Cooking Up Some Electricity

Solid Oxide Fuel Cells for the Developing World

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Point Source Power

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Metal-Supported Solid Oxide Fuel Cell Concept

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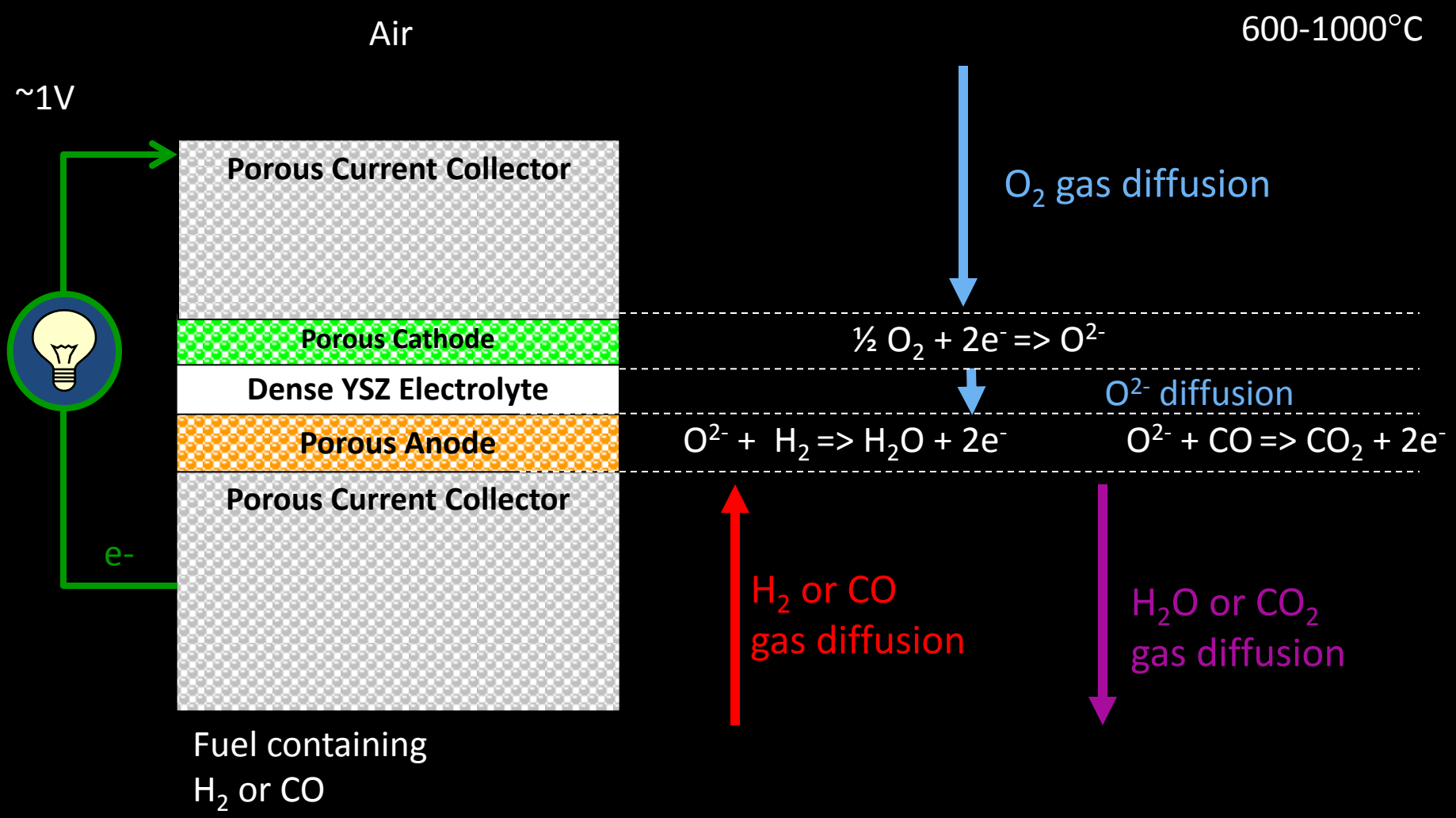
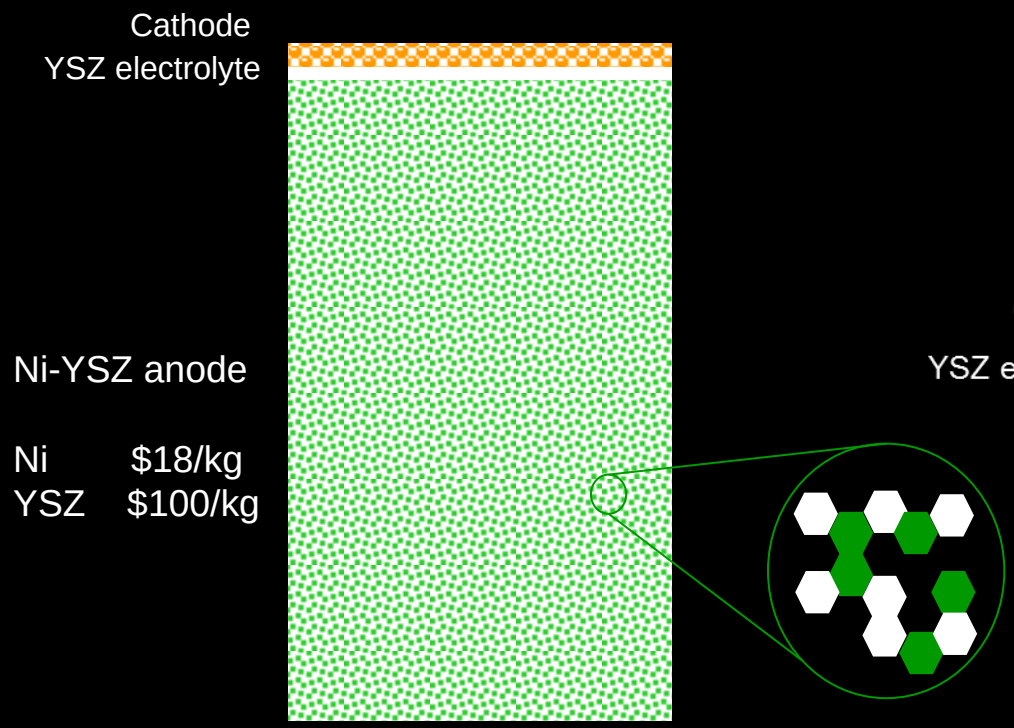
Solid Oxide Fuel Cell (SOFC) Operation

