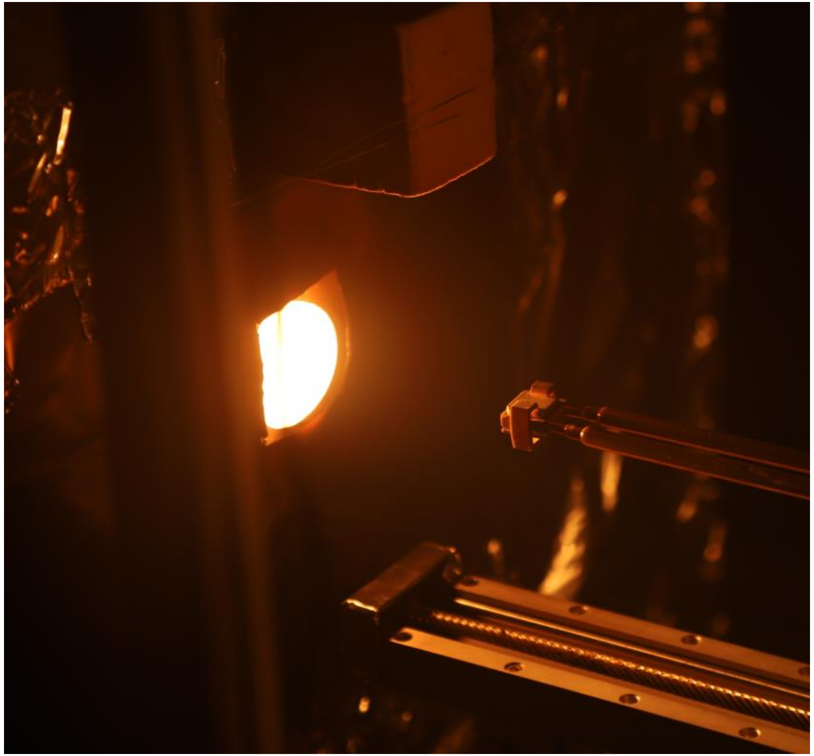
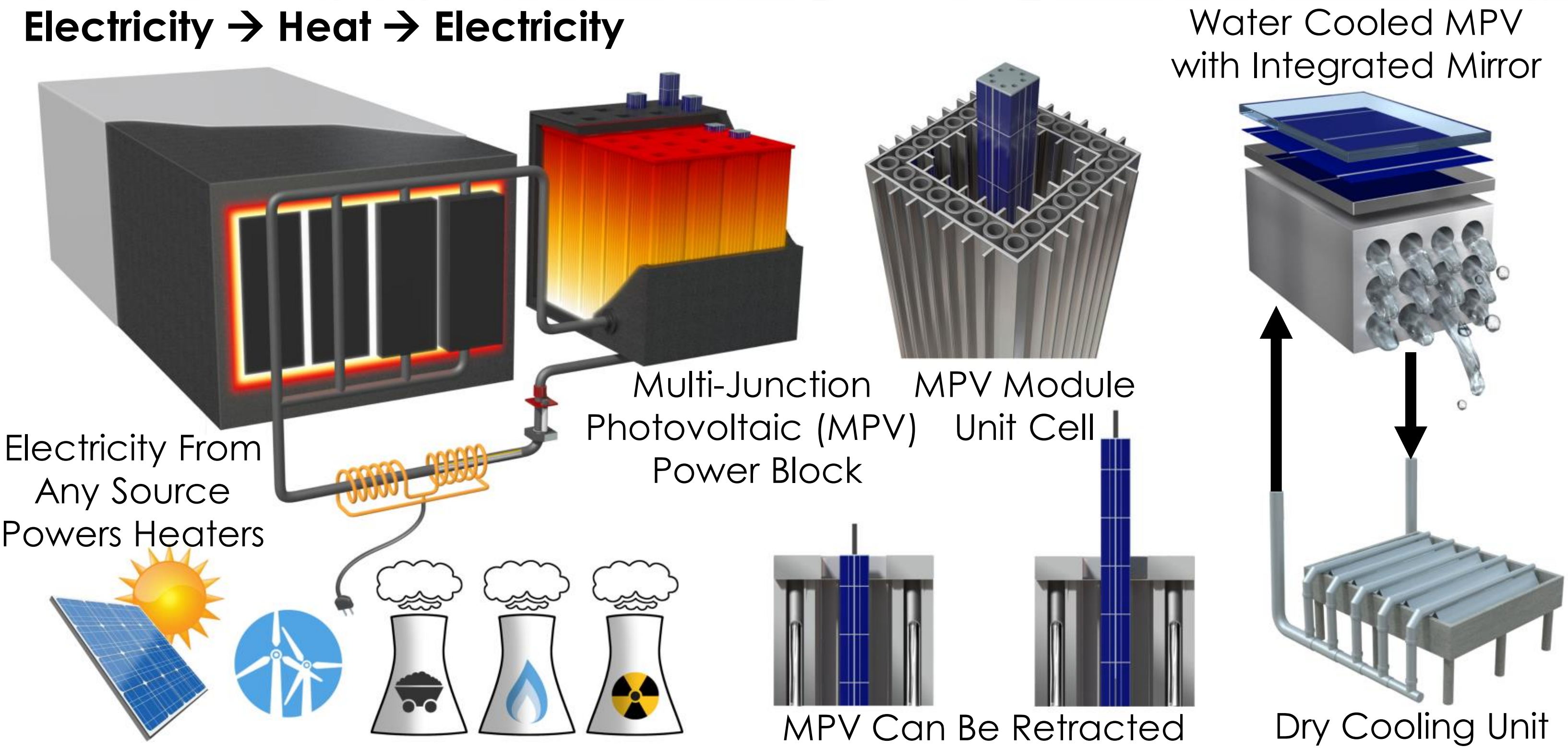
Thermal Batteries – *Concept, Economics and Progress to Date*

Asegun Henry
Robert Noyce Career Development Chair
Associate Professor
Department of Mechanical Engineering
Massachusetts Institute of Technology



Thermal Batteries



C. Amy et al., Energy Environ. Sci., 12, 334-343 (2019)

Why is the cost so low?

Storing heat is 10-100X cheaper than storing electricity electrochemically in a normal battery.

Simple estimate:

Cost per unit energy — Cost of the medium — Energy Stored — Roundtrip Efficiency

$$CPE_{min} = [\$/kg] \div [\underbrace{C_p \cdot (T_{High} - T_{Low})}_{\text{Energy Stored}} \cdot RTE]$$

$$\$10^{-6}/J = [\$0.5/kg] \div [\underbrace{2000\ J/kg/K \cdot (500\ K) \cdot 0.5}_{\text{Cost of the energy stored in the blocks}}]$$

Li-ion battery cell cost $100-200/kWh → $3.6/kWh

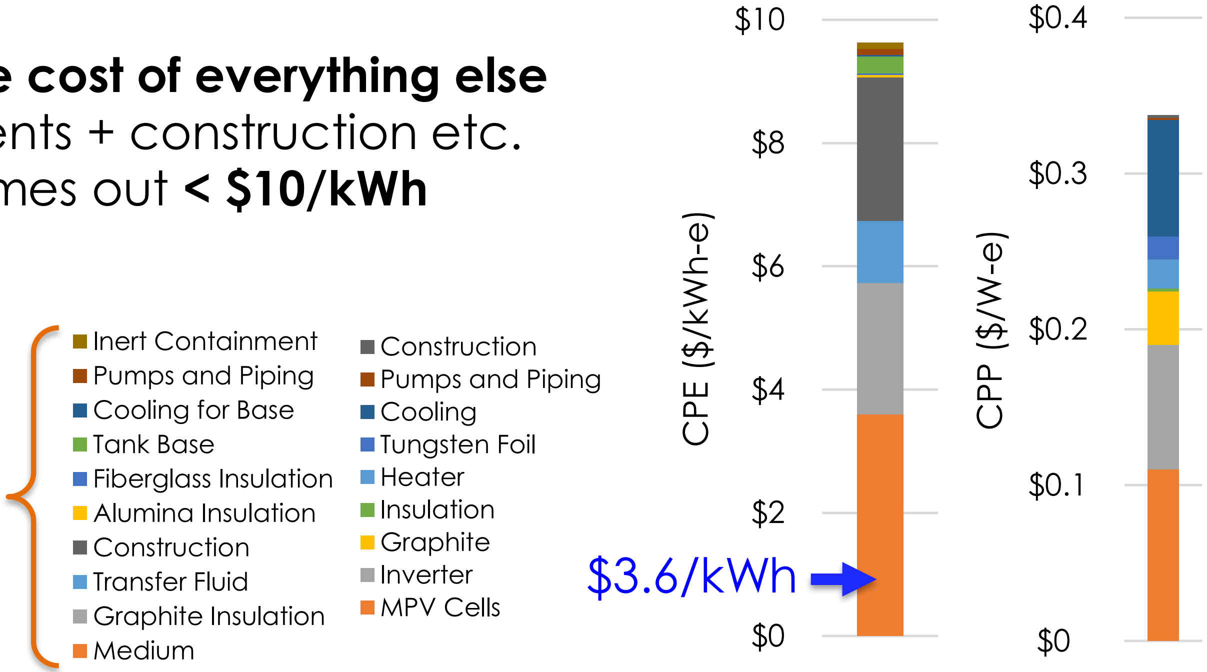
Cost of graphite blocks

Cost of the energy stored in the blocks

Why is the cost so low?

