2024-03-22T14:41:43.873

AR2 0 Buoyant flame
Alexander Rusch, 2024-03-22T14:56:08.131

Reactor Design

With Vacuum

- Further overcomes buoyancy
- Creates redundancy

Iron Flame

- Pilot flame necessary to sustain reaction
- Unstable flame due to powder delivery pulsations

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Slide 24

MW1 Too long for a bullet point, can we make more clear and consise.
Mieke Wilkinson, 2024-03-22T03:40:28.631

GM2 replace with better video of swirl
Gaelan Moffat, 2024-03-22T14:42:12.655

AR3 Lets put a bunch of different views of powder flame (this is the slide to really shove it in their faces with wow
Alexander Rusch, 2024-03-22T14:58:26.542

Reactor Design

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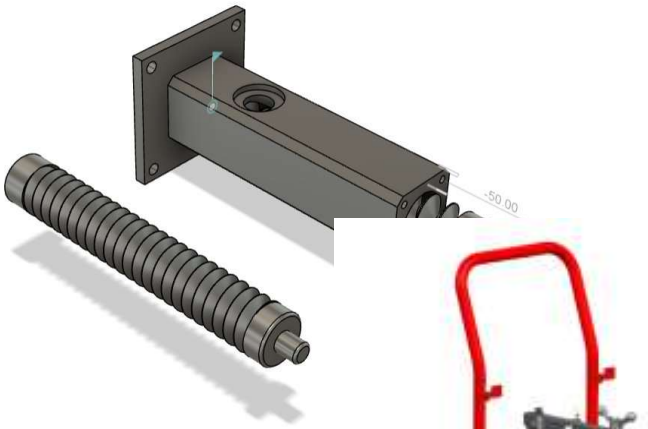
Powder Delivery



Design Considerations:

- Delivers a constant flow of iron
- Flow rate of 0.1 – 2.71 g/s (Variable flow rate)
- Simplicity
- Easy integration with reactor system (mountable, weight)
- Cost
- Machinability/Printing and flexibility

Powder Delivery Systems Considered:

- Motor driven auger system (and their premade counterparts)
- Vibratory delivery system
- Metal cutting torch iron dispenser (https://qccmfg.com/products/powder-dispensers/portable-powder-dispensers/)

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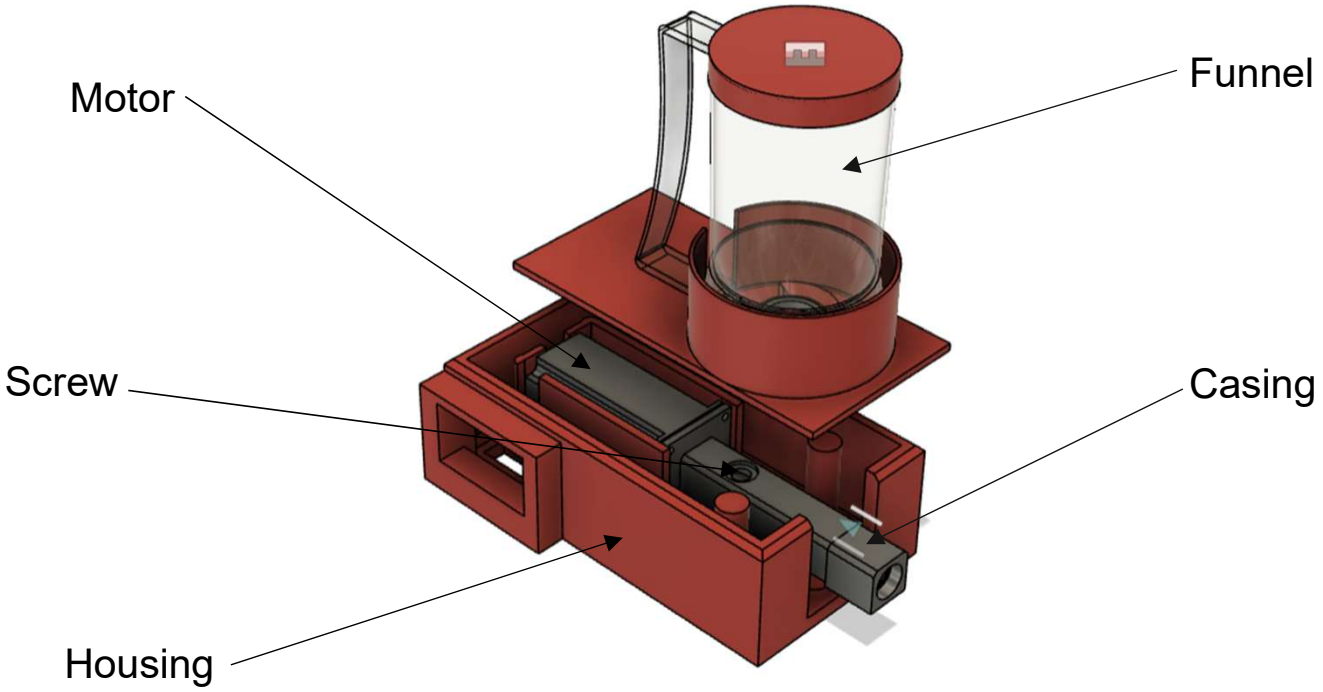
GM2

