University of Colorado Boulder

A Prototype Reactor for Pyrolysis of Human Waste to Biochar With Concentrated Solar Power

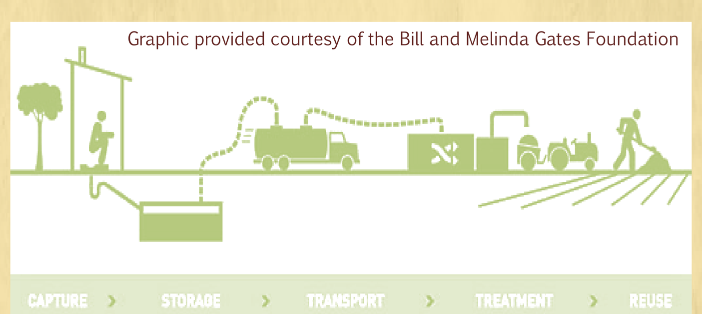
Richard P. Fisher, Allan Lewandoski, Tesfayohanes W. Yacob, Ryan B. Mahoney, Dragan Mejic, Cori Oversby, Sara Beck, Barbara J. Ward, Josh Kearns, R. Scott Summers, Karl G. Linden, and Alan W. Weimer

The Problem

- 2.5 billion people (~40% of global population) lack access to basic sanitation, with about 1.1 billion people still defecating in the open
- Pit latrines fill quickly, have to be emptied manually, and are hazardous to users
- Untreated waste dumped into environment, near houses, in streets, in nearest water source (if there is one)

Reinvent the Toilet Challenge

- Sanitation has not seen meaningful innovation since the flush toilet, 200 years ago
- Need new sanitation!
  1. Affordable & desirable
  2. Fast processing time
  3. Off-the-grid
  4. Valuable & reusable products



The Sol-Char Toilet Prototype

- We are demonstrating our proof-of-concept prototype, a solar-thermal pyrolyzing toilet to convert hazardous human waste to useful biochar and pasteurized urine fertilizer
- The Sol-Char Toilet uses concentrated solar power, delivered by fiber optics, to rapidly dry, disinfect, and pyrolyze human waste
- Our first prototype is designed to process 2 kg feces and 4 kg of urine in about 4 hours of sunshine

Parabolic dishes concentrate solar energy

Fiber optics transmit energy to a high temperature reactor

Reactor thermally decomposes human waste

Useful end products are created

Concentrated Solar Power (CSP)

- Renewable and abundant sunlight can be concentrated using reflective surfaces
- Parabolic mirrors are the most efficient (optically) solar concentrators
  - ➢ Can achieve concentrations of nearly 5000 suns
  - ➢ More suns = more energy flux = higher temperaures
  - ➢ Require high-accuracy dual-axis tracking to function in practice

Direct +Diffuse Irradiance

- Low concentration systems do not require tracking
- For example: flat plate PV, heliotropes (plants, algae, etc.) or solar water heaters
- Wide-angle view of the sun (θ ≈ 90°)

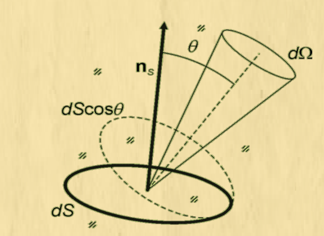
Direct Normal Irradiance

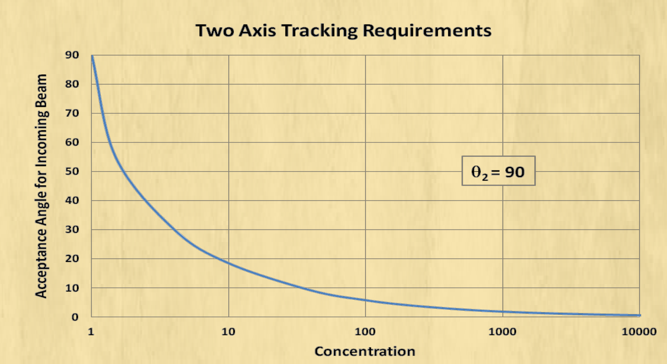
- Medium and high concentration systems require single- or dual-axis tracking, respectively
- For example: line-focus (trough) and point-focus mirrors (dish)
- Very narrow view of the sun (θ ≤ 10°)