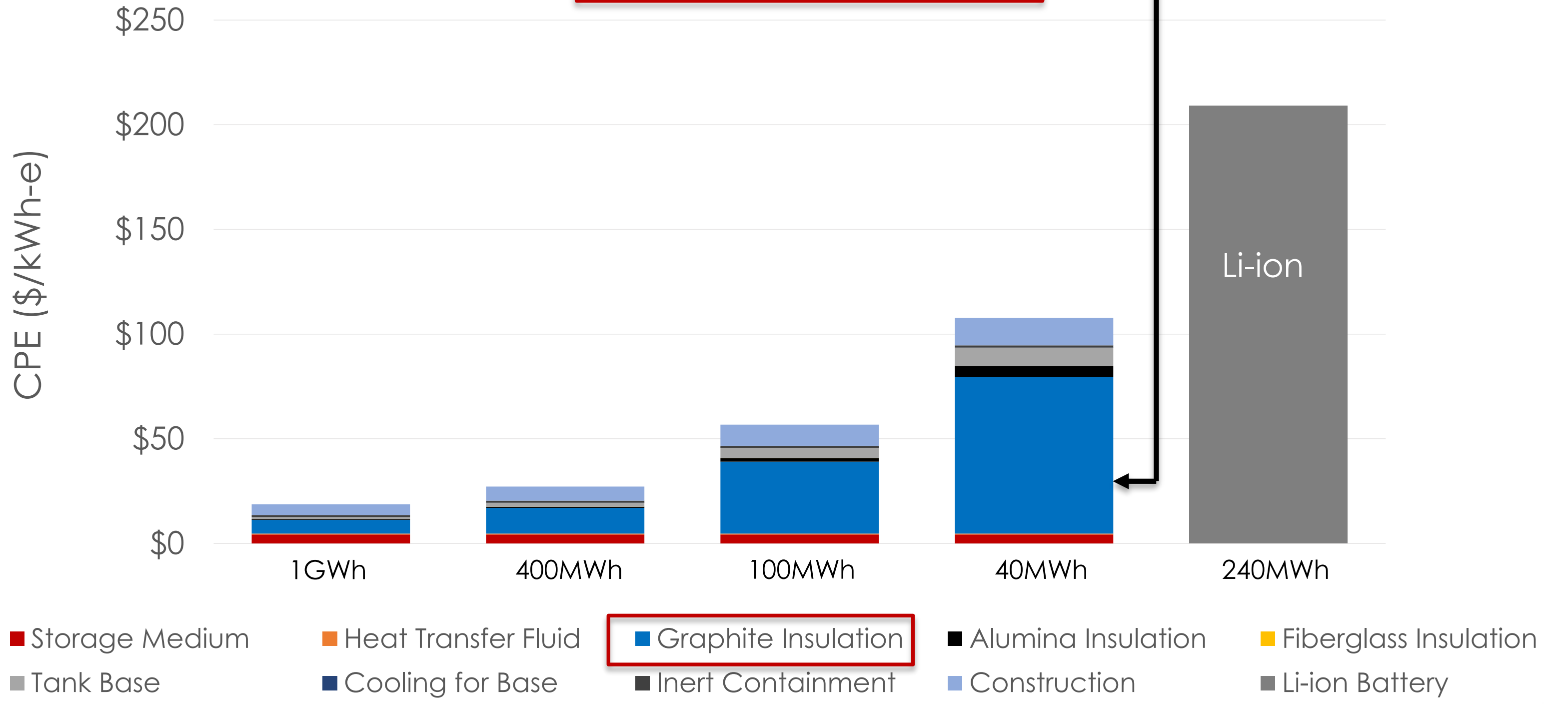
Even after we add the cost of everything else
i.e., other components + construction etc.
The cost still comes out **< $10/kWh**

With other system costs added **< $10/kWh**

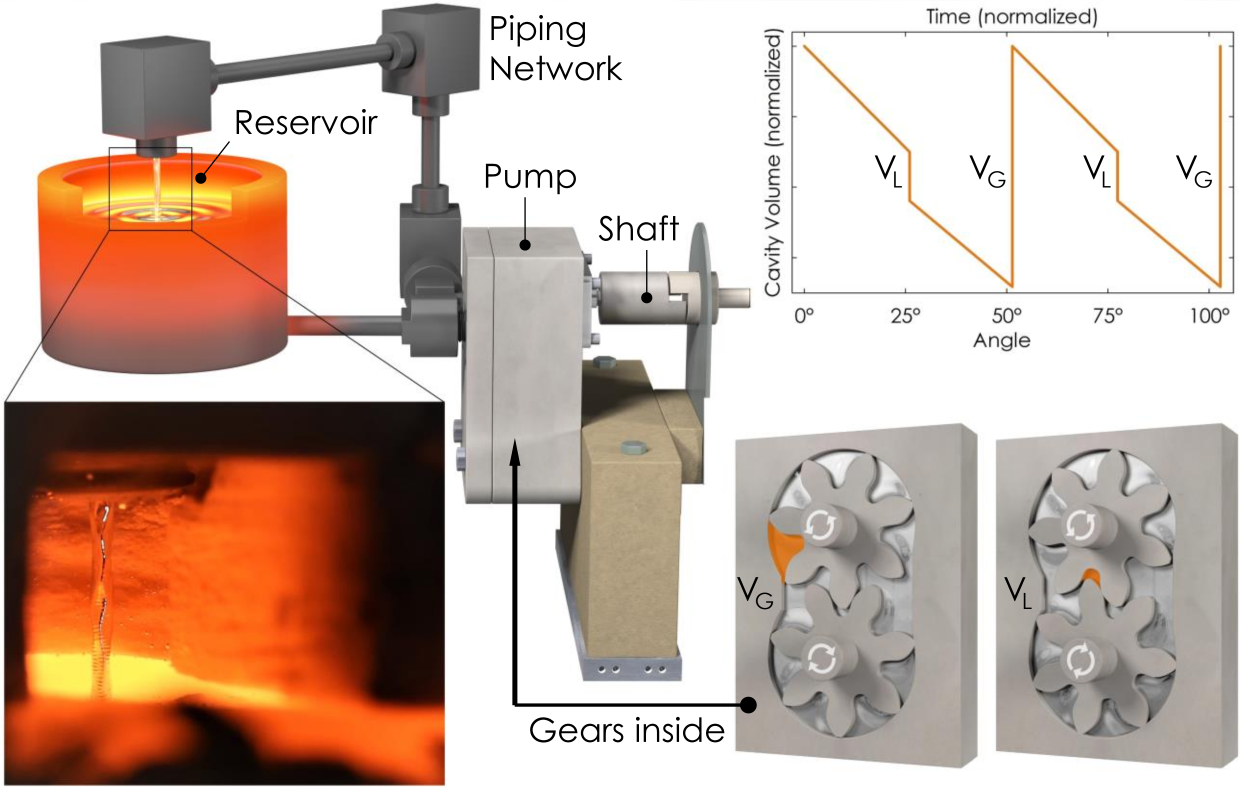


Economics vs. scale: The bigger the better

The cost of thermal batteries decreases with increased size because the insulation cost decreases

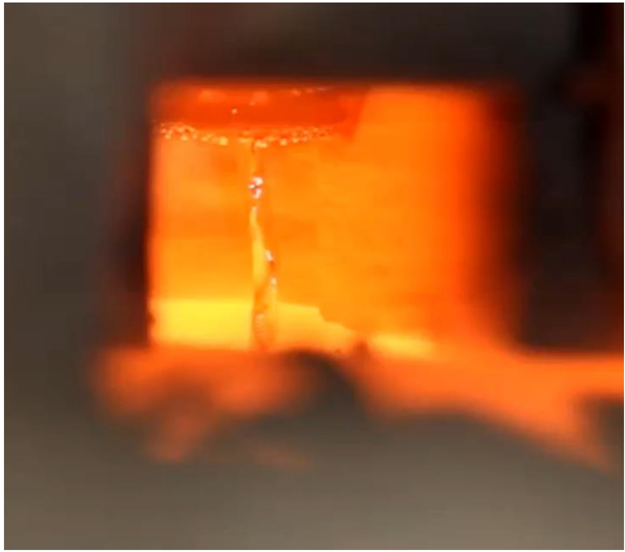


Pumping



C. Amy et al., **Nature** 550, 199–203 (2017)

Pumping at 1400°C

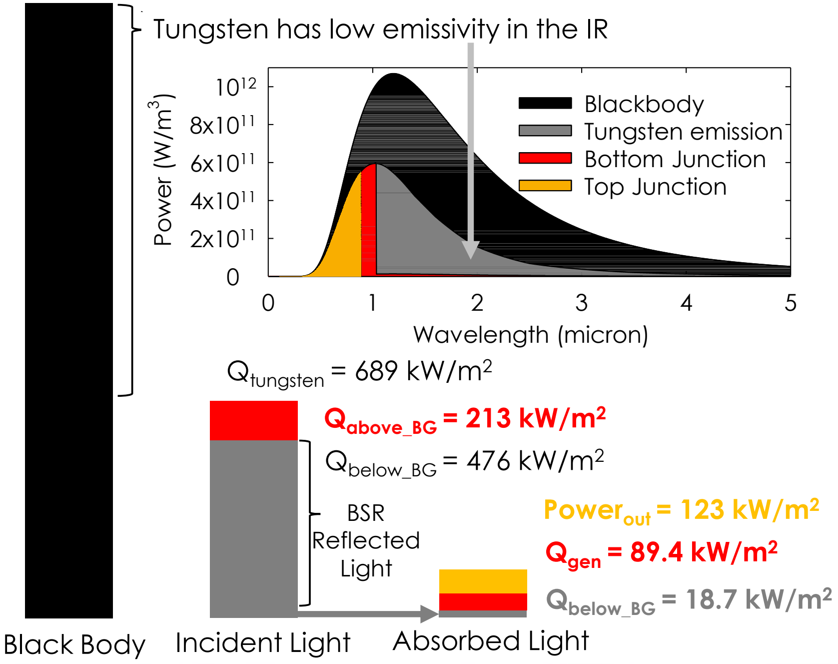


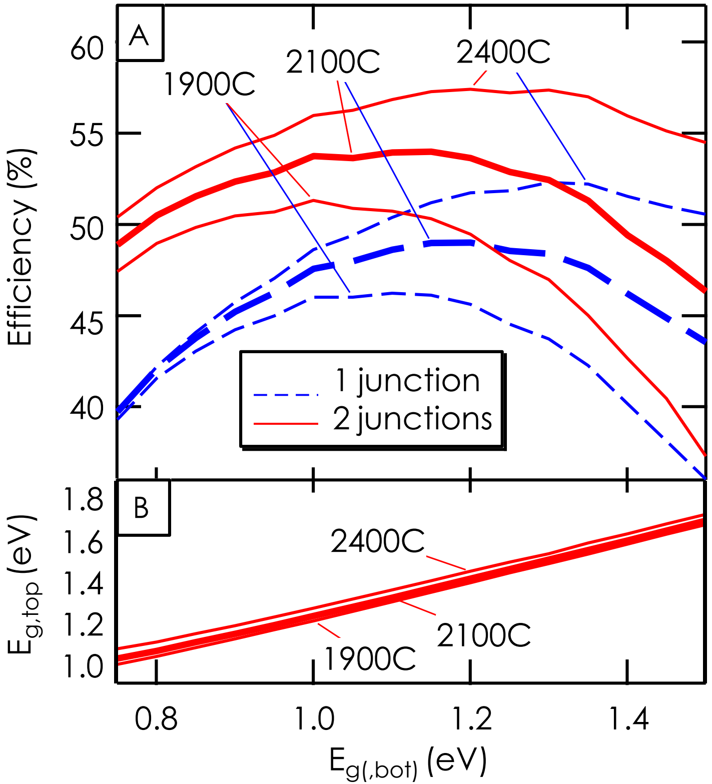
C. Amy et al., Energy, 233, 15, 121105 (2021)

Why Multi-Junction Photovoltaics?