Powder Delivery

GM1



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Slide 27

GM1 add auger
Gaelan Moffat, 2024-03-22T14:54:24.819

GM2 Change colour of arrows or shell
Gaelan Moffat, 2024-03-22T14:54:58.366

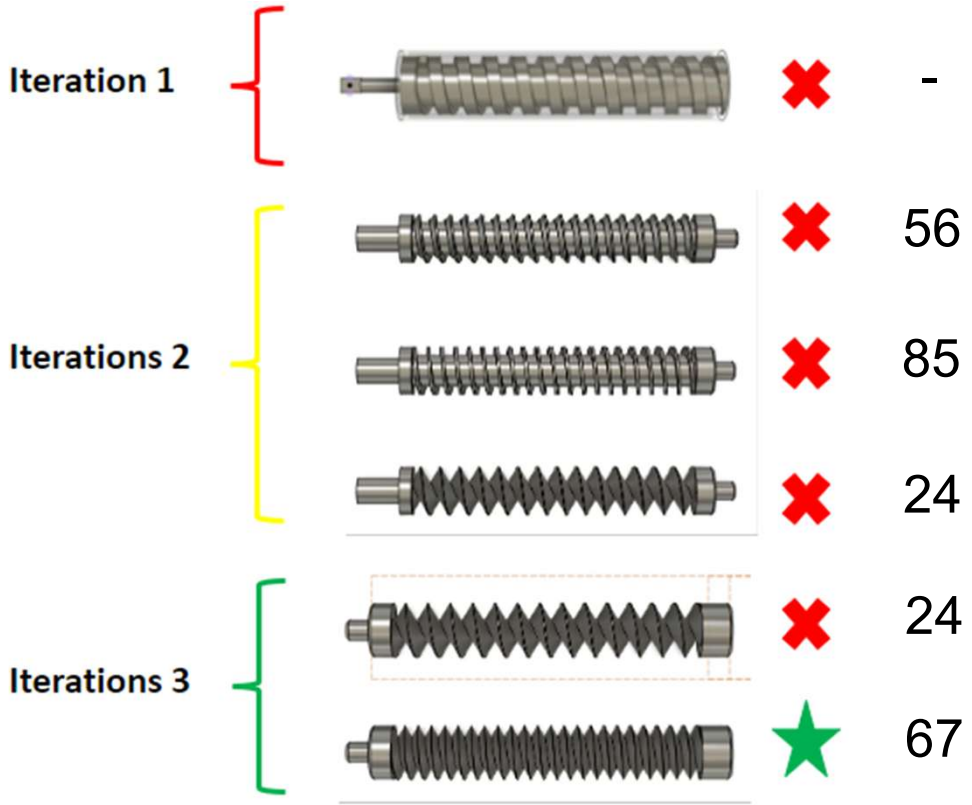
GM2

Powder Delivery

First Iteration

esig

RPM for 5kW burner



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Slide 28

GM1 add video of worse video
Gaelan Moffat, 2024-03-22T14:45:25.938

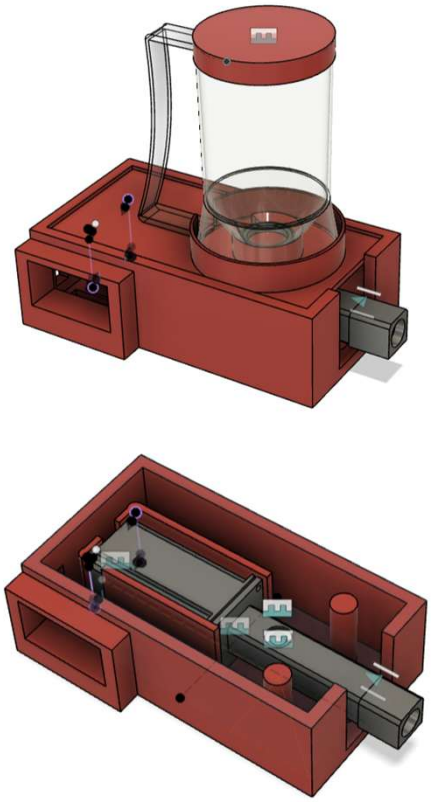
GM2 add video in powerpoint app
Gaelan Moffat, 2024-03-22T14:46:07.485

Powder delivery