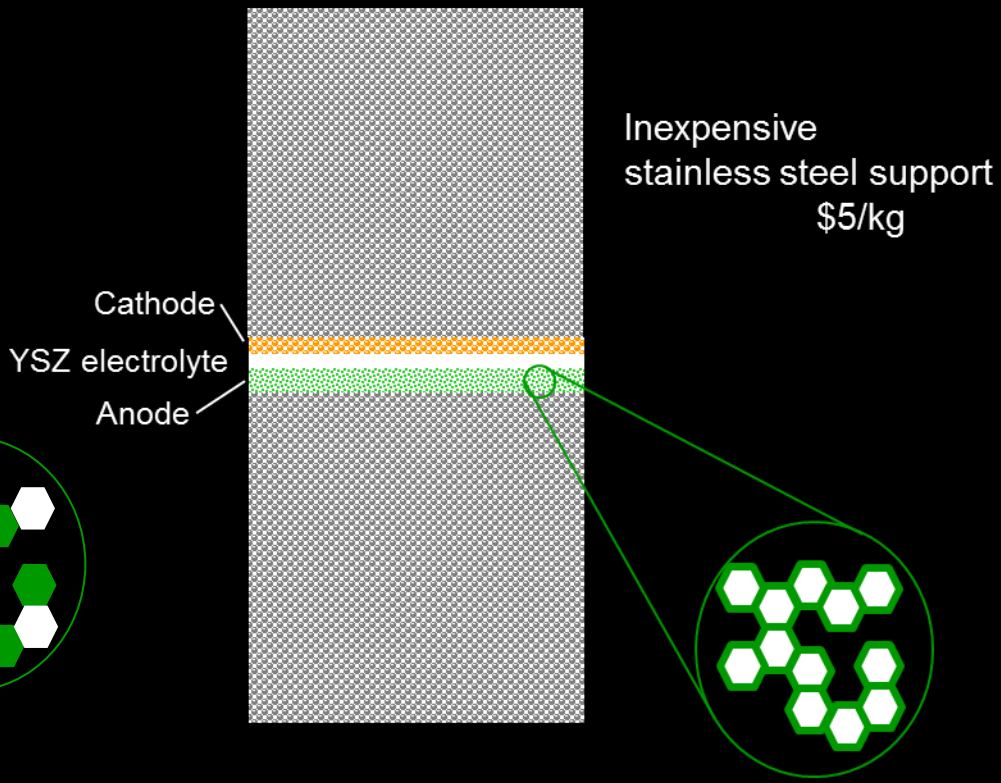


Conventional Ceramic Anode-Supported SOFC

LBNL Metal-Supported Cell



Expensive, brittle



Inexpensive, robust

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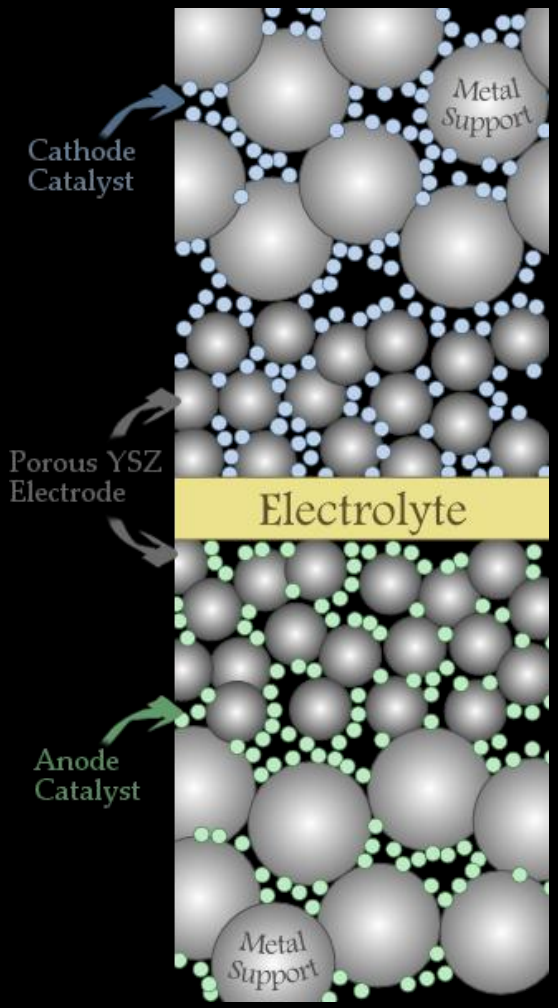
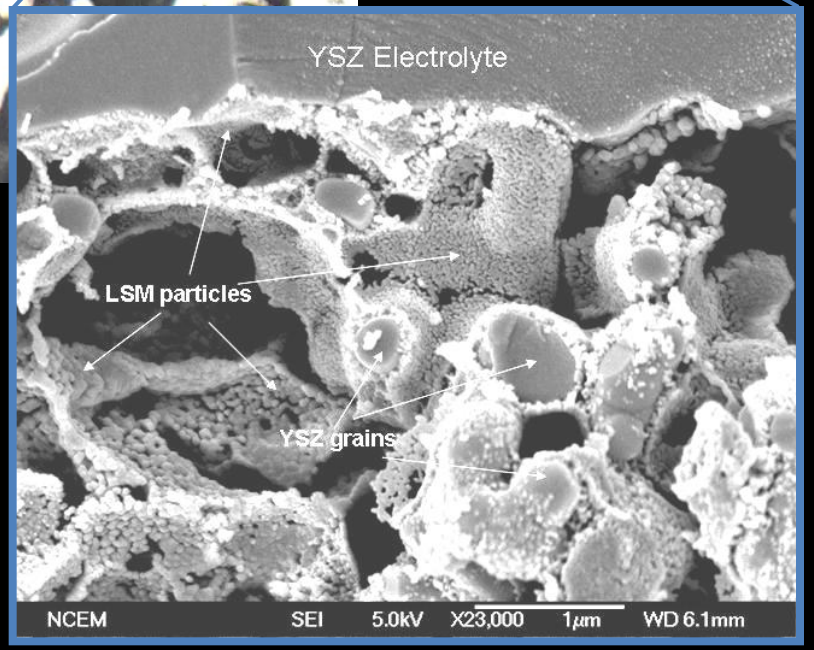
LBNL Design: Co-Sintered Stainless Steel Support and YSZ Electrolyte





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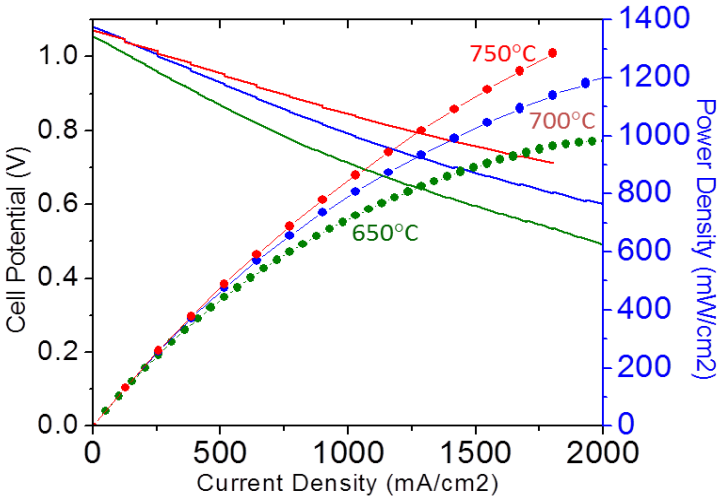
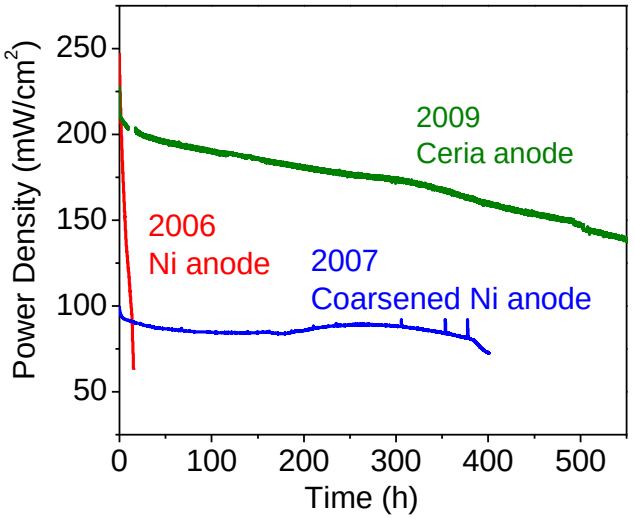
Performance with Hydrogen Fuel





Very high power density
- Infiltrated electrodes are effective

Lifetime: >500h

Not sufficient for grid

Not yet competitive for grid, transportation, home CHP

But, most of the world does not have a grid, car, or home power…

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We make fuel cell systems for people without access to an electric grid.

Empowering the off-grid world

Opportunity

~$60B spent annually for off-grid lighting and phone charging services.

600 million off-grid mobile subscribers.

1.3 billion people will still be off-grid in 2030.