Efficiency = $\text{Power}_{out} \div \text{Qtotal}$ =
123 ÷ (123 + 89.4 + 18.7 + 4.6) = **52%**

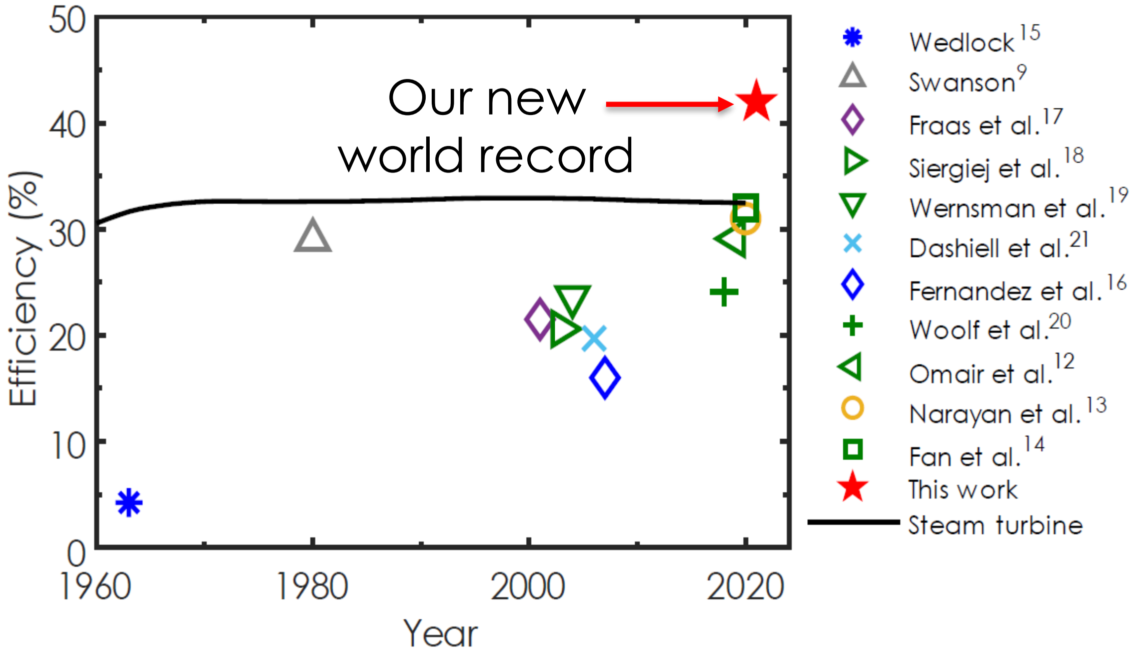
$Q_{blackbody}$ = 1.95 MW/m²





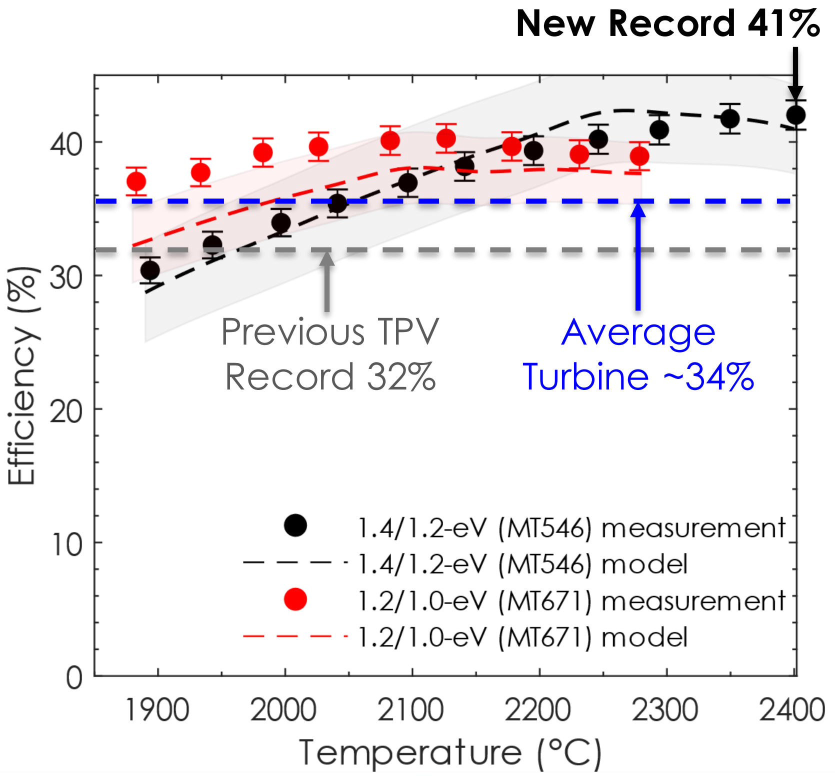
Thermophotovoltaic Cells

- Photovoltaic cells that convert light from a terrestrial heat source are also called thermophotovoltaic (TPV) cells
- TPV has not been used much for power generation because the efficiency has been lower than a turbine
- The world record efficiency for TPV was 29% for 40 years
- Record was broken last year at 32%
- We set a new record 41%



Technological Breakthrough: MPV Cells

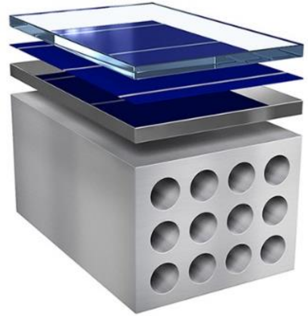
- Our new record = 41%
- RTE for thermal batteries = MPV efficiency
  - < 1% charging loss in converting electricity to heat
  - < 1% per day heat loss to environment
- > 35% RTE is needed for arbitrage
- 40% is high enough to commercialize
- 40% is higher than average turbine
- Target is to reach 50%
  - Improve mirror reflectivity from 94% to 98%
  - 98% reflectivity in TPV was recently demonstrated
  - Use 4 terminal devices to exceed 50%



Why Use MPV Instead of a Turbine?

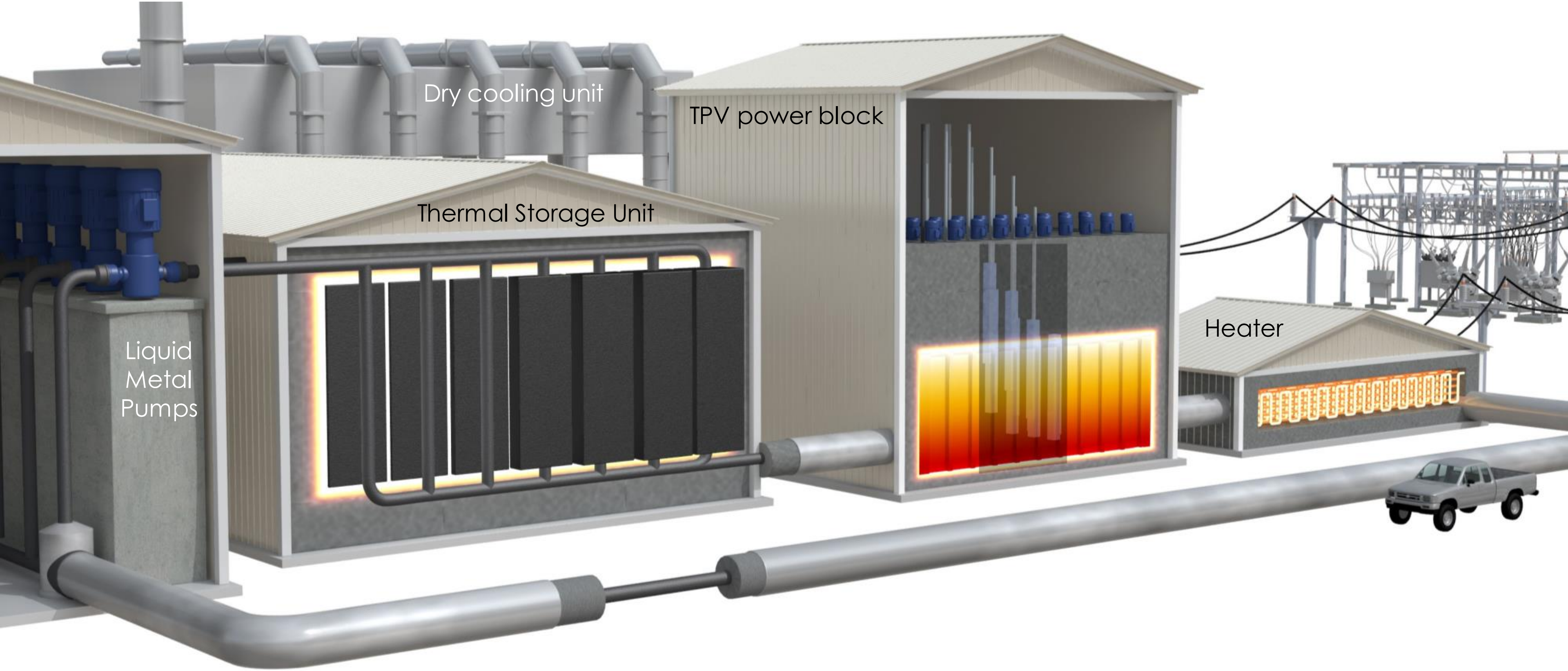
- Turbine
  - Doesn't currently exist
  - **Large barrier to new turbine deployment**
  - > $100M of R&D
  - New materials + New HXs
  - Min-Hour response time to full load
- MPV
  - **Much lower barrier to deployment**
  - **Lower cost < $0.5/W-e**
  - Similar efficiency (50-55%)
  - Fast response time (seconds)
  - Fundamentally new cost/learning curve
  - Lower maintenance