Conservation of Étendue

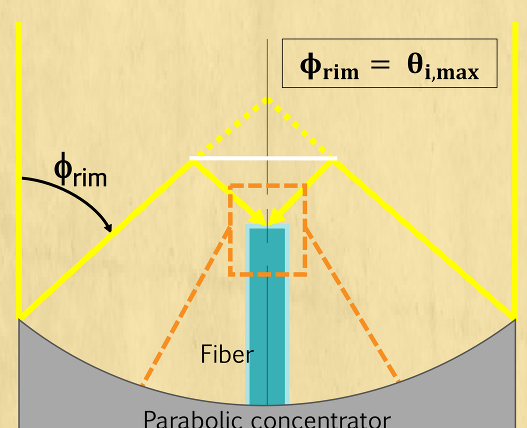
- Analogous to the Second Law of Thermodynamics, derived from first principles
- Étendue is always conserved or increases, but never decreases
- Apply to both the source (emitter) and the receiver

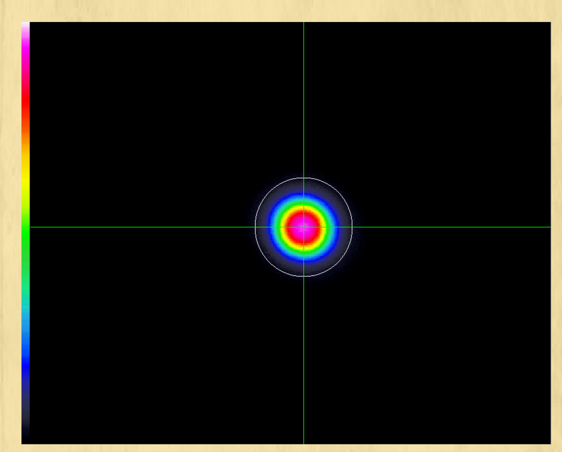
$$C = \frac{S_1}{S_2} = \frac{\sin^2 \theta_2}{\sin^2 \theta_1}$$



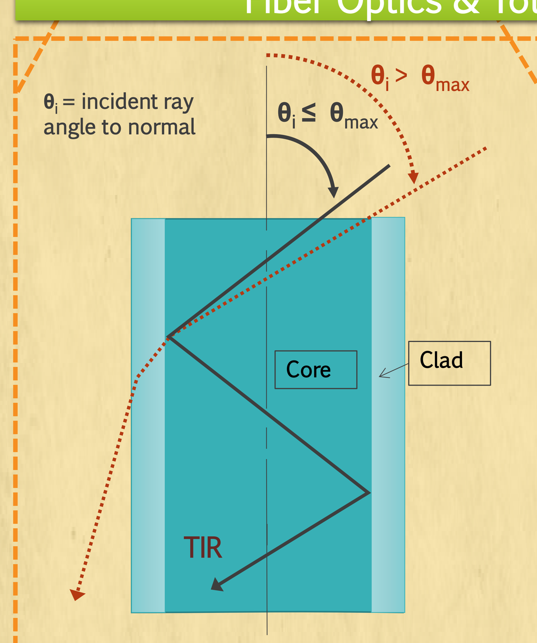


Parabolic Concentrators



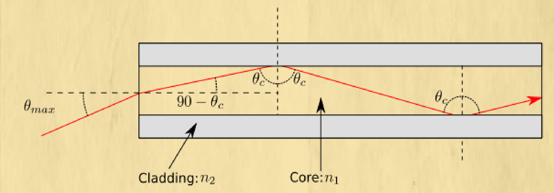


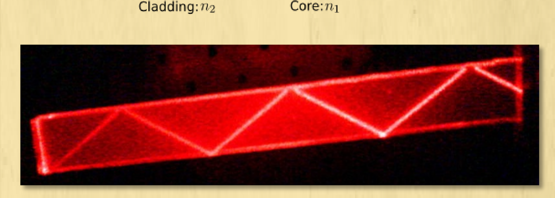
Fiber Optics & Total Internal Reflection