MW1

Powder Delivery Housing

- Contains all powder delivery components
- Easily mountable onto reactor



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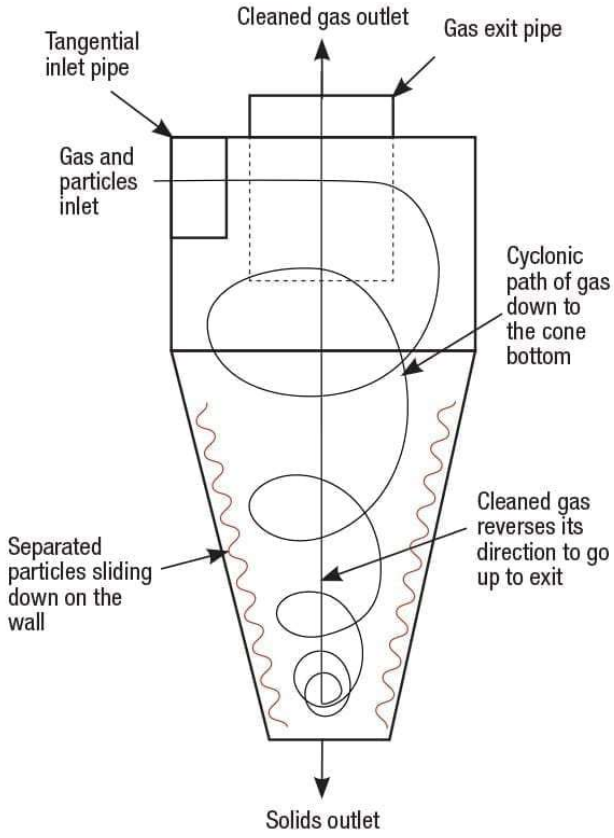
Slide 29

MW1 Remove fusion joints

Mieke Wilkinson, 2024-03-22T14:50:25.446

Off-Gas Handling

	Pressure Drop (Weight 1)	Energy Cost (Weight 3)	Efficiency (Weight 2)	Particle Size (Weight 5)	Cost (Weight 4)	Total
Gravitational Separation	1	5	1	1	4	39
Cyclone Separation	5	5	3	3	5	61
Electrostatic Separation	2	1	4.5	4	1	38
Filters	3	3	4	5	3	57
Wet Scrubbers	3	3	3.5	5	2	52