Turbomachinery
vs.
MPV

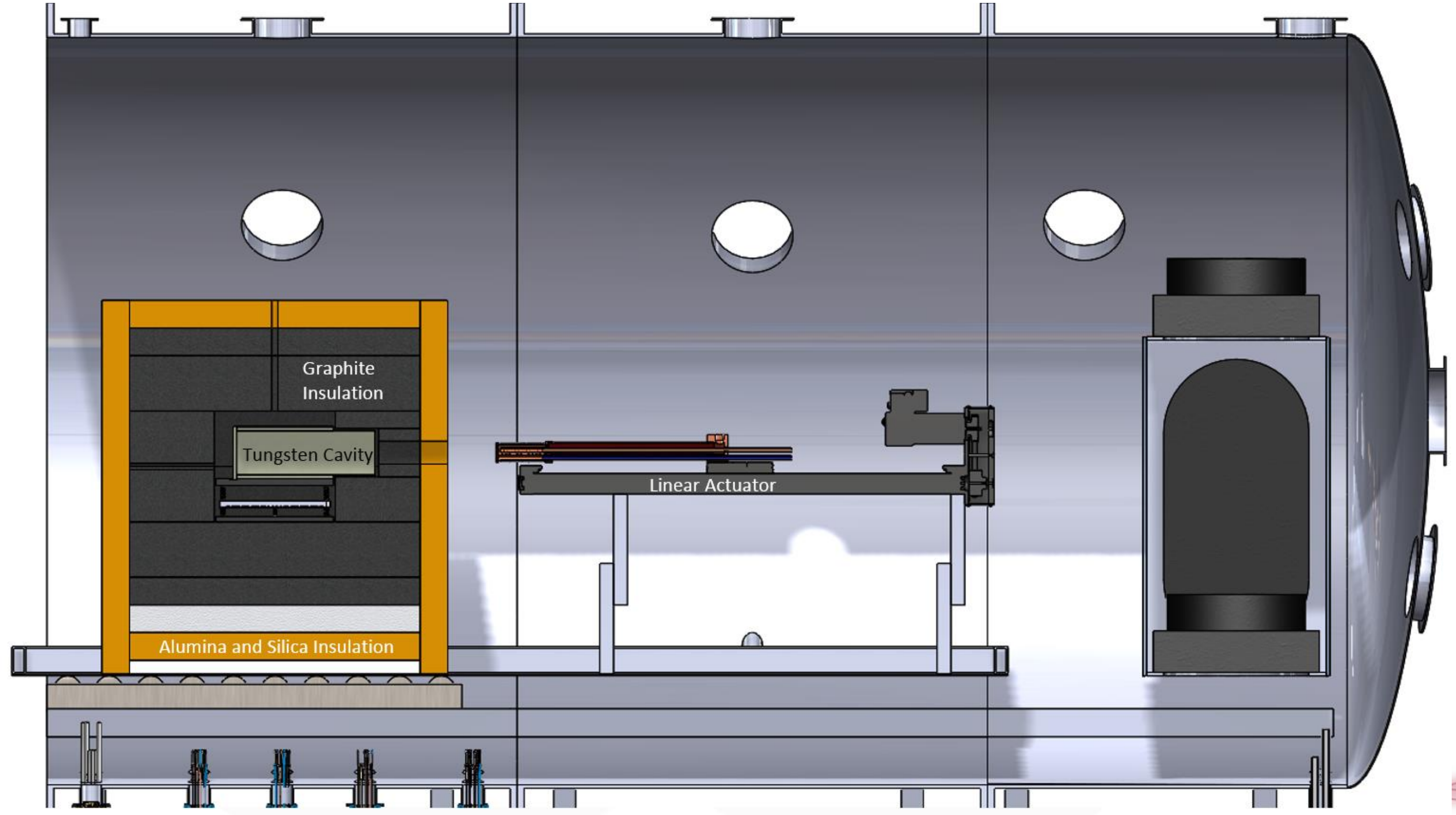


What will the full system look like?

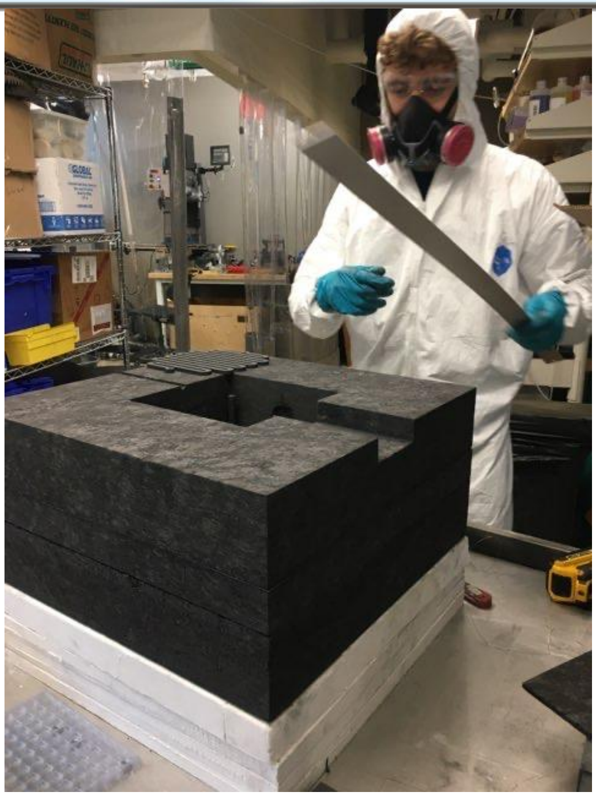
Full scale system mockup: 1 GWh = 100 MW x 10 hrs of storage



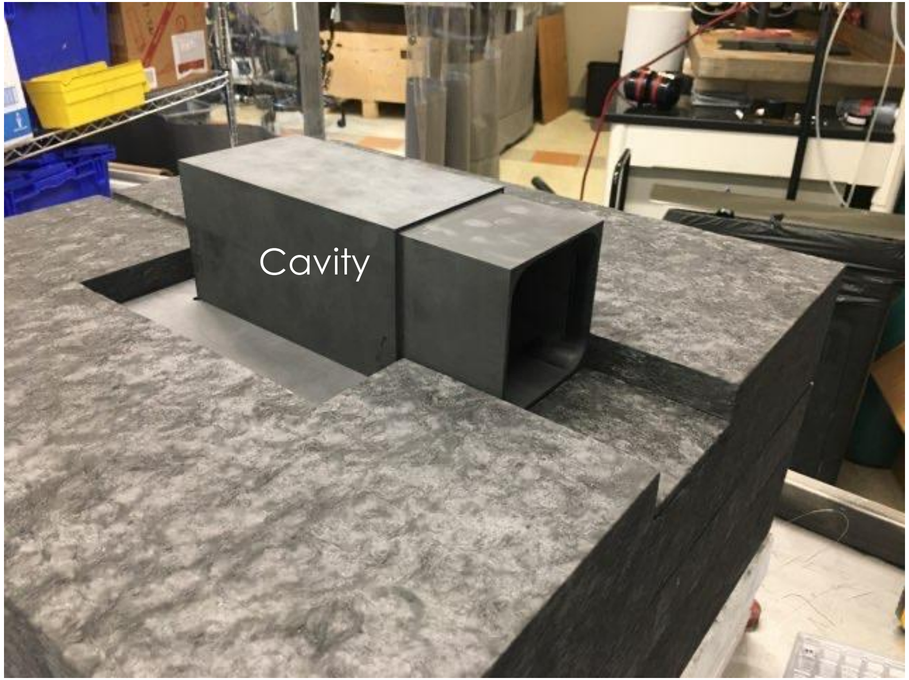
High Temperature Cavity (2150°C)



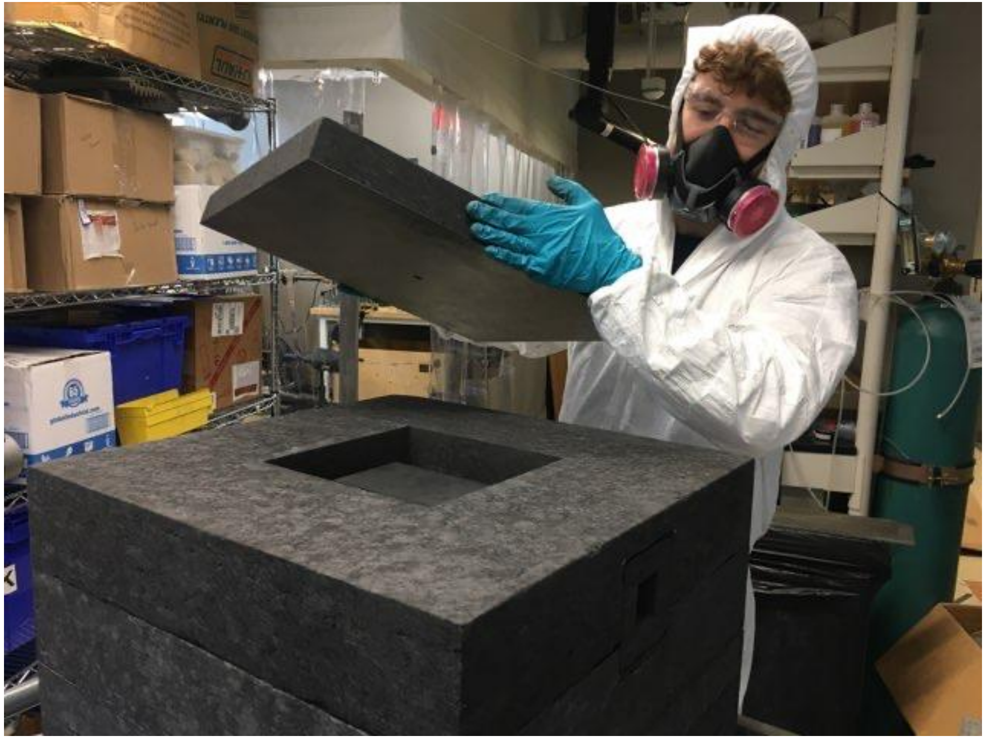
High Temperature Cavity (2150°C)