- Total Internal Reflection, TIR, is a refractive phenomenon
- Critical angle (measured from normal) defines the acceptance cone for TIR

$$\sin\theta_{max} = \sqrt{n_{core}^2 - n_{clad}^2}$$





Our CSP System

- Designed to provide 500W – 1000W from 8 total concentrators
- 2000 suns, diam. = 0.6m → 0.0135m
- Silver-polymer reflective film
- Concentrator substrate machined from solid aluminum
- Fused-end fiber bundles → minimizes interstitial space between fibers

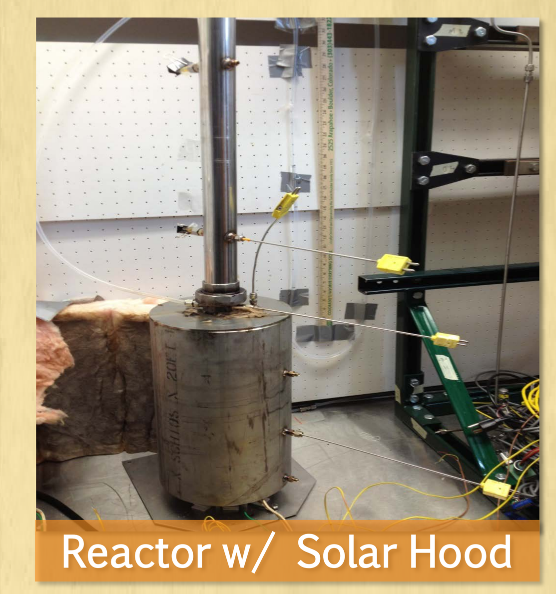
The Reactor

- Pyrolyzes raw human waste to produce a sterile, value-added biochar product and pasteurized urine to be used as soil amendment and fertilizer, respectively
- Pyrolysis is an oxygen-limited thermal decomposition process
  - ➢ Yields high-energy carbon rich residues along with tars, combustible gasses, ash
  - ➢ Occurs at temperatures ≈ 300°C and higher (torrefaction precedes pyrolysis)

- Solid and liquid waste are separated at the user-end with a urine-diverting squat plate
- Feces collects in one reactor during the day while the other is illuminated with CSP
- Urine pumps through a coil welded to the solar hood and is pasteurized by excess heat