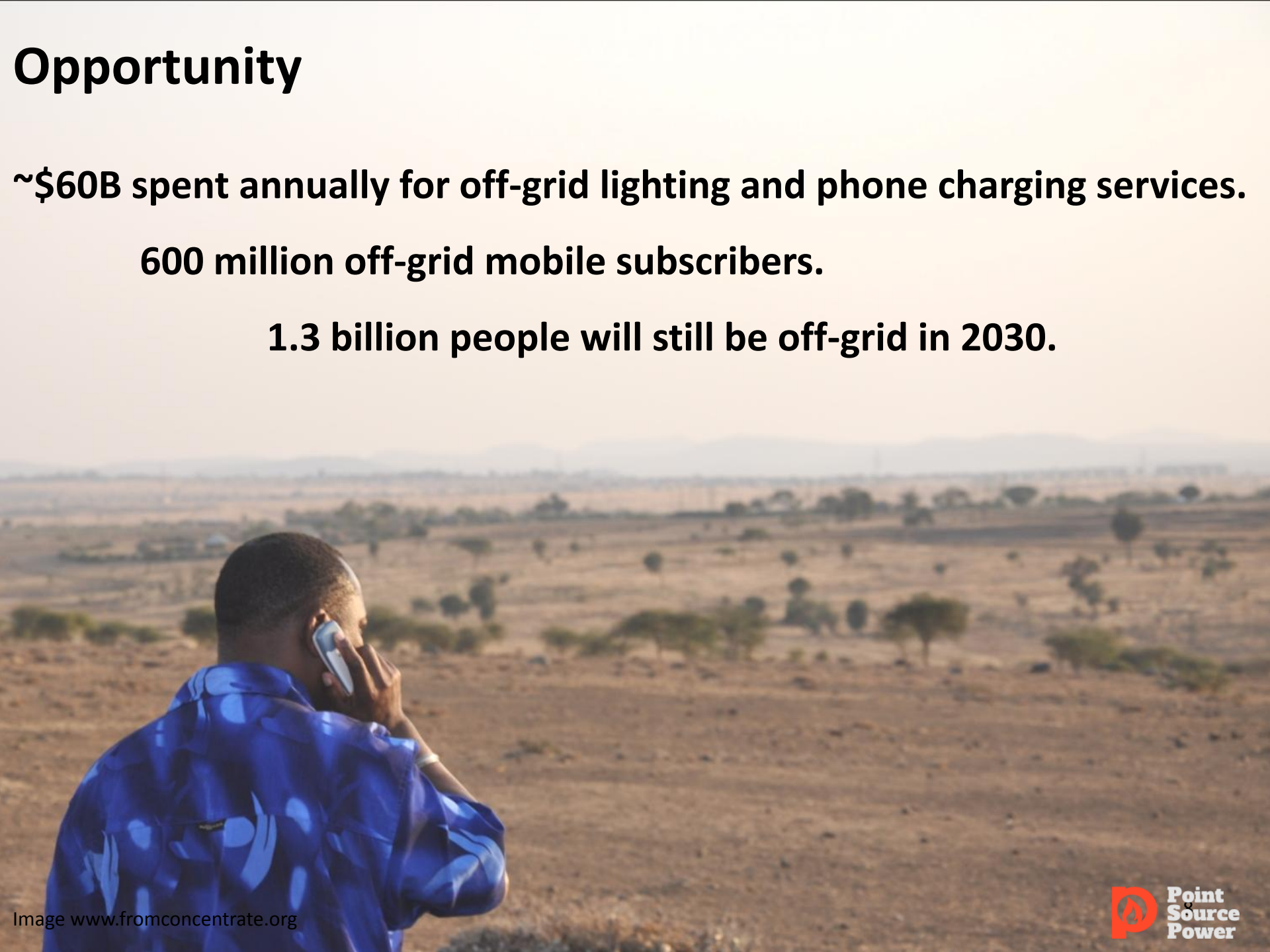

Image www.fromconcentrate.org

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Product Concepts

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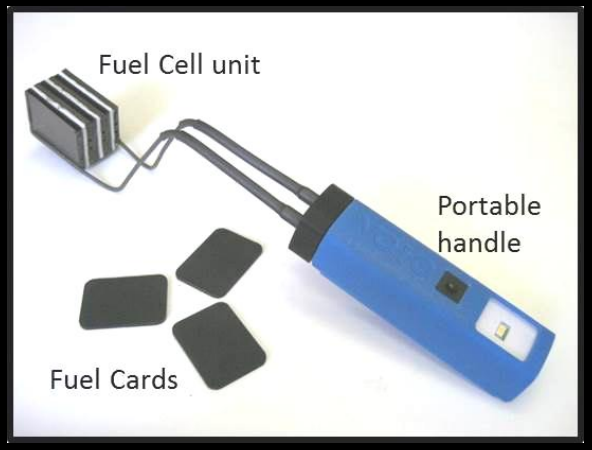
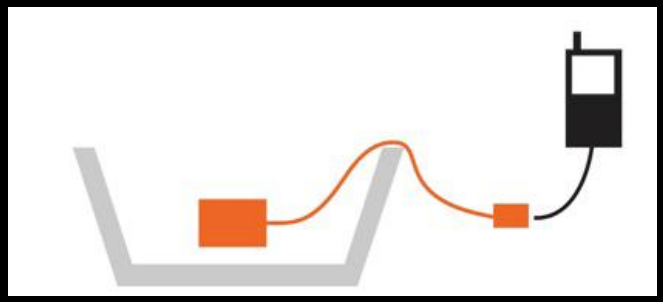
LED lighting and mobile charging at home

Tailored to Jiko charcoal cookstoves (many millions deployed)





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Costs of Available Energy

Energy Access in Developing World is expensive or non-existent

Kerosene
$2/week

Solar Lantern
Phone Charger
$40

20W Solar $150

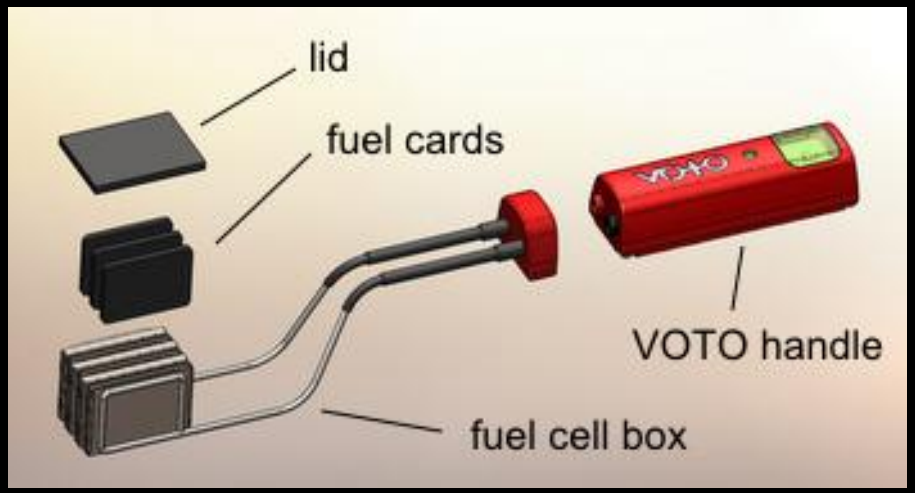
AA ~$100-300/kWh!!

Kiosk charging ~$100/kWh!!

VOTO

Retail Product

Complete starter kit $18



Fuel Cards
$0.50/month

Consumable
Fuel Cell
$6
2-3months

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VOTO Product Development

Alameda, CA

Kenya

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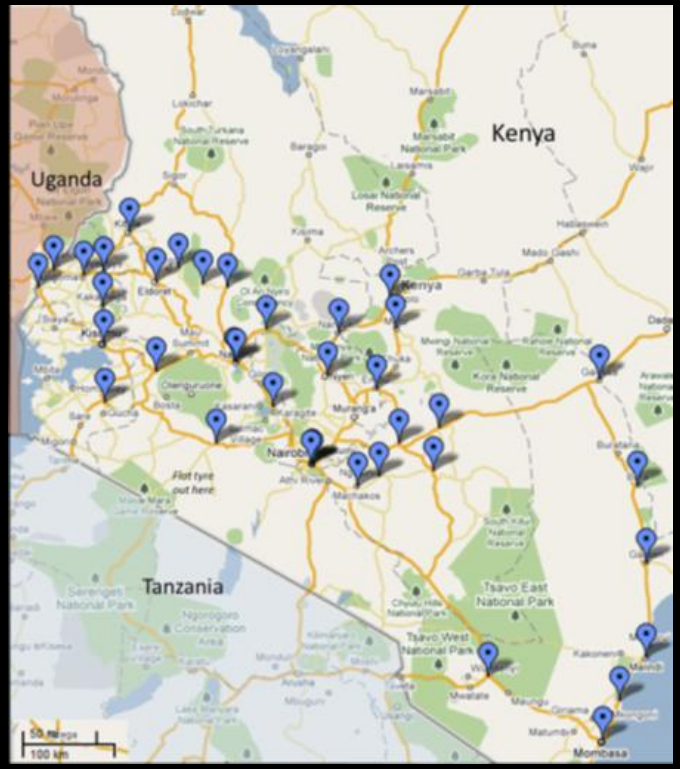
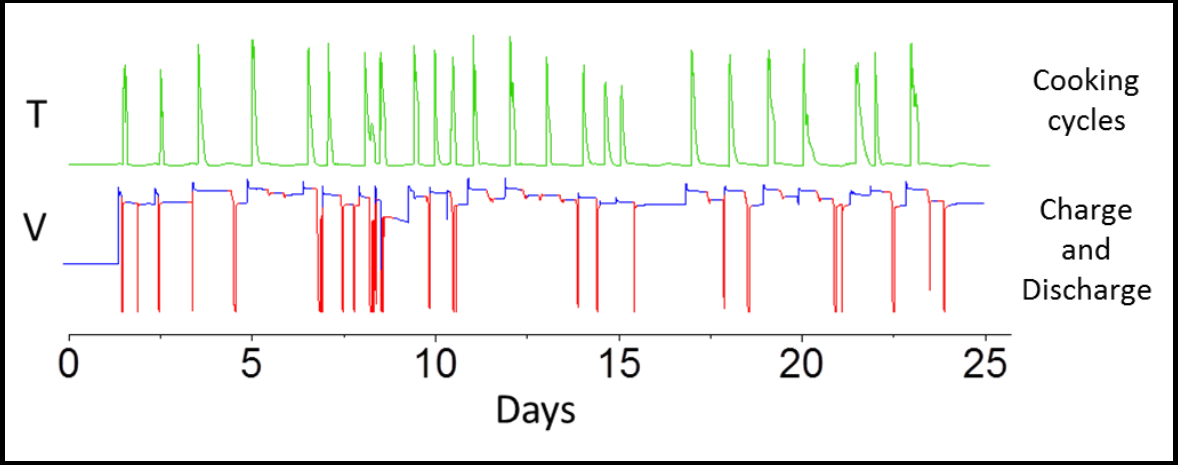
Field Trials