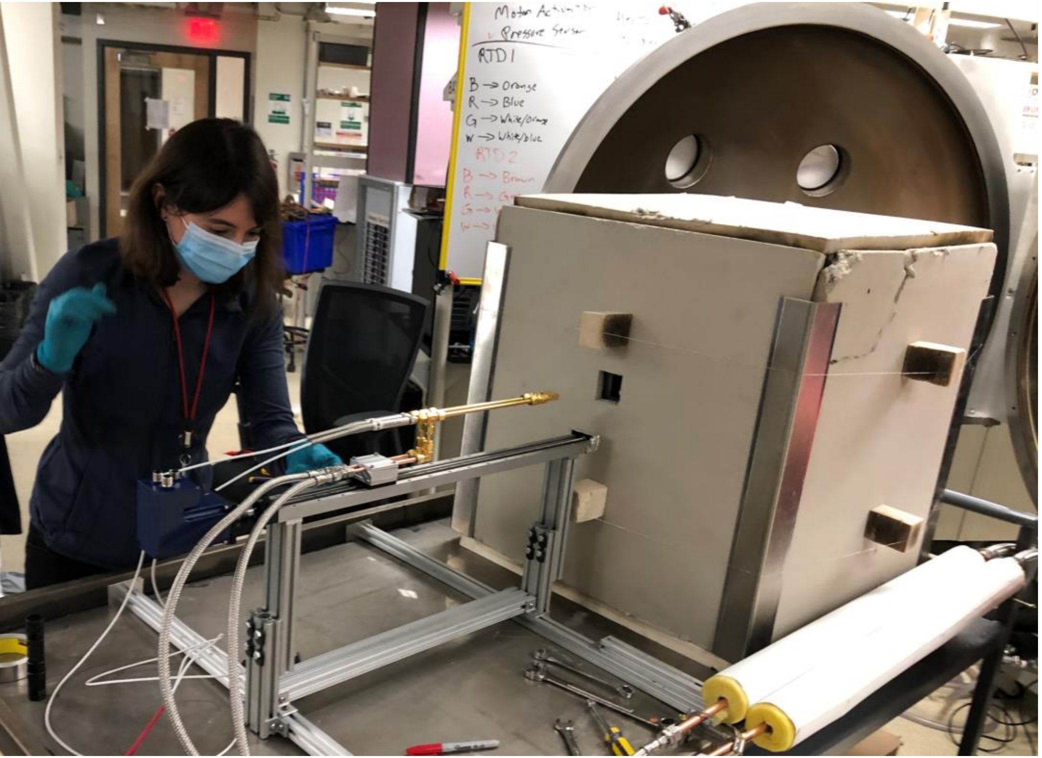
High Temperature Cavity (2150°C)

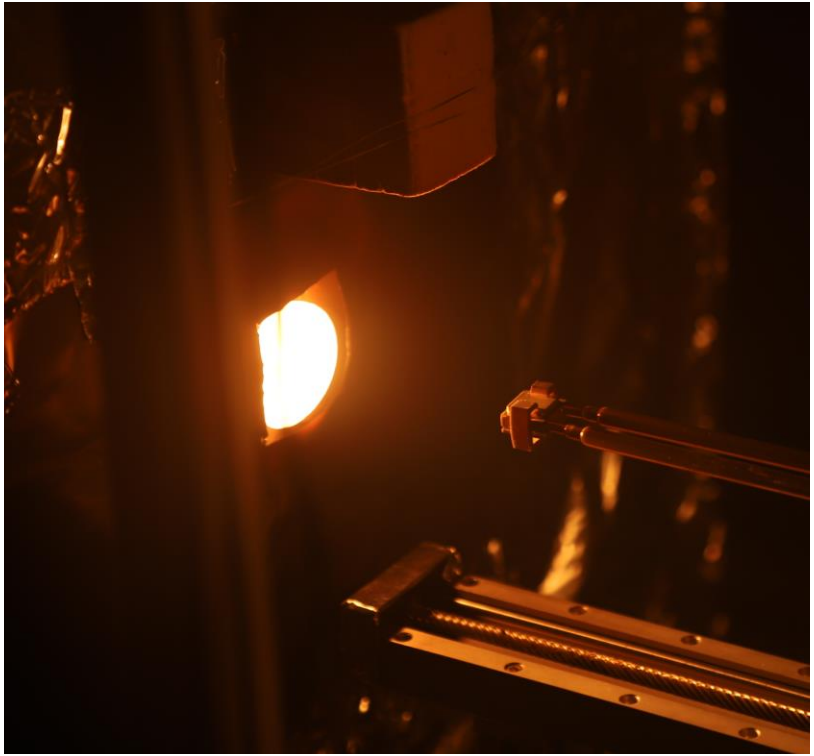


High Temperature Cavity (2150°C)

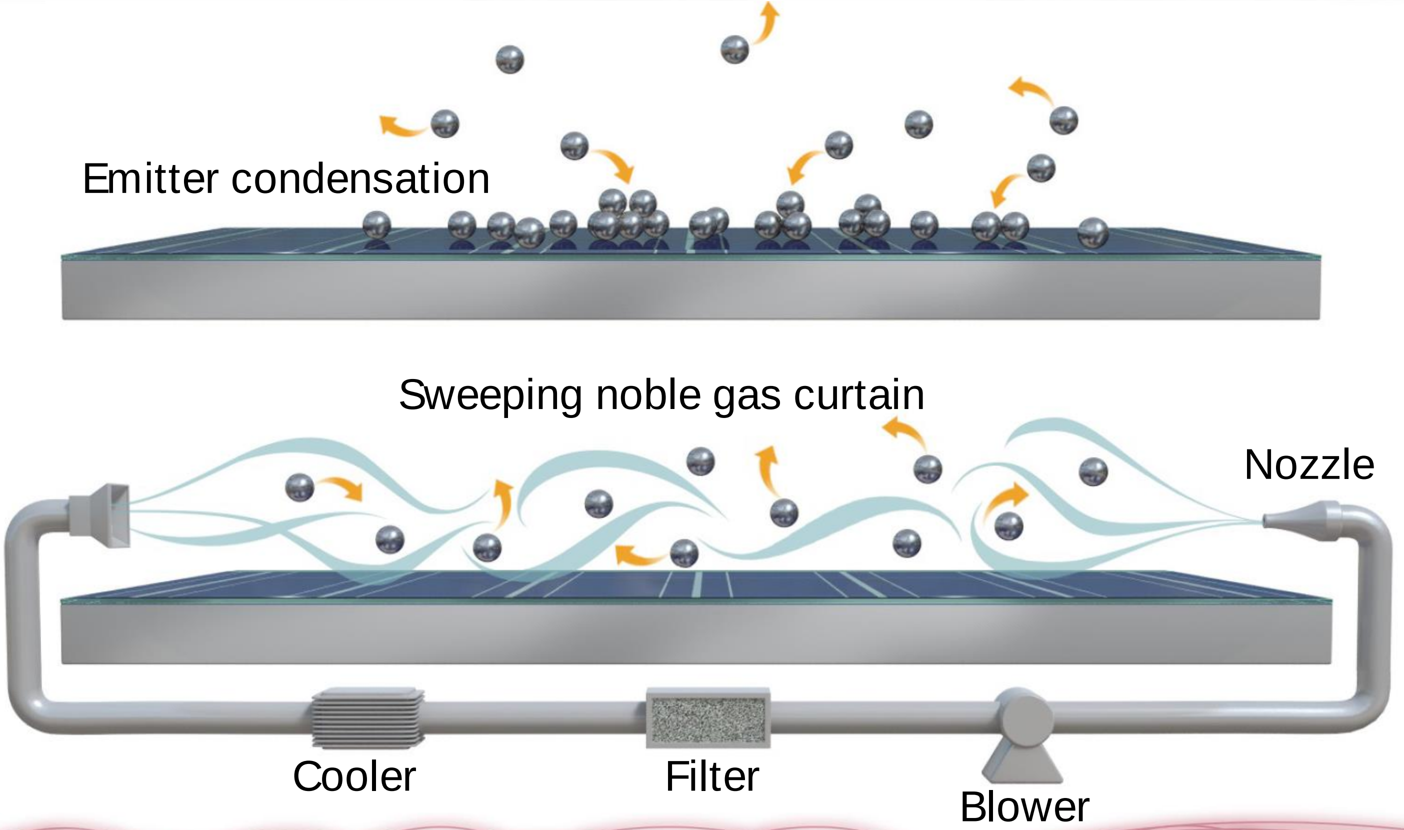


High Temperature Cavity (2150°C)