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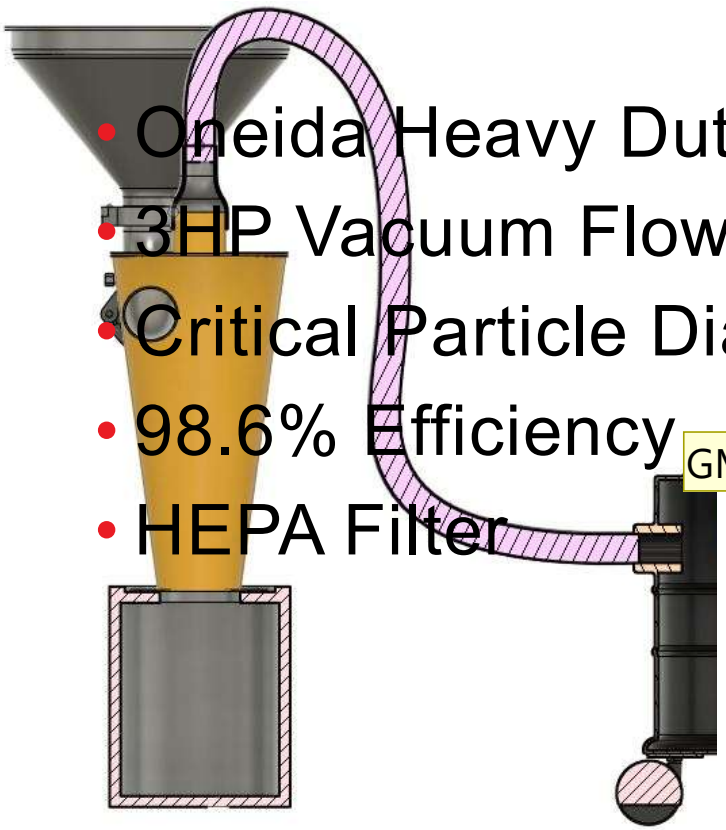
GM2

Off-Gas Handling

- Oneida Heavy Duty Cyclone Separator
- 3HP Vacuum Flow Rate: 1.7m^3/s
- Critical Particle Diameter: 0.24 µm
- 98.6% Efficiency
- HEPA Filter



GM3

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Slide 31

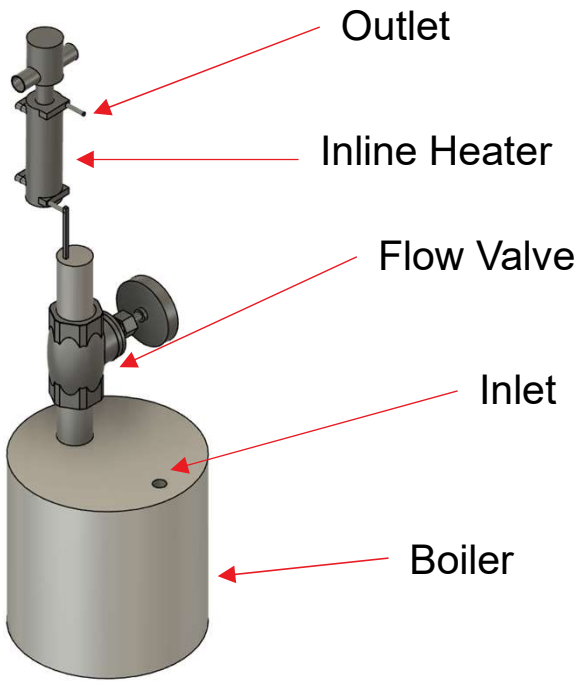
GM1 add mieke's annotated pic
Gaelan Moffat, 2024-03-22T14:39:38.169

GM2 Add collected particles and compositions?
Gaelan Moffat, 2024-03-22T14:46:56.470

GM2 0 mention the importance of separating beyond safety but for economics and reuse maybe
Gaelan Moffat, 2024-03-22T15:05:40.967

GM3 Add table of experimental values proving this
Gaelan Moffat, 2024-03-22T15:04:07.466