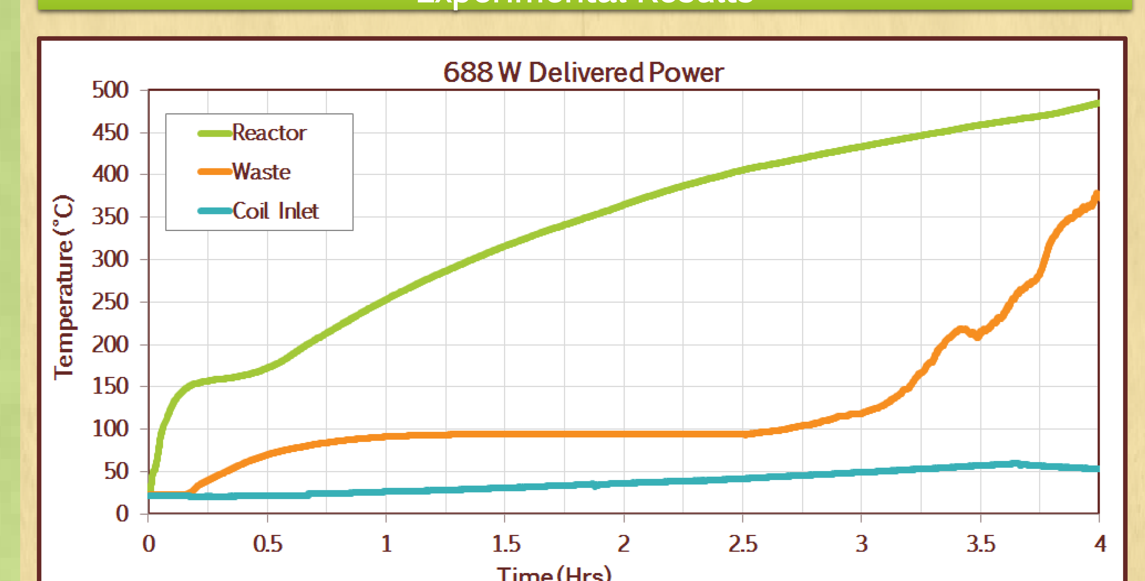
Reactor Design

- Exterior surfaces are painted with PyroMark® 2500 paint
  - ➢ Max. temperature of 1100°C
  - ➢ Absorptivity of 95% solar spectrum
    - – 53% Infrared, 44% Visible, 3% UV
  - ➢ Emissivity of 88%



- Solar hood has a matching “male-type” cone
- Forms a seal with the “female-type” funnel on the reactor
- Prevents soot, smoke and tar from depositing on the inner wall of solar hood

Experimental Results



- 2 kg of synthetic feces prepared and loaded into reactor
- Electric heaters powered for 4 hours, deionized water pumped at 750 mL/min through urine coil for 4 hours
  - ➢ We have observed the waste temperatures continue to rise
- T(t = 4hrs) = 375°C, pyrolysis taking place, sterilization of waste ensured

Synthetic Feces Recipe

NASA Formulation #2

75% water – 25% solids

Solids

- 30% nutritional yeast – biomass
- 20% PEG 400 – thickener
- 20% peanut oil – lipids
- 15% shredded cotton balls – cellulose
- 5% miso paste – metabolites /color
- 5% $Ca_3(PO_4)_2$ – metabolites

The Model

- We're using a multiphysics software package to model the conductive, convective, and radiation heat transfer along with chemical reactions w/ an assumed kinetic model

Reaction Kinetics from Literature

$$^{*}\; F_1 \xrightarrow{k_1} G_1,\; F_1 \xrightarrow{k_2} S_1 \qquad F_2 \xrightarrow{k_3} G_2,\; F_2 \xrightarrow{k_4} S_2 \qquad F_3 \xrightarrow{k_5} G_3,\; F_3 \xrightarrow{k_6} S_3 \qquad + \text{Inert}$$

$$R_i = k_i(w_i - w_{i,0})^{n_i}$$

$$k_i(T) = k_{i0} e^{-\frac{E_i}{RT}},\ for\ i = 1, \dots, 6$$

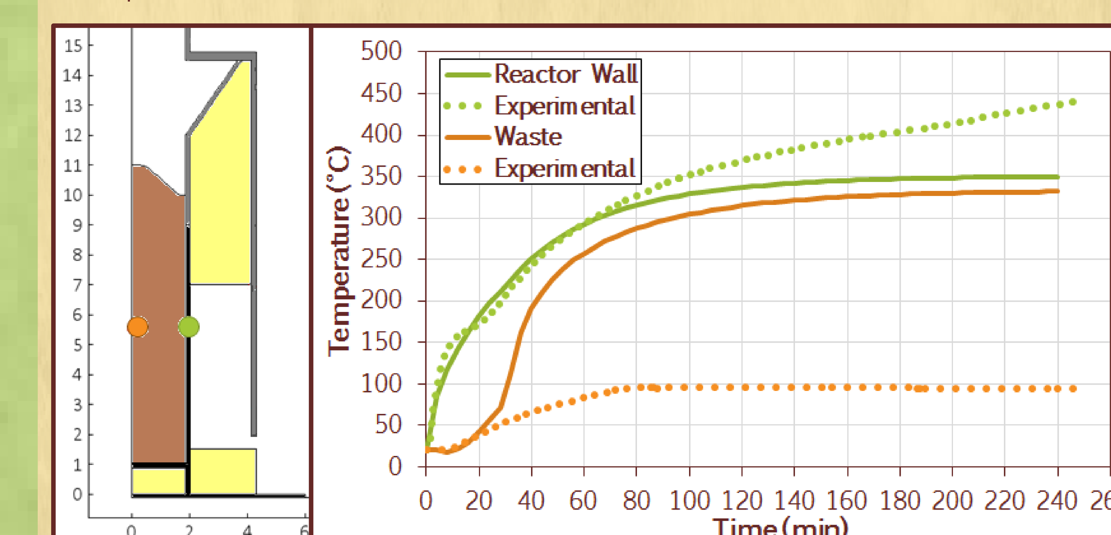
$$^{\dagger}Q_{pyro} = [1 - X(T)]Q_F + X(T)Q_S$$