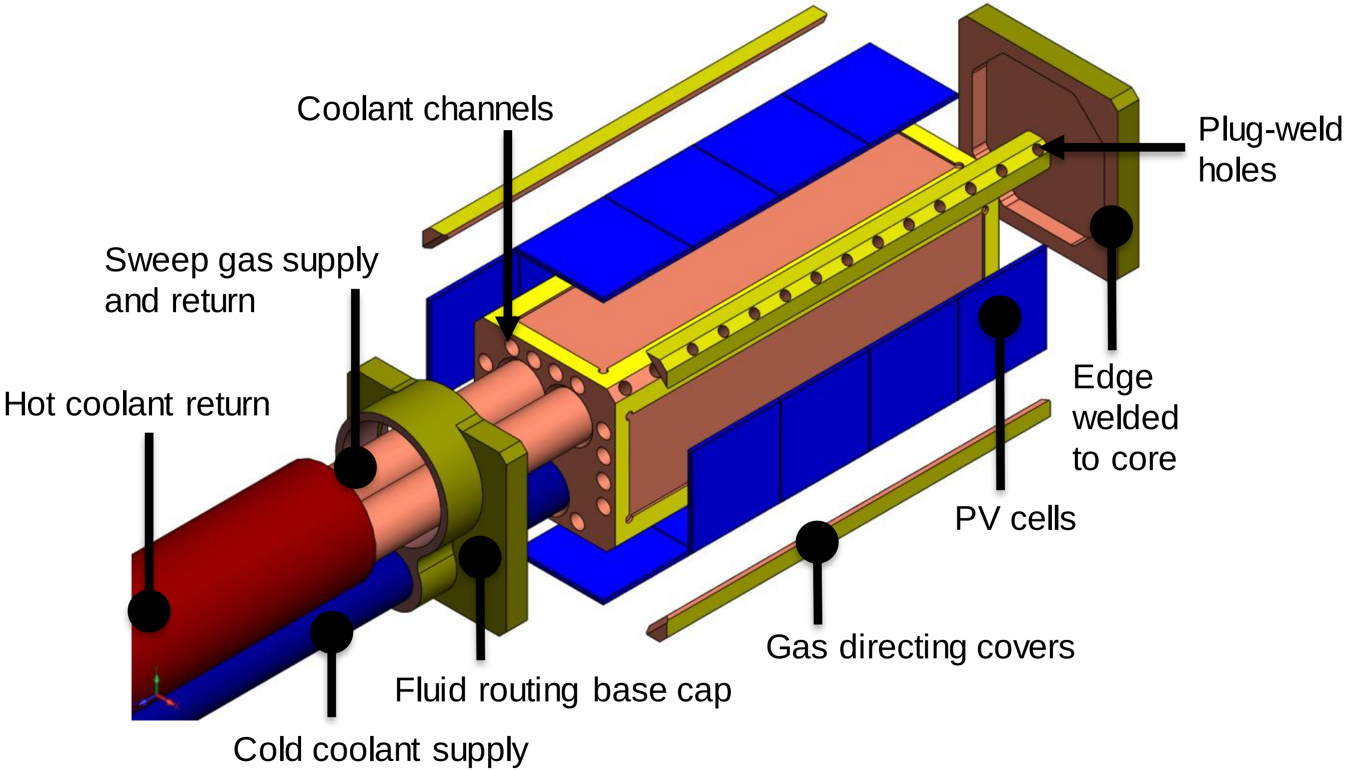




Sweeping Noble Gas Curtain (SNGC)

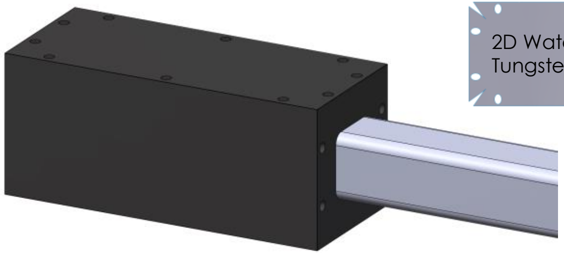


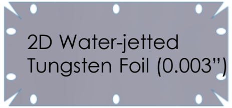
Sweeping Noble Gas Curtain (SNGC)

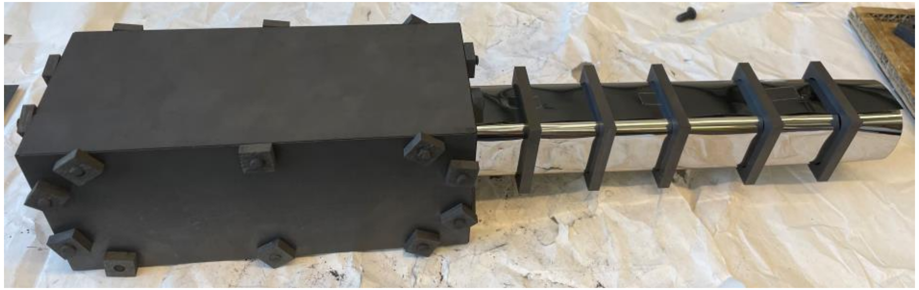


Tungsten Liner

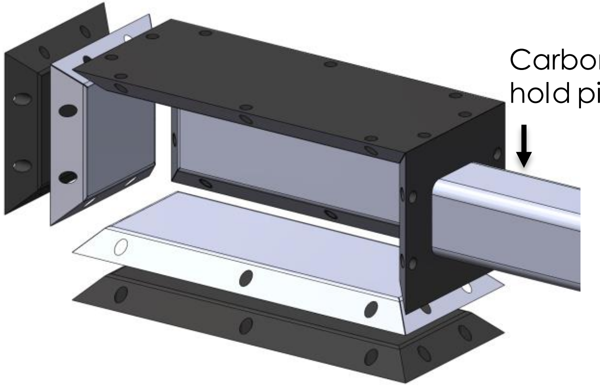
Assembled Cavity and Entry Tube







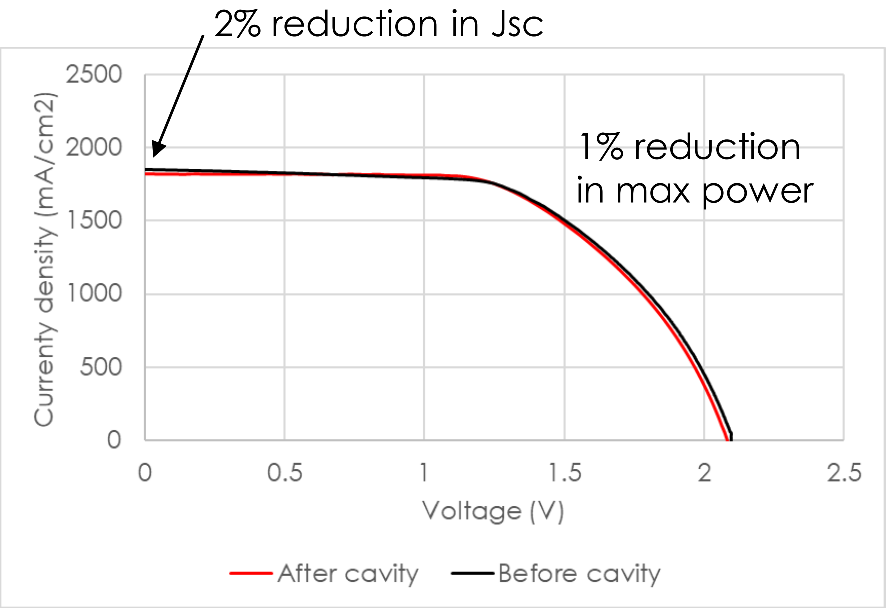
Exploded View Showing Layers

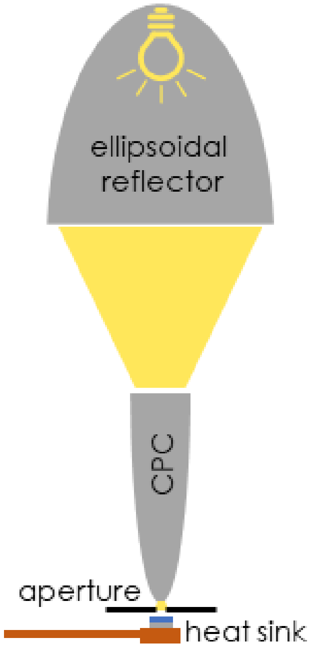


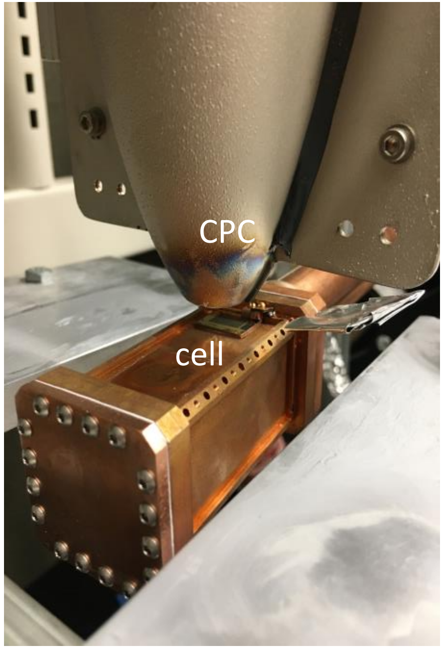
Carbon-fiber bolts
hold pieces together

SNGC Demonstration

- IV curves taken with bulb concentrator before and after >6 hours of testing in the cavity