Steam Generation



- Mass Flow Rate: 1.31 g/sec
- Inlet Temperature: 15°C
- Outlet Temperature: 300°C

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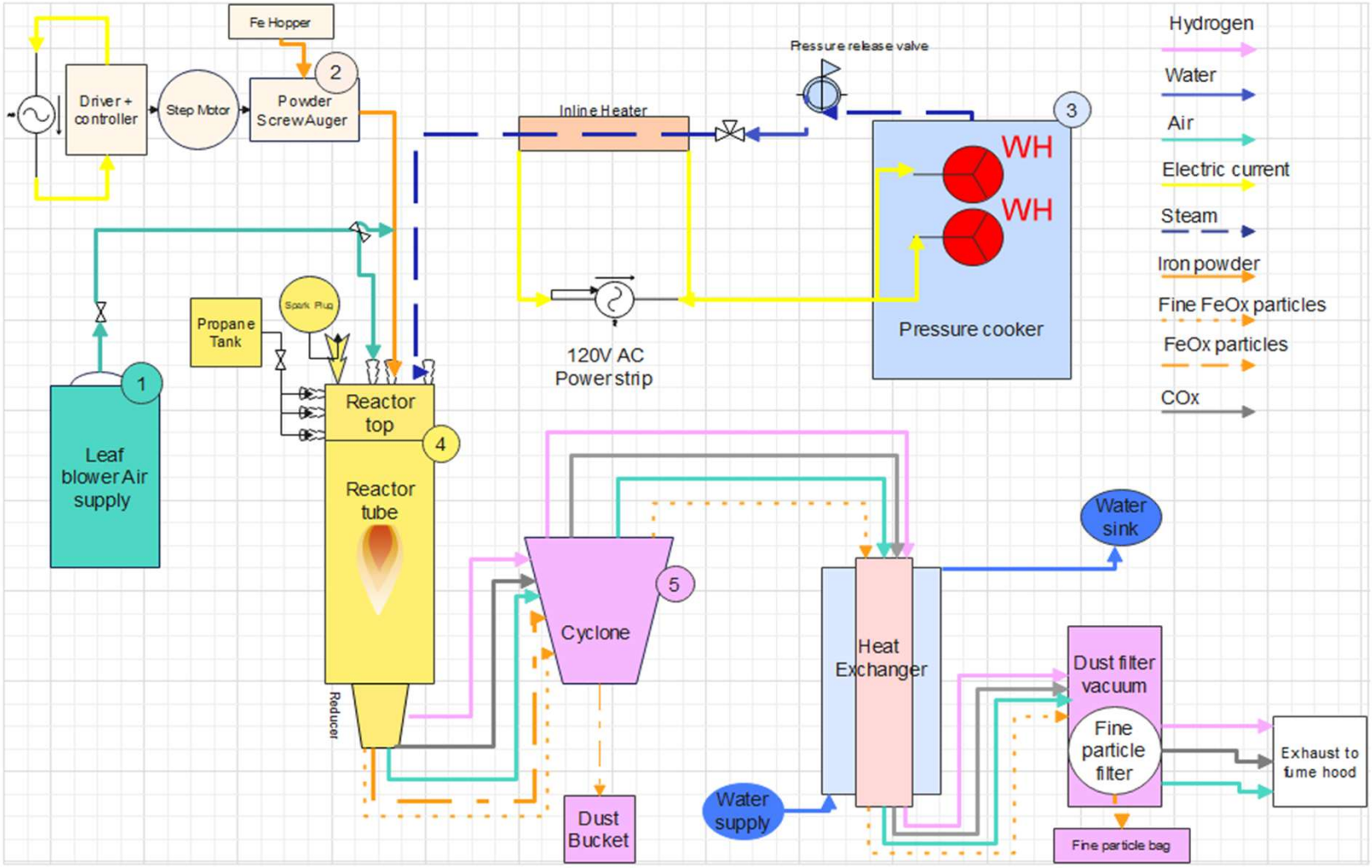
Safety