- Sampled from non-digested and digested wastewater fecal sludge, dried for 1h at 105°C then pyrolyzed to 800°C in a TGA
- One set of 20 kinetic parameters fit varying heating rates – 5, 10, 20, 30 K/min
- Will run TGA experiments in Dec to develop a similar kinetic model for raw, untreated feces to be incorporated into our model

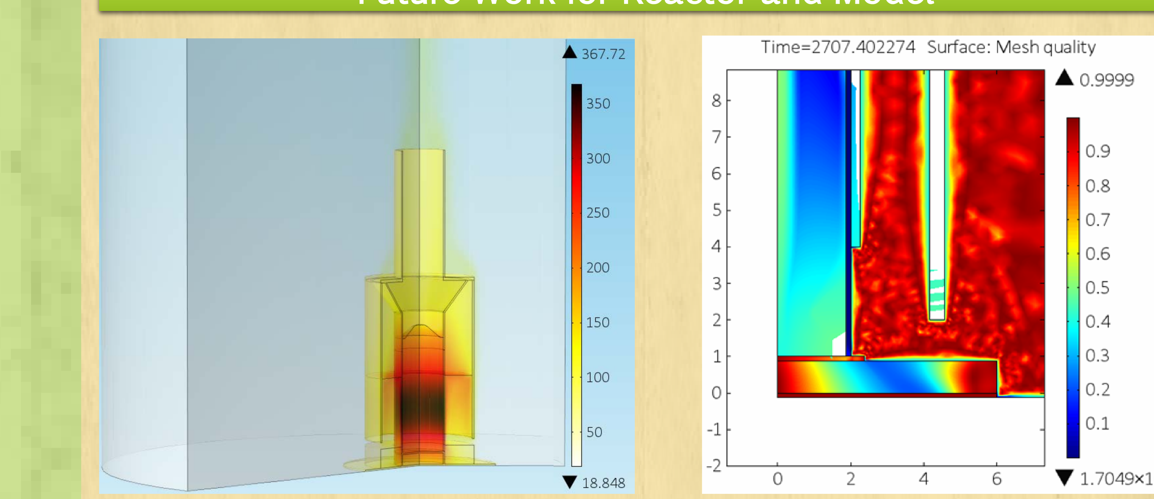
*Adapted from J.A. Conesa, et al. *Kinetic Study of the Pyrolysis of Sewage Sludge* (1997)
†C. Gomez, et al. *Influence of Secondary Reactions on the Heat of Pyrolysis of Biomass* (2009)

Model Validation

- Simulations account for various solar irradiance conditions → power delivered by fiber optics
- We have experimentally tested different insulation configurations and compared experimental to simulated results



Future Work for Reactor and Model



- Re-design and optimize reactor system for better heat transfer, thermal efficiency, and capacity/throughput → continuous reactor vs. batch reactor
  - ➢ Continuous reactor can decouple storage from processing capacity and still remain mechanically robust and simple; also inherently scalable
  - ➢ Batch reactor can allow for modular construction and simplest mechanical components; also inherently un-scalable
- Incorporate moving mesh to multiphysics simulation
  - ➢ Can account for the significant volume reduction that is observed during pyrolysis experiments with both synthetic and real feces (nearly 90%)
- Incorporate pre-drying/de-watering process upstream of feed to reactor system
  - ➢ Drastically reduces energy burden on the CSP system

Acknowledgements

Contributors:

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