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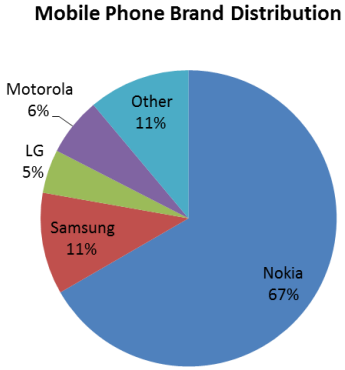
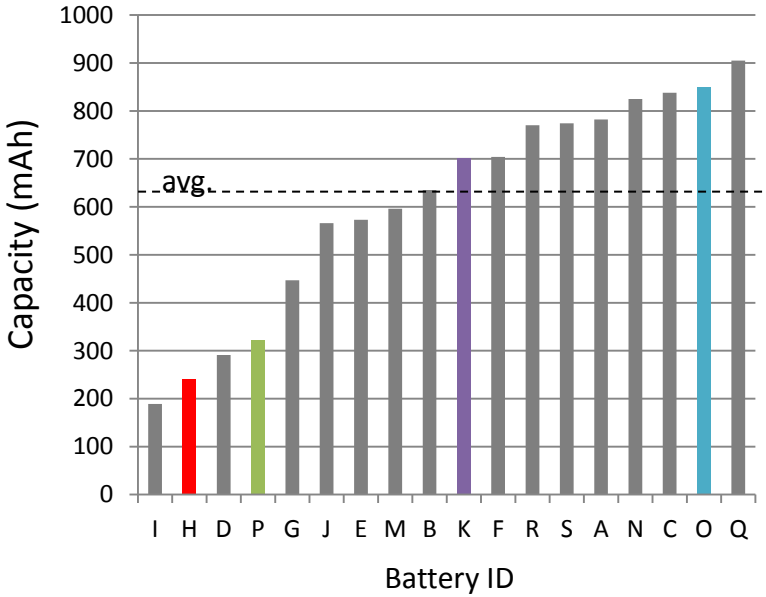
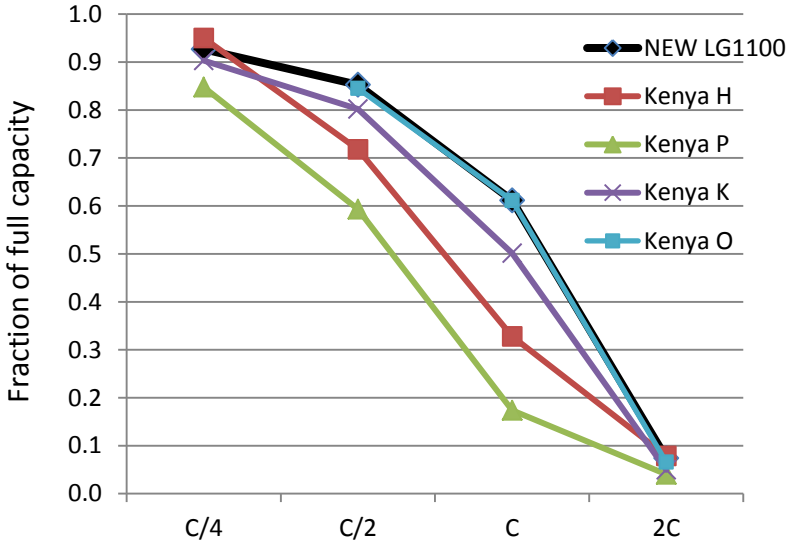
Heavily-Used Mobile Phone Batteries



Kenyan Li Batteries Capacity



Kenyan Li Batteries charge C-rate Capability



No standard battery as design target

<C/2 for charging efficiency

Users get very different experience from “full charge”

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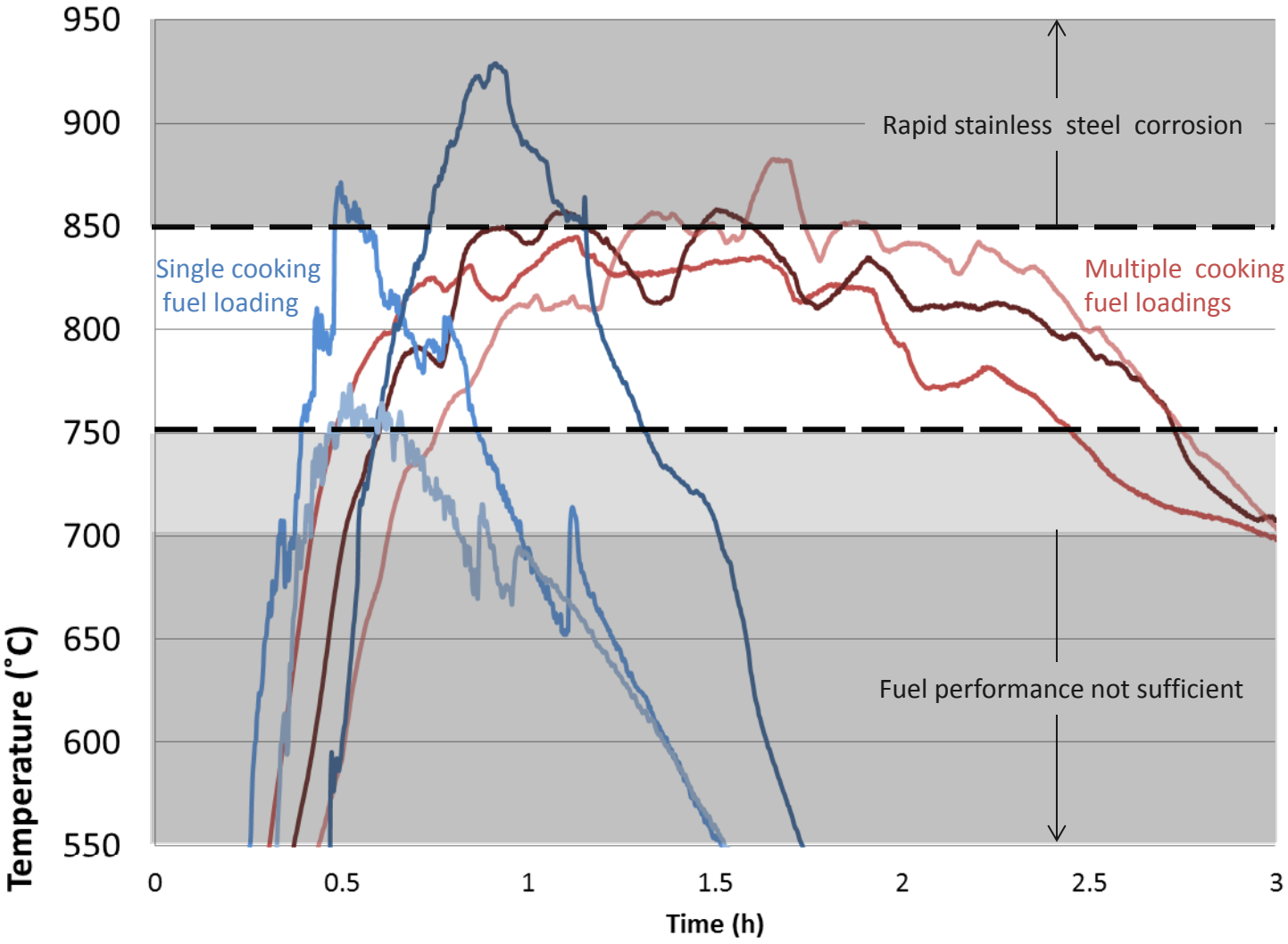
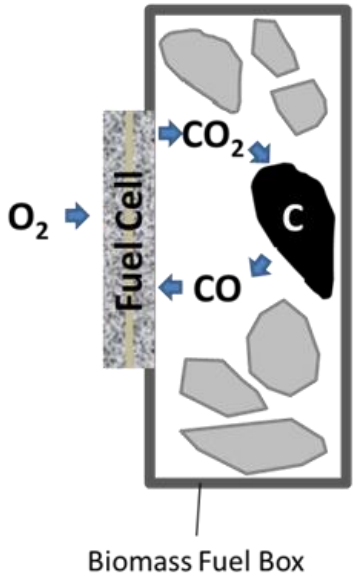
Temperature Operating Window





Lower limit with natural charcoal activity

Tradeoff between lifetime and performance

Possible to maintain stove temperature within the window

But: is this how Kenyans actually cook?