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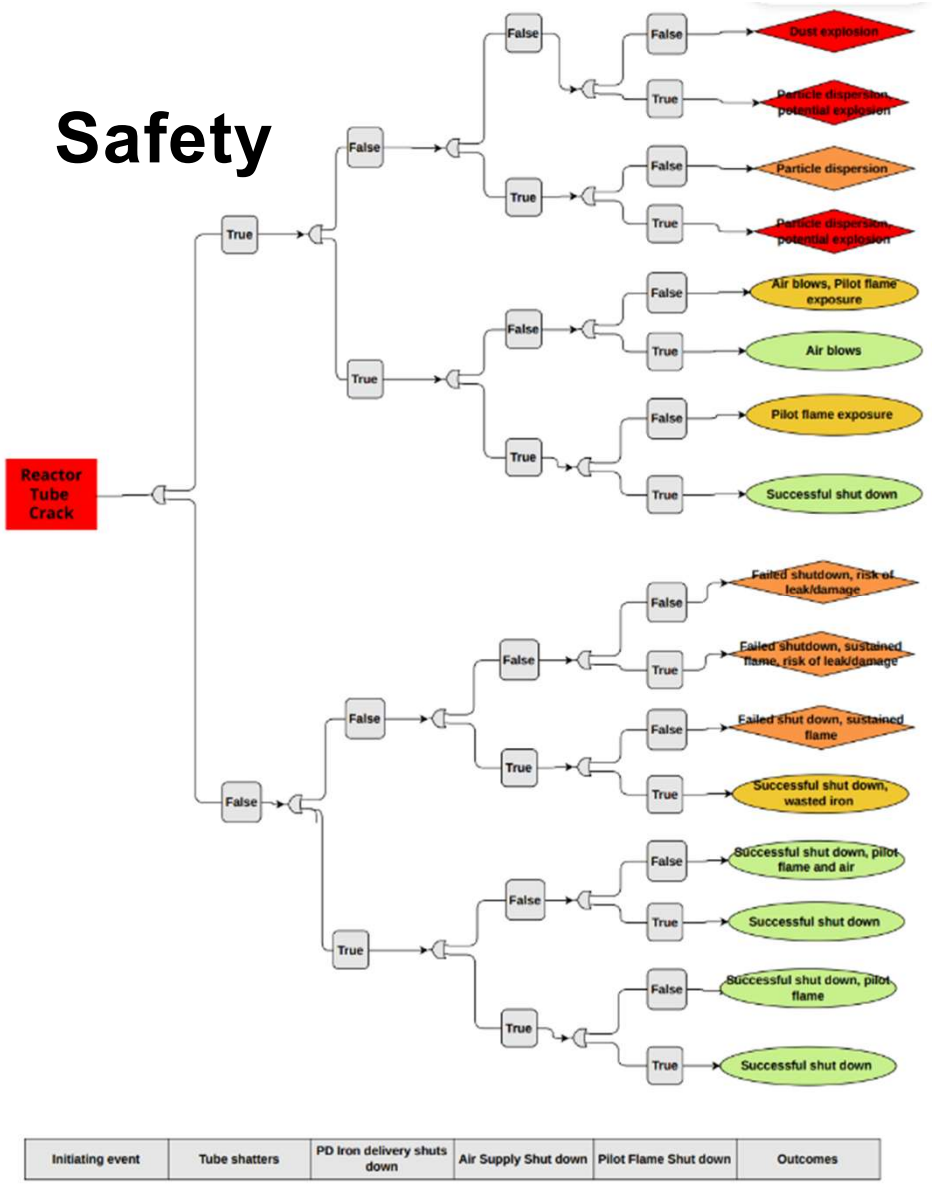
Safety



Initiating event	Tube shatters	PD Iron delivery shuts down	Air Supply Shut down	Pilot Flame Shut down	Outcomes

Severity / likelihood	Negligable E	Minor D	Moderate C	Critical B	Catastrophic A
Frequent 5			X		
Probable 4					
Remote 3					
Extremely Remote 2					
Extremely Improbable 1					