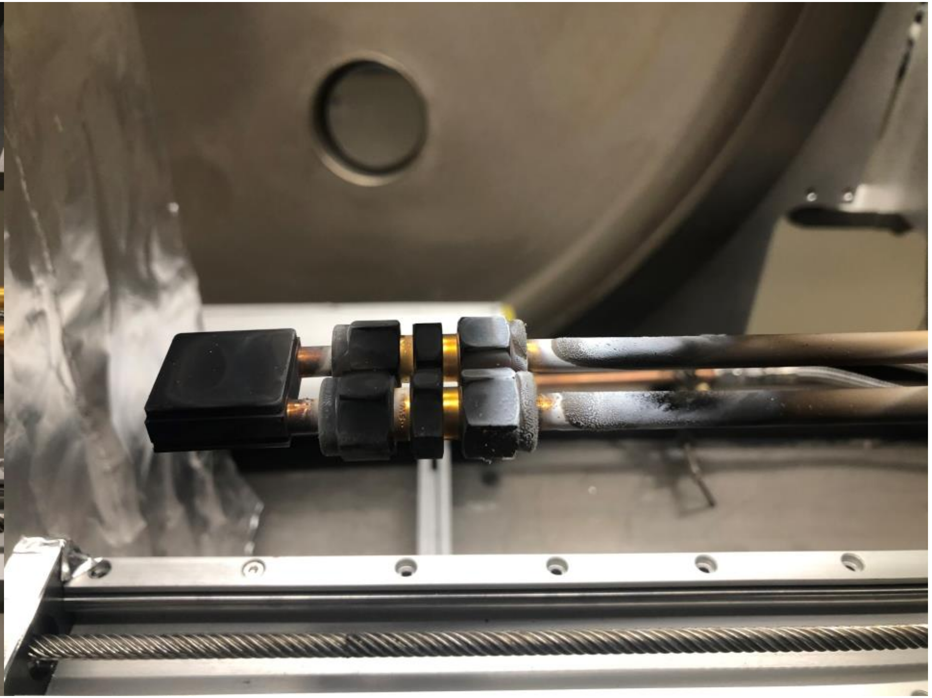






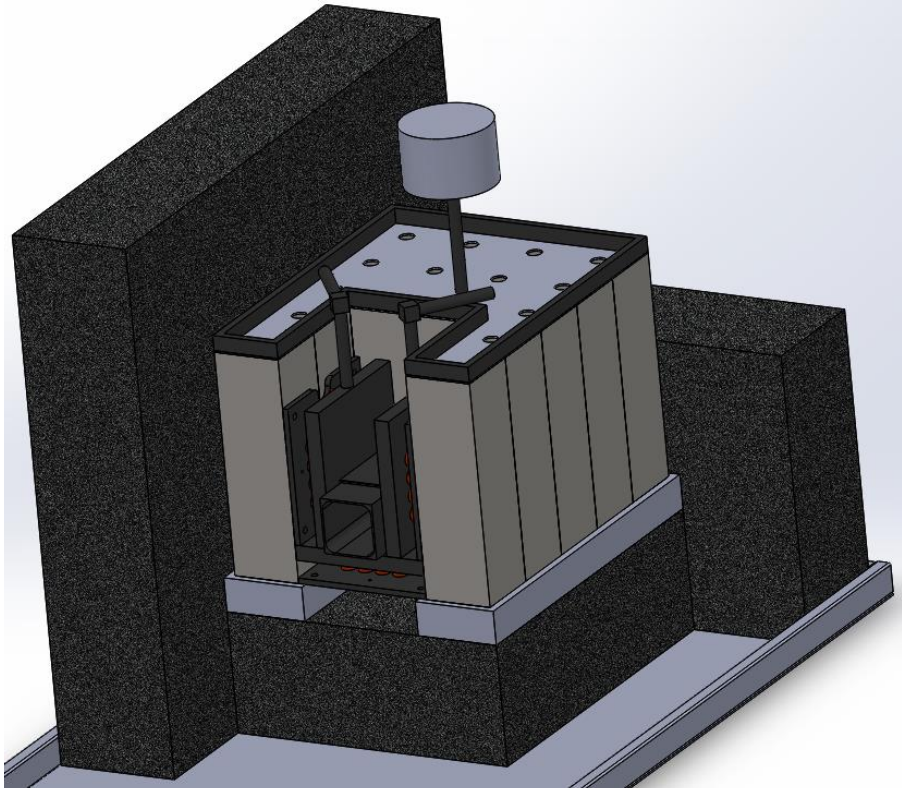
Without deposition prevention

2150C without W liner or SNGC protection



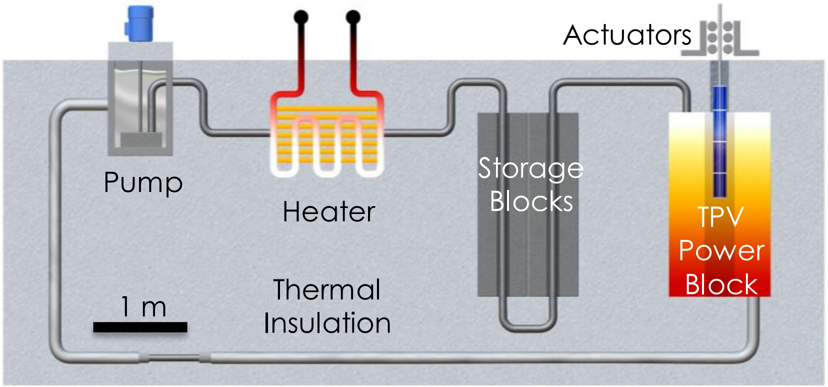
What's Next?

- Build a prototype 1-10 kWh
- Pumping
- Full 1900-2400°C cycles
- Emitter Deposition Protection
- TPV modules
- Long term testing



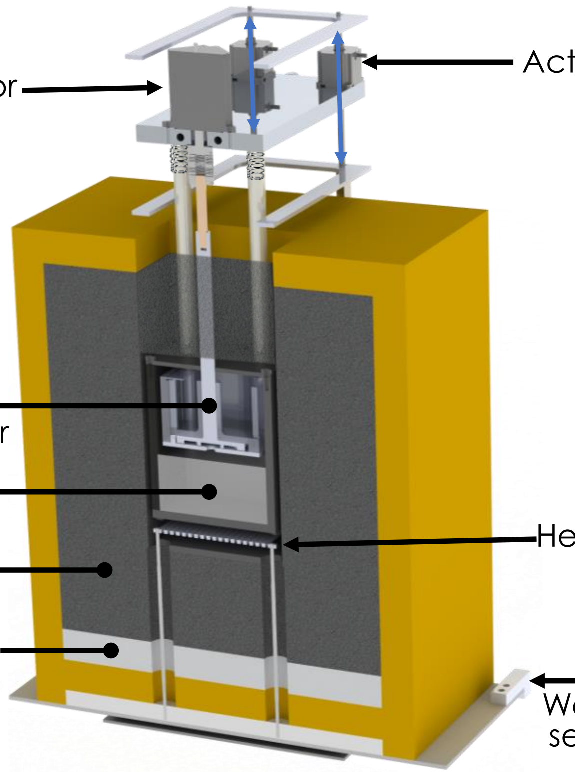
What's Next?

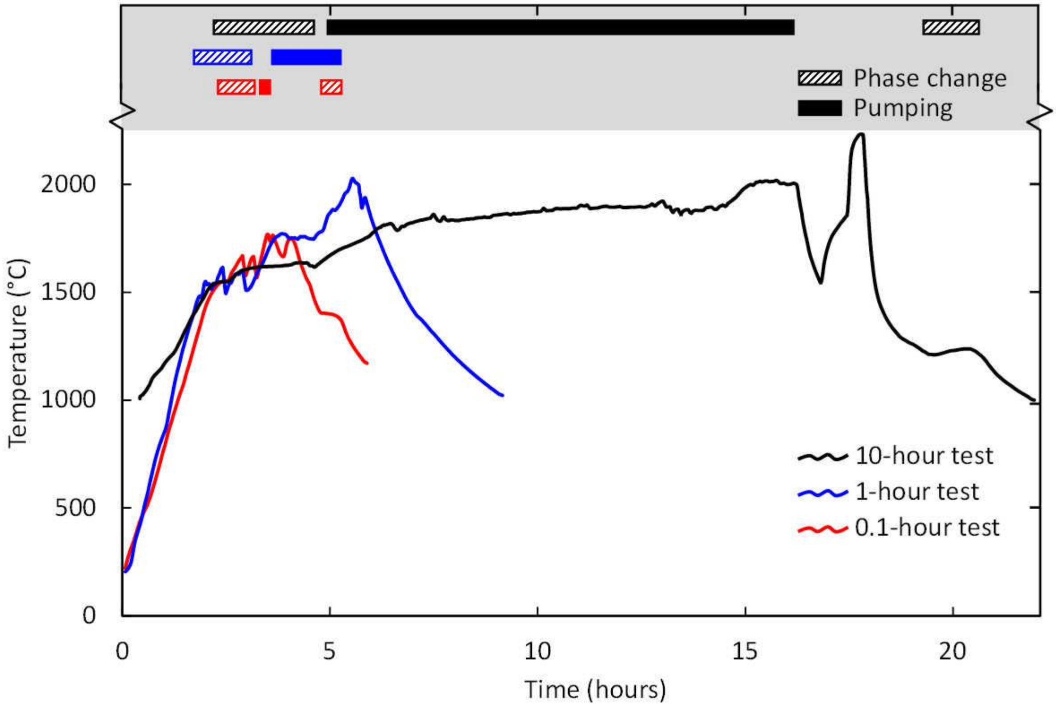
- 1 MWh pilot demonstration
- Single repeat unit
- Same dimensions as large scale
- 4 graphite blocks (0.6 m x 0.6 m x 2 m)
- 200 kW TPV modules ~ 2 m^2 → 20,000 cells
- Long term cycle testing



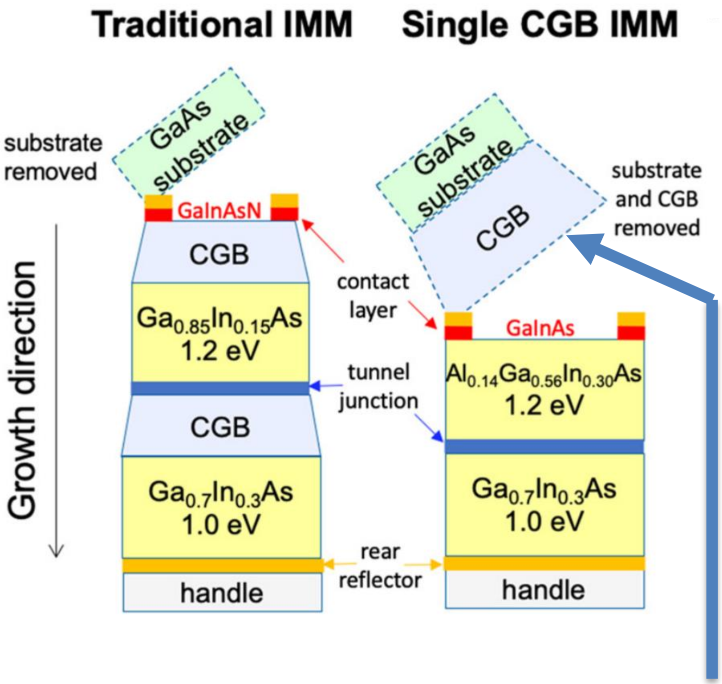
Questions?