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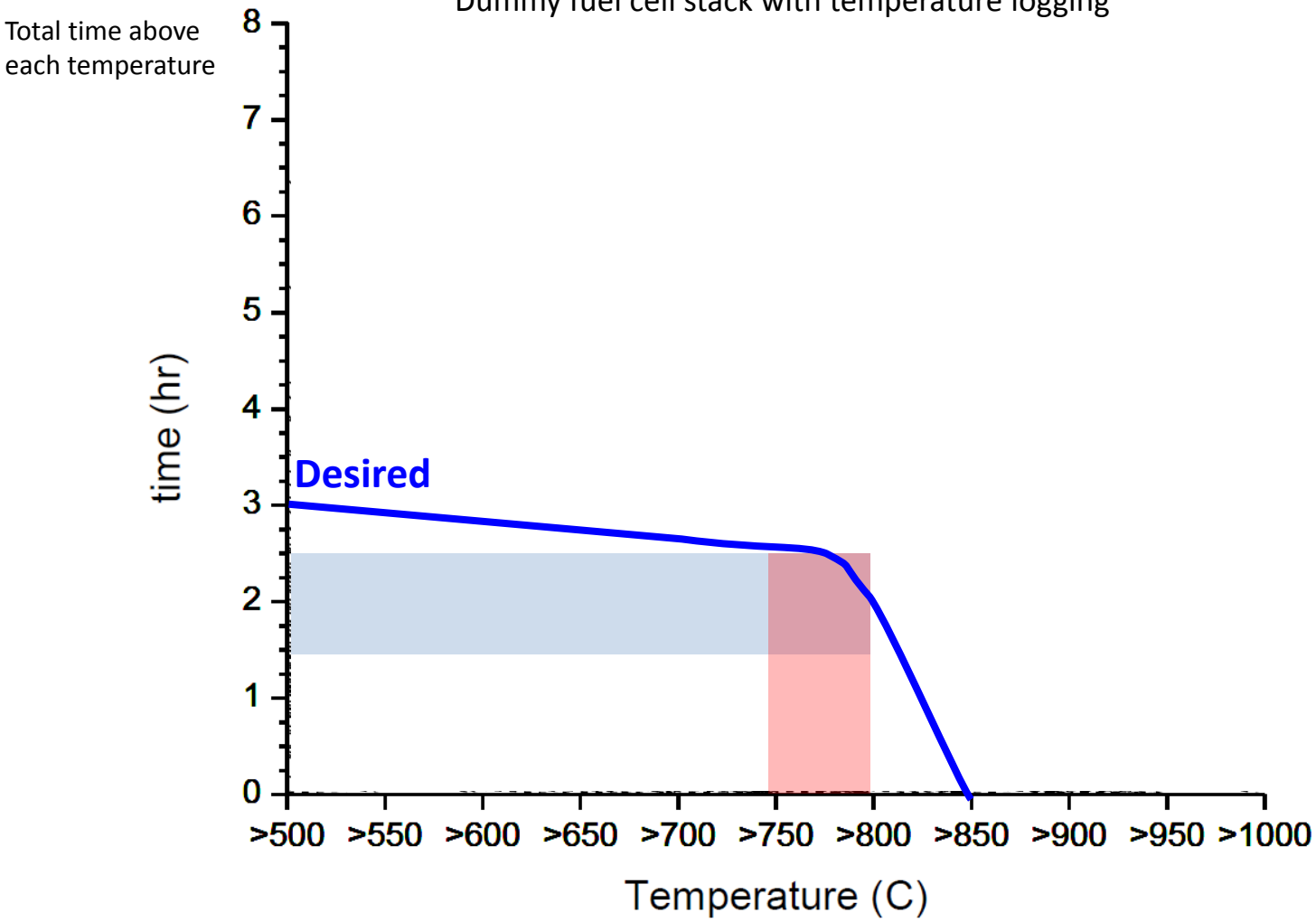
Kenyan Household Jiko Cooking Temperatures

Dummy fuel cell stack with temperature logging



- Resize stack for small hot zone in center of stove
- Improve performance at <750°C

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Charcoal for Fire

- Required for heat
- Destroys the cell

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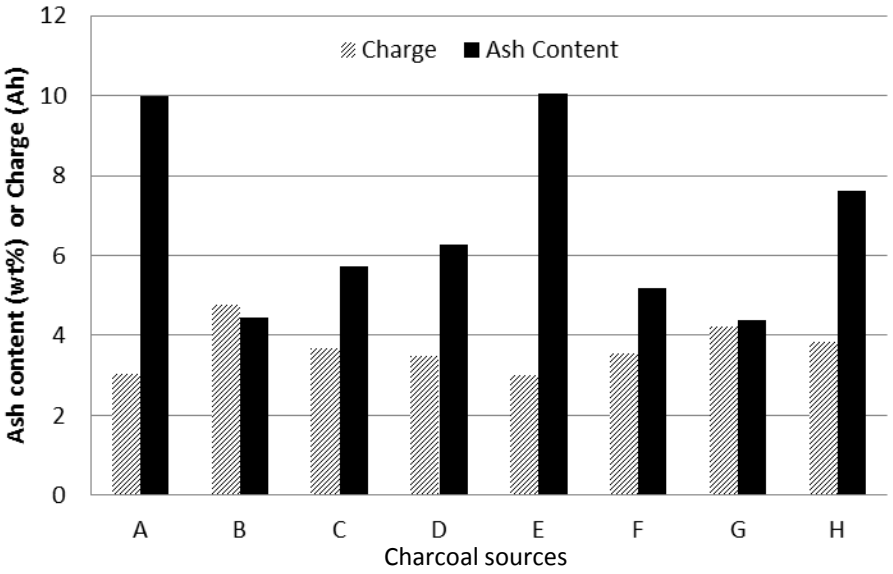
Charcoal Quality and Ash Content is Highly Variable



Impurities (wt%)

Sample	S	Cl	K	Ca	Fe	Br(ppm)	Sr
Mesquite	0.08	0.16	1.06	4.67	0.08	17.9	0.05
Kenya	0.17	0.14	0.88	24.1	0.27	51.7	0.25

Ash Composition

Phase	Concentration (wt%)
$CaCO_3$	63
$K_2Ca(CO_3)_2$	22
KCl	7
K_2CaCl_3	5
CaO	3

Charge variability
- Can we find a reliable, high-quality charcoal source?

Ash = source of cell failure

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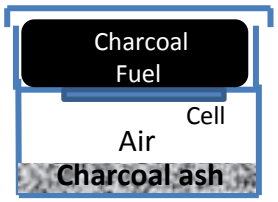
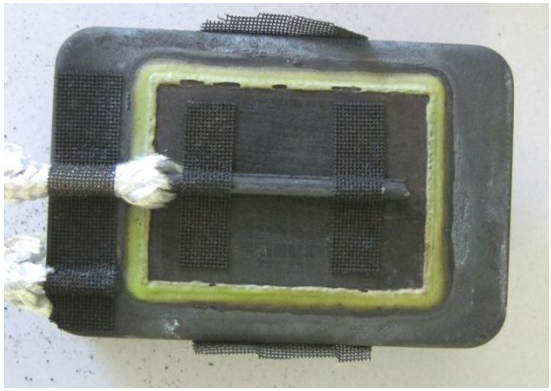
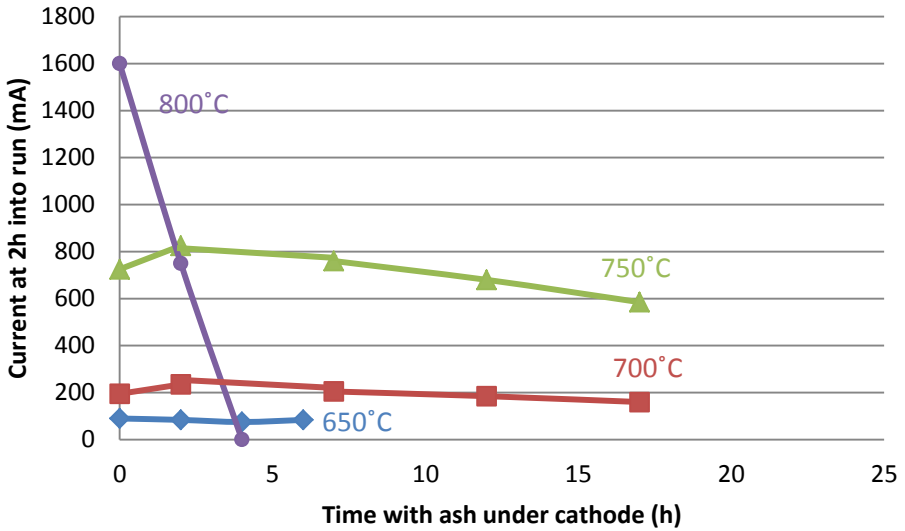
Temperature-Dependence of Charcoal Ash Poisoning