- Each component is analysed for deviations
- Each deviation is rated for its "Risk"
- Summary results in HAZOP report

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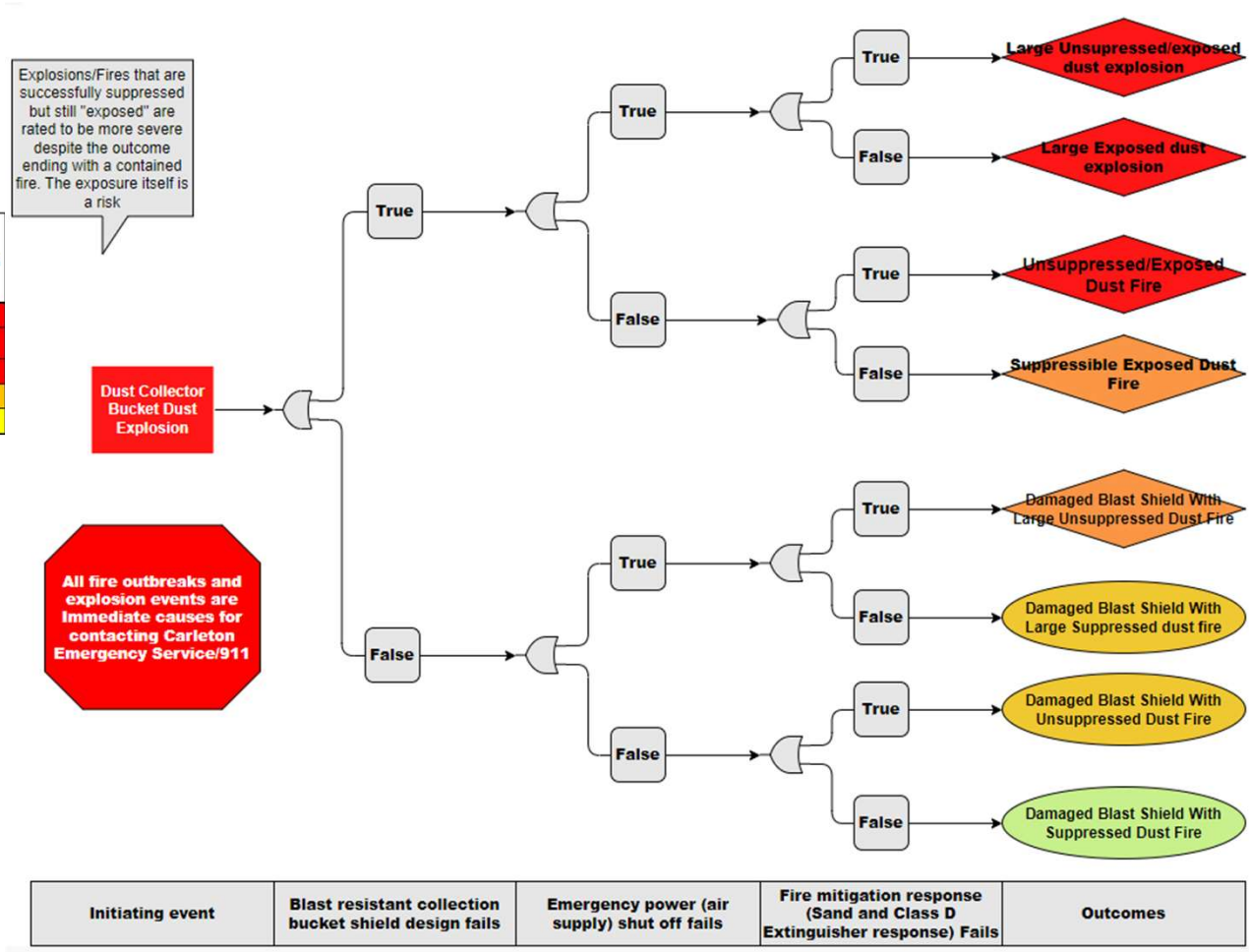
ZM1