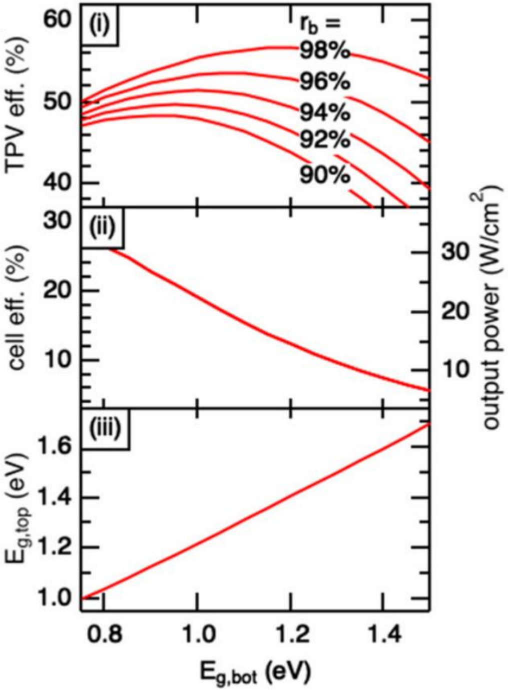
Pumping Silicon at 2000°C



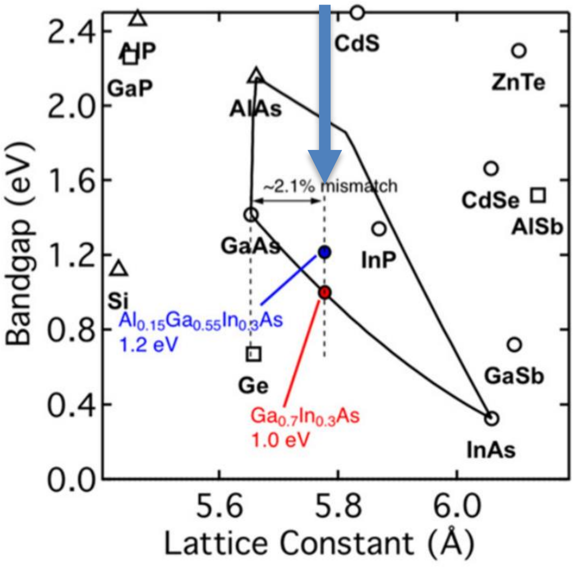


MPV Cell Development





Lattice Matched Junctions
Minimize Defects

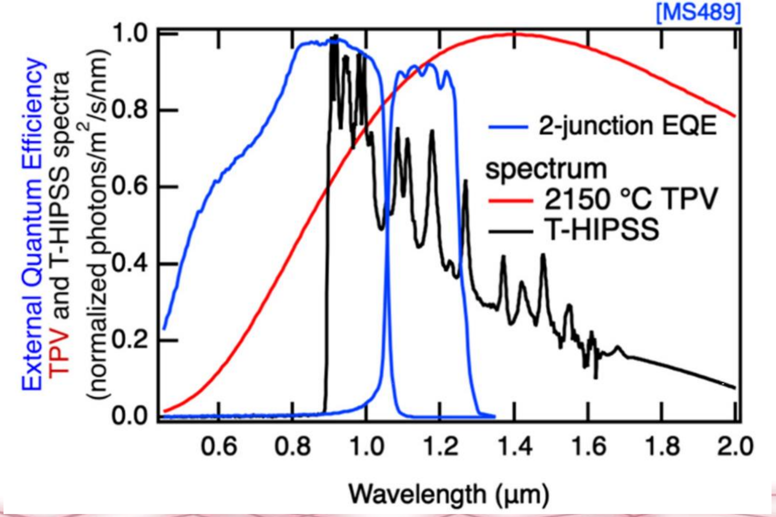


Compositionally Graded Buffer (CGB) Layer
Transitions Lattice Parameter
Removed to Minimize Sub-Band Gap Absorption

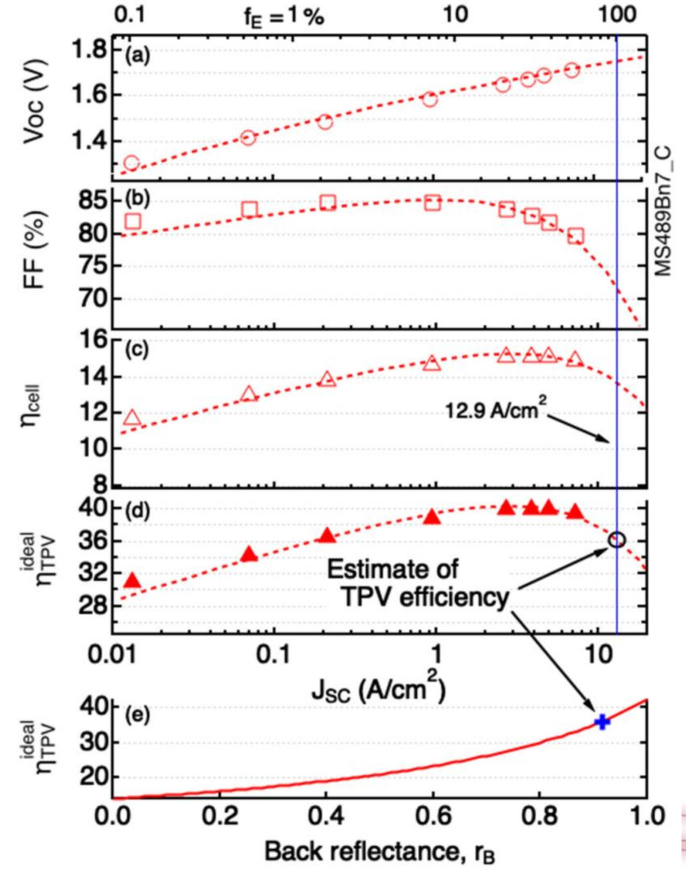
K. L. Schulte *et al.*, Journal of Applied Physics 128, 143103 (2020)

MPV Cell Development

- Back reflectance measured ~ 92%
- Peak cell efficiency ~40%
- Limited by series resistance (high current)
- More optimization of series resistance
- Thinning and reduction of highly doped layers

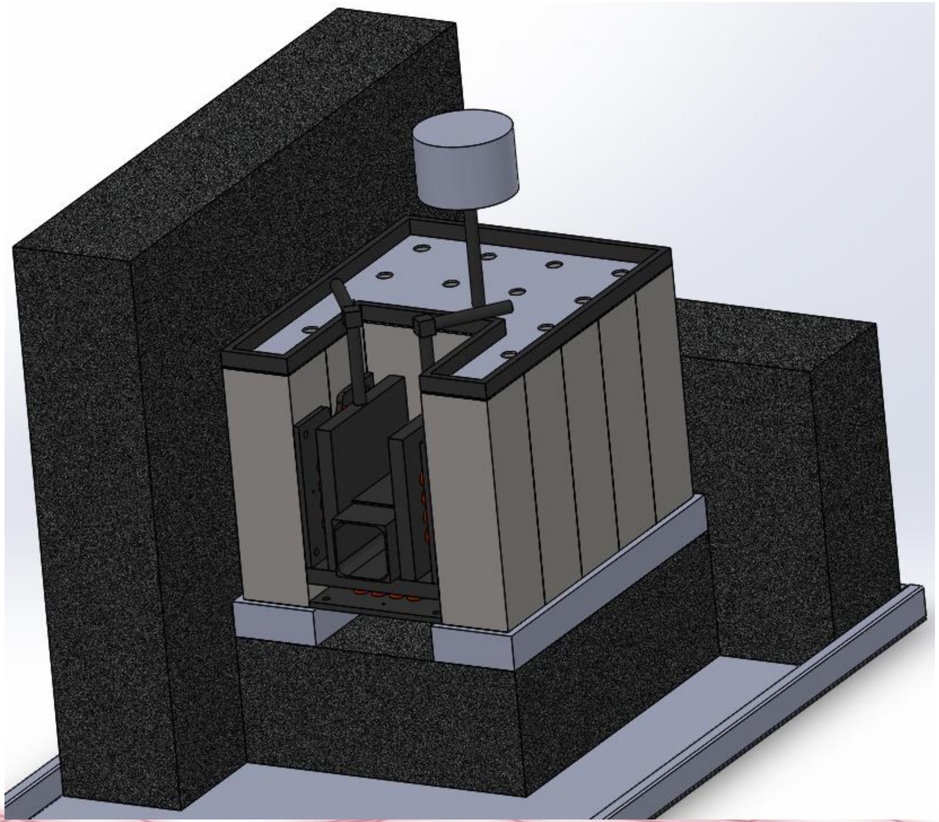


K. L. Schulte *et al.*, Journal of Applied Physics 128, 143103 (2020)



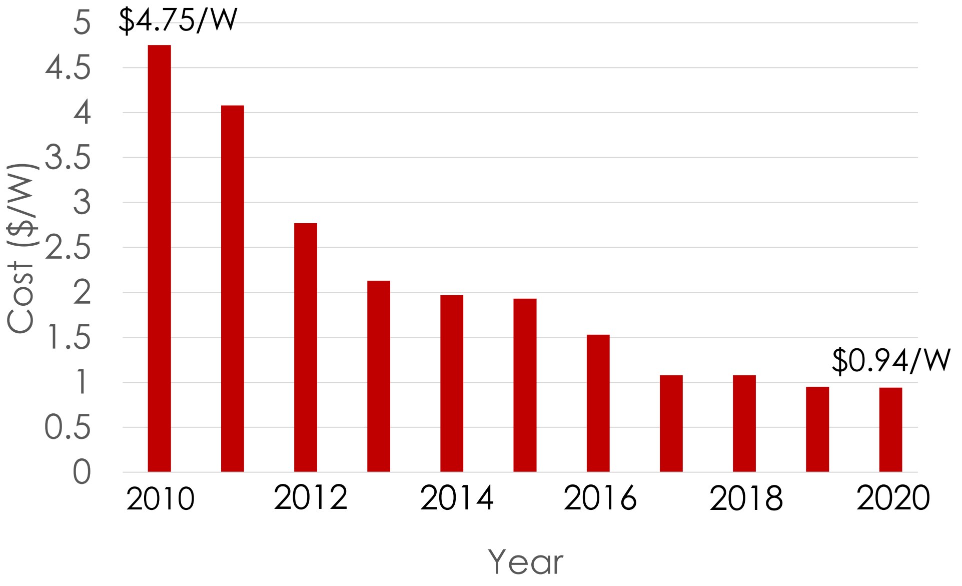
What's Next?

- **Build a prototype**
- Pumping