Poisoning is highly T-dependent
- 700-750°C may be OK

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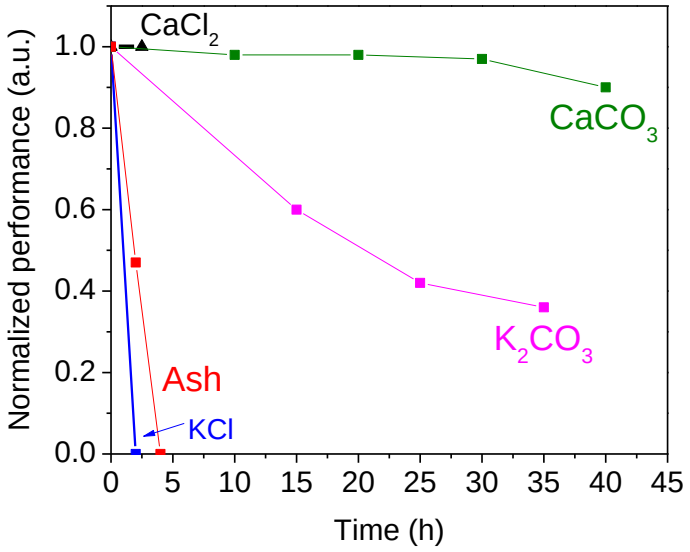
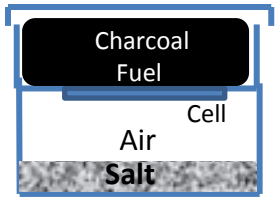
Salt Components of Ash

Effect on Cell





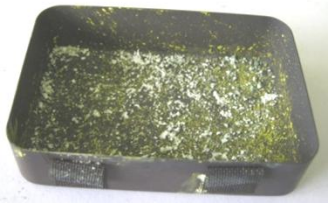
Effect on Steel

KCl ~5h

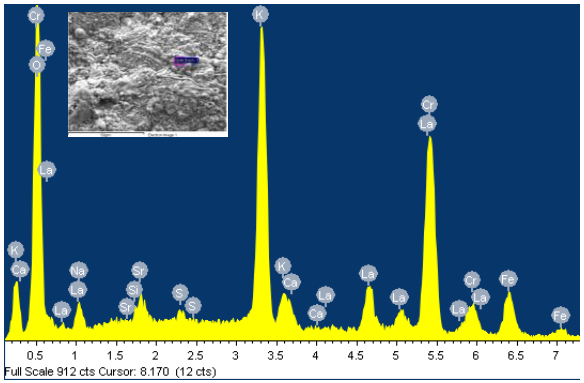
$CaCl_2$ ~5h

K_2CO_3 ~40h

$CaCO_3$ ~40h



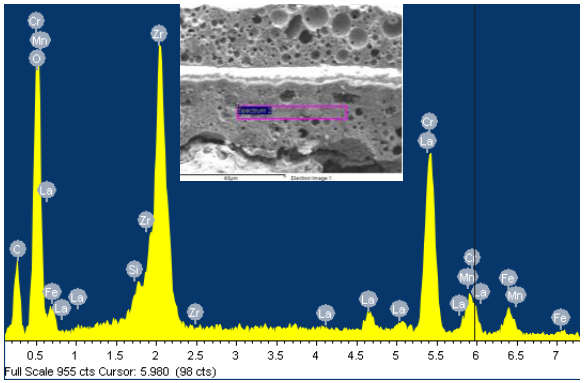
Cell surface (steel)



K,Cr

$$2K_2CrO_{4(g)} + 6e^- + 3V_O^{\bullet\bullet} \Rightarrow Cr_2O_3 + 3O_O^x + 2K_2O_{(g)}$$

Inside cell (YSZ)



Cr

Cl kills steel via corrosion
K kills cell via chemical poisoning
Ca and CO_3 inert

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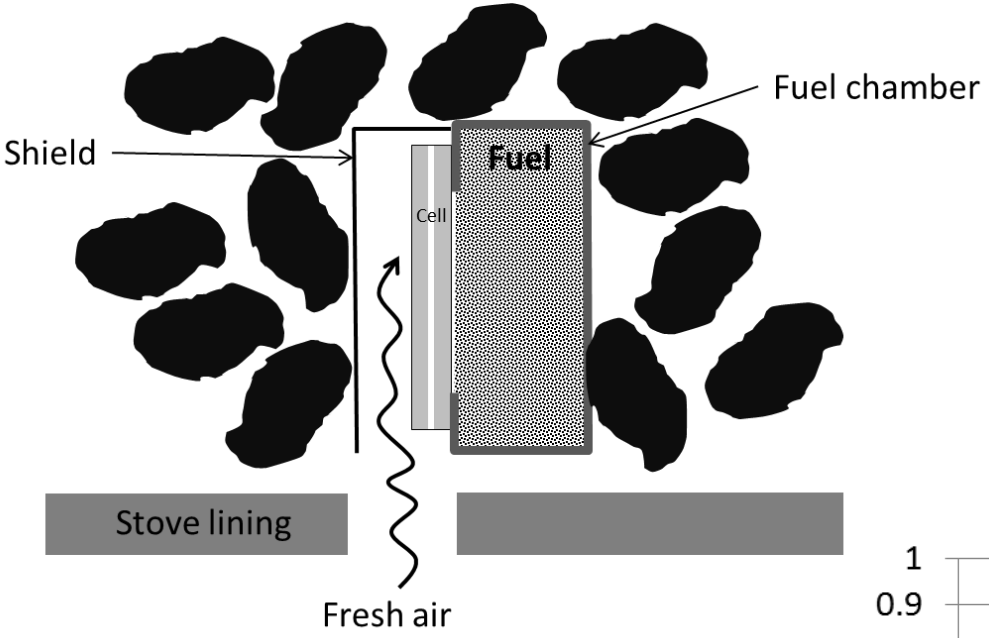
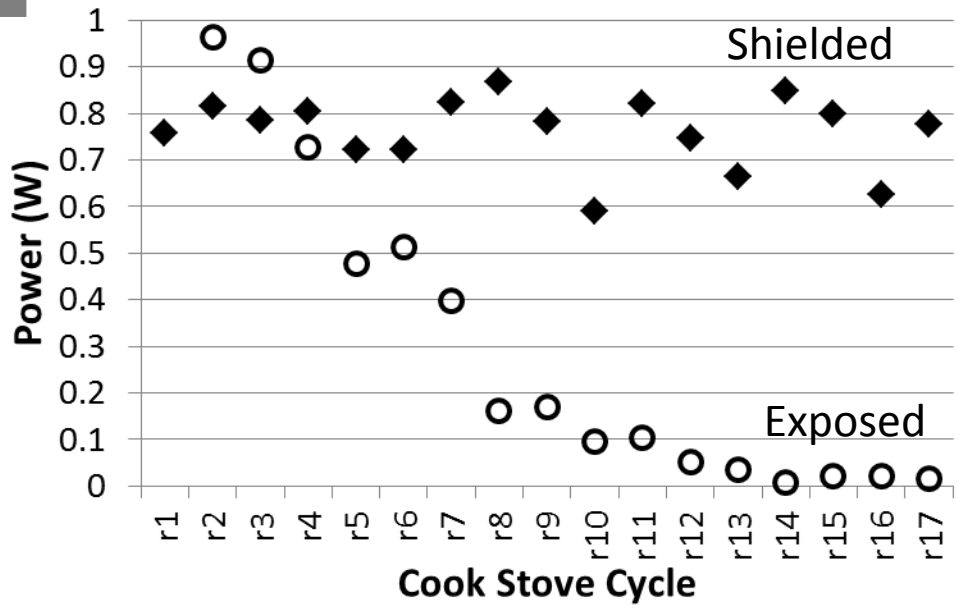
Shielding from Fire Impurities



Sacrificial shield protects cell

Tradeoff lifetime vs. stack cost/complexity



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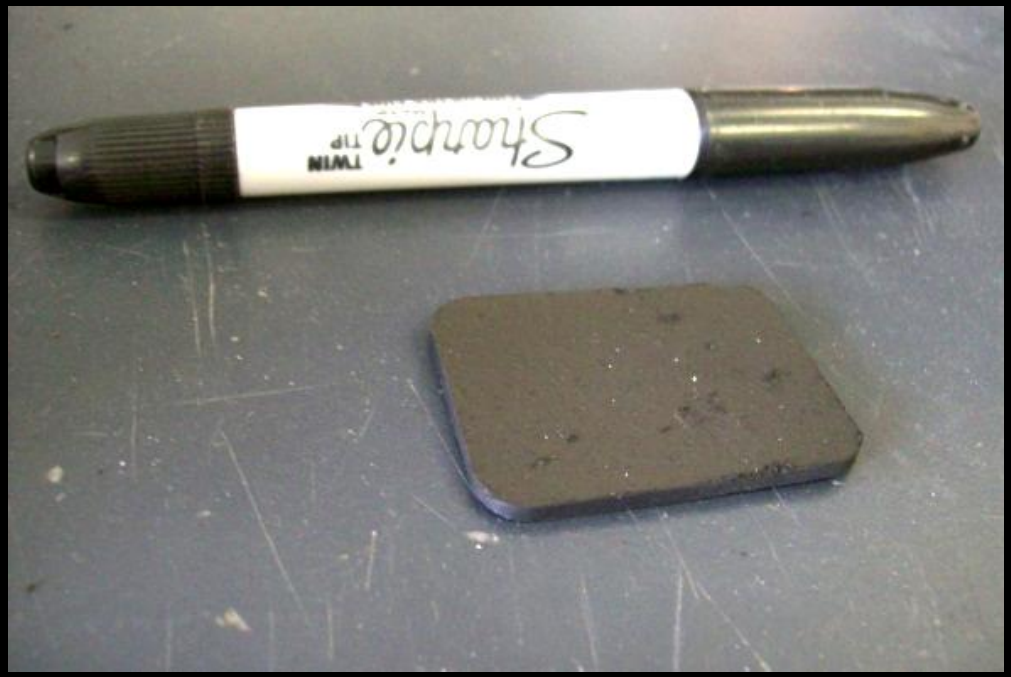
Charcoal for Fuel



- Doesn’t work well

- Destroys the cell

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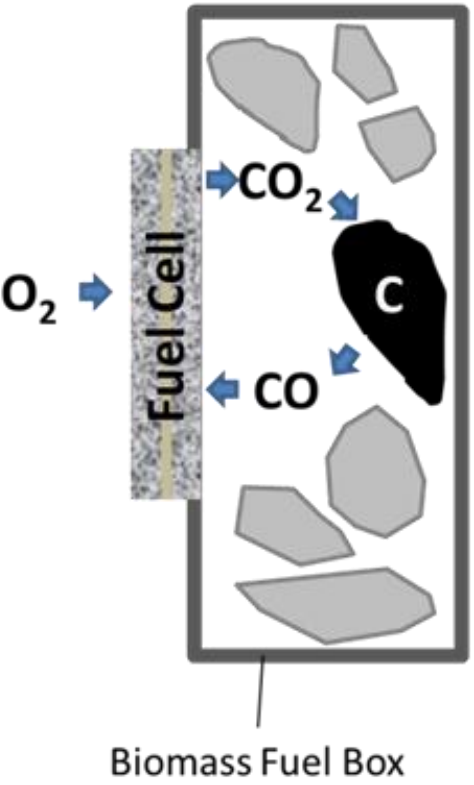
The Carbon Cycle

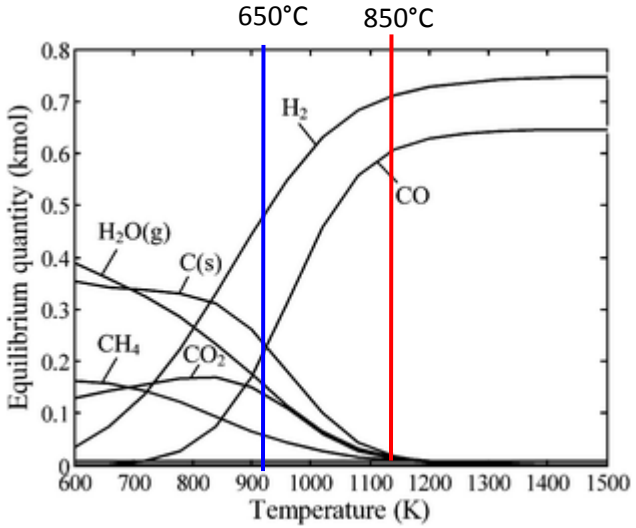


Electrochemical reactions

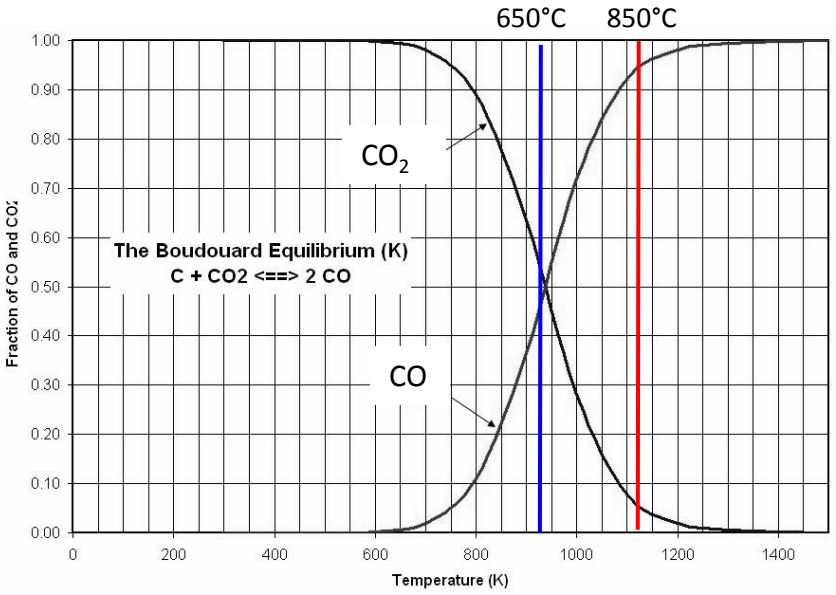
$H_2 + O^{2-} \rightarrow H_2O + 2e^-$

$CO + 1/2\ O^{2-} \rightarrow CO_2 + e^-$

Gasification of charcoal $C + H_2O \rightarrow H_2 + CO$



Bouduard production of CO $CO_2 + C \rightarrow 2CO$



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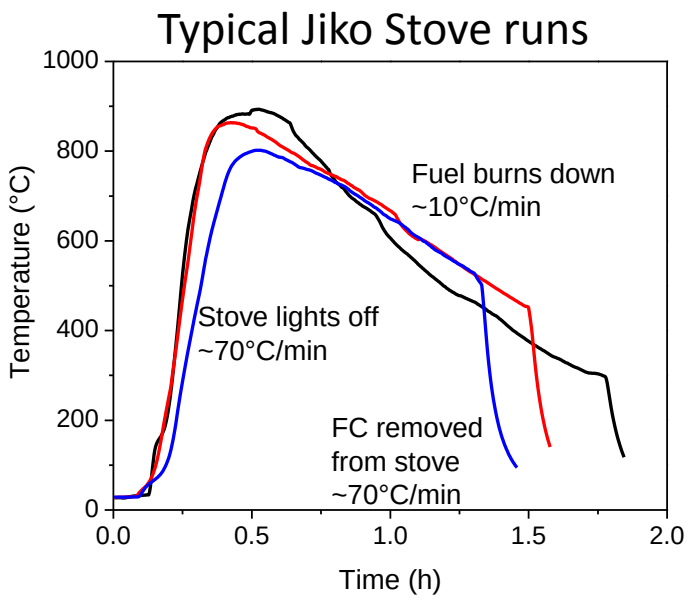
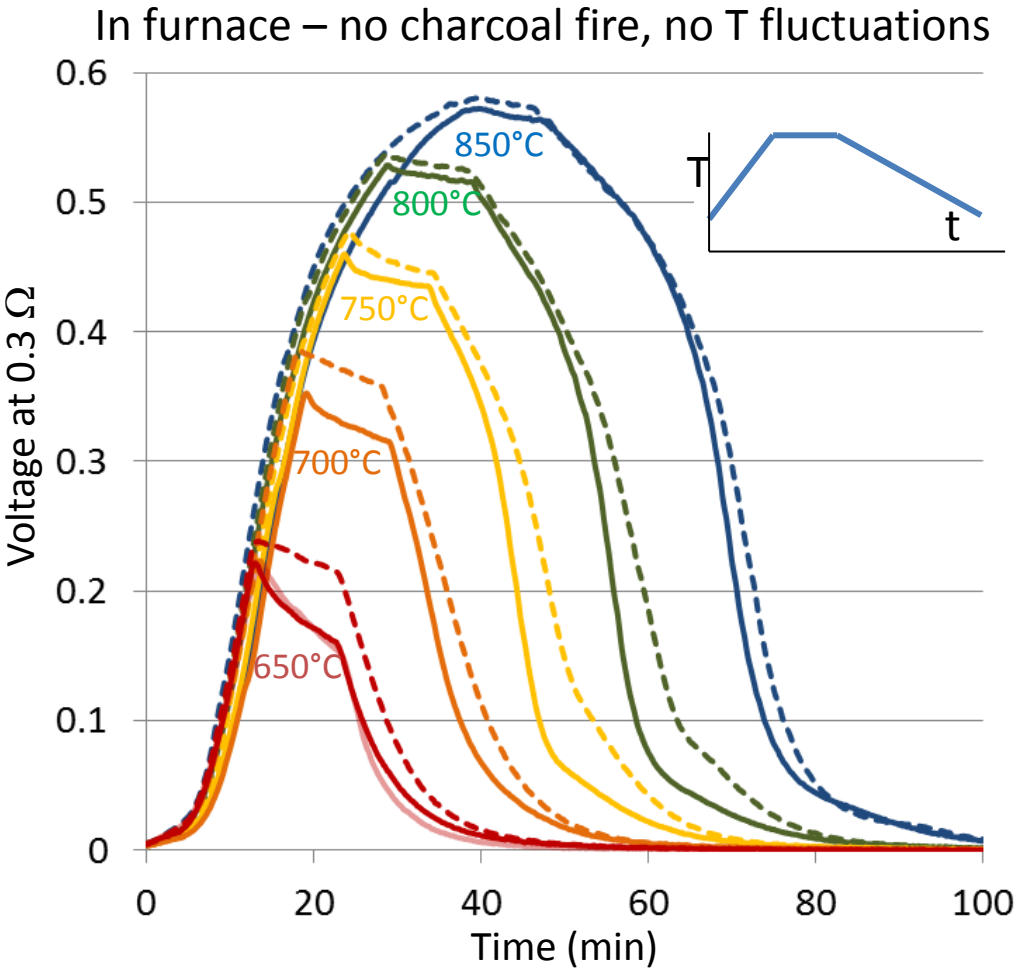
Performance with Stove-like Temperature Profile





Energy produced (Wh) = W*h

- Temperature affects both dramatically

Highly T-activated

- Cell AND fuel (CO) production T-dependent
- CO equilibrium not achieved

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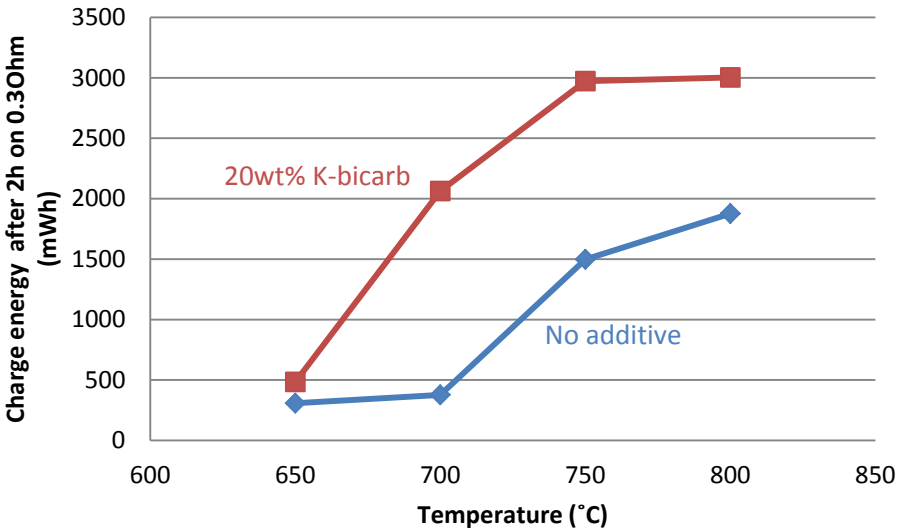
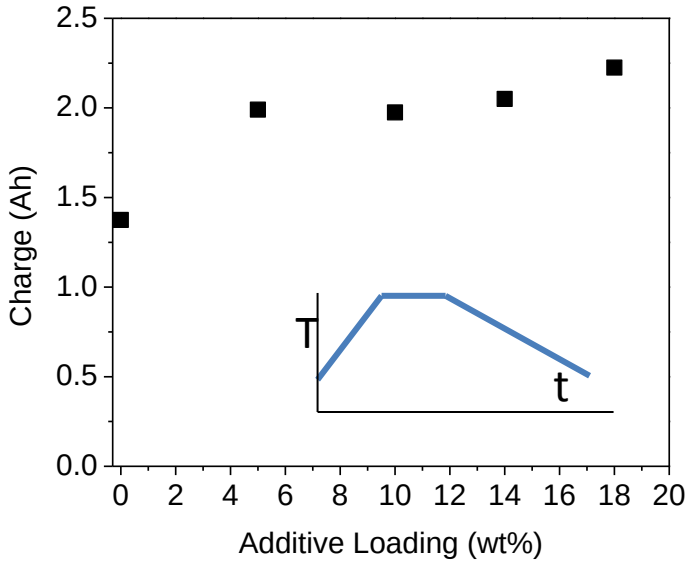
Improve Low-temperature Performance by Catalyzing CO Generation

Many catalysts suggested in literature
- Fe, Ni, Li, K, Ca, Na, eutectic (Na-Li-K)
  - K is most active for our conditions
    - K-carbonate, K-bicarbonate best salts
      - K-carbonate is deliquescent
        → K-bicarbonate

Isothermal Performance



Cooking Session



Small addition of K-bicarb yields significant improvement

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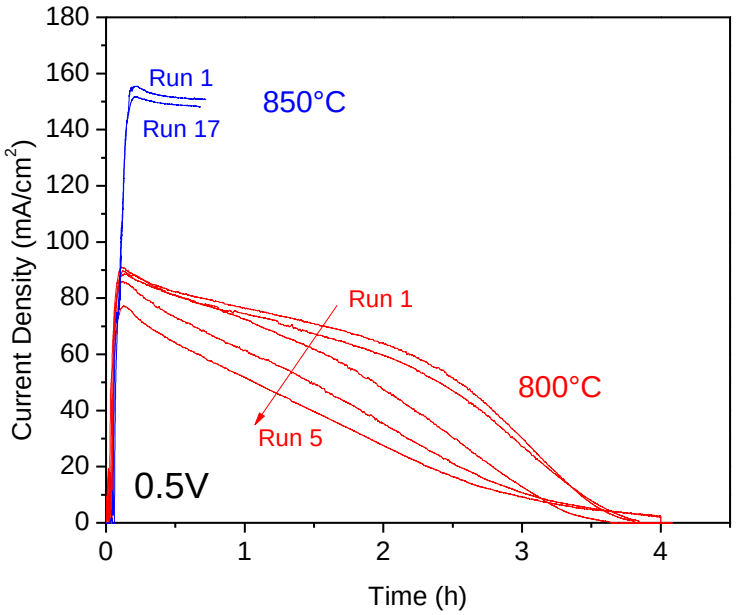
Charcoal Fuel Consumption Impacts Cell Lifetime

Isothermal Furnace (no cooking charcoal)



Upon consumption of charcoal

Charcoal + K-bicarb → ash + K-salt + oxidizing atmosphere

- Corrosion of steel
- K-Cr poisoning of cell catalysts

Tradeoff charcoal card size/cost vs. run time

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Summary: Product Development is a long series of Tradeoffs

"HA HA HA" -Mother Nature

High temperature required for good charcoal performance

K boosts performance

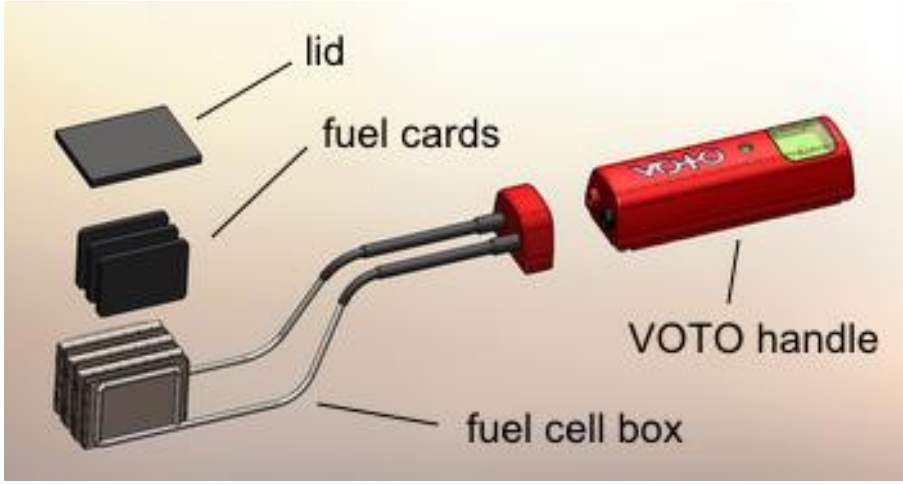
Too-High temperature kills the device

- steel corrosion
- steel softens
- seals melt
- cell catalysts coarsen

K kills the cell

Solutions:

- Prevent ash and oxidizing conditions in the anode
  - Limit run time
  - Lid covers anode chamber
- Shield cathode from fire
- Small stack in hottest part of fire



- Accept limited lifetime

Consumable
Fuel Cell
$6
2-3months

Acknowledgements

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Funding at PSP:

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- Board members Pierre Lamond and Henri Moissinac

NSF SBIR

PSP Team

Kenya Operations

Joseph Nganga