Safety

Severity / likelihood	Negligable E	Minor D	Moderate C	Critical B	Catastrophic A
Frequent 5					
Probable 4				X	
Remote 3					
Extremely Remote 2					
Extremely Improbable 1					

- Recommended safety procedures
- Recommended safety design mitigation
- Awareness of Hazards
- Design of emergency/ Shutdown Procedures



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Slide 35

ZM1 Typo in blast shield design

Zachary Meunier, 2024-03-22T12:03:42.985

Future Considerations

- Heat Exchanger
- Backhaus filter and/or electrostatic separation
- Replacing propane pilot with plasma torch
- Adding a Sterling Engine for heat extraction

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Thank you to our sponsors

Energy and Particle Technology Laboratory

Carleton University | Faculty of Engineering and Design

Natural Resources Canada | Ressources naturelles Canada

Canada

CanmetENERGY / CanmetÉNERGIE

Website

Questions?

MW1

New Section Slide 2

Option 2

Carleton University

Slide 39

MW1 These need to be deleted if not used

Mieke Wilkinson, 2024-03-26T18:12:36.992

Content Slide – Wave Above

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Table with Wave Above

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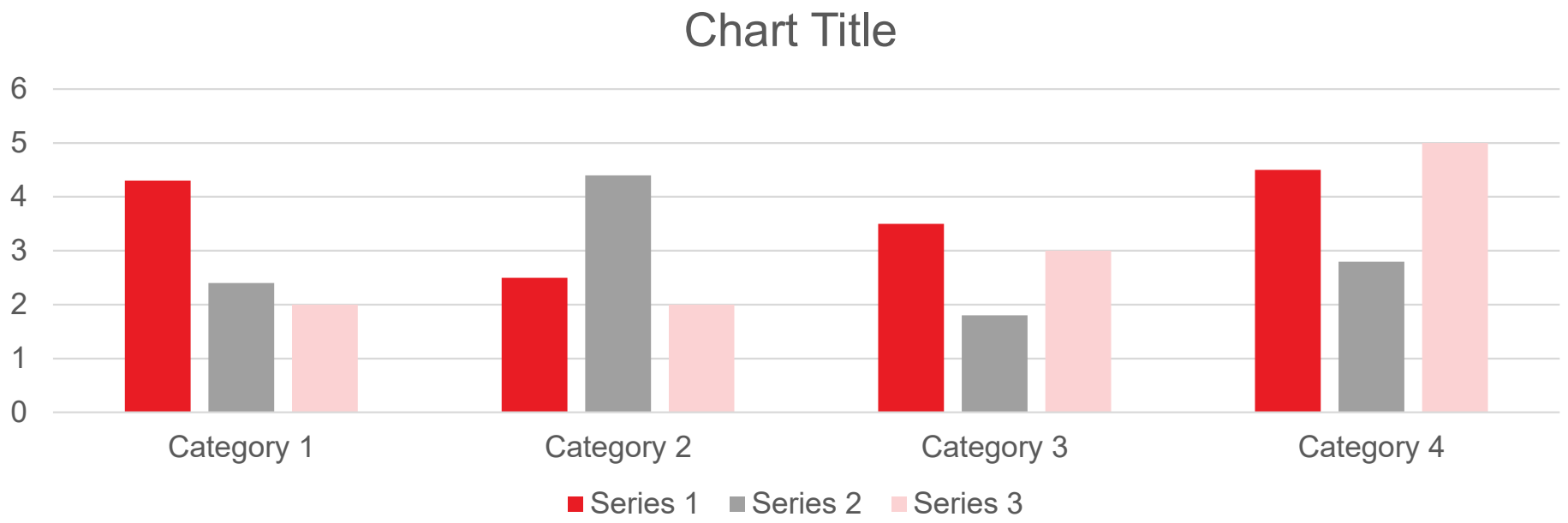
Chart with Wave Above



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Two Columns – Wave Above

Thank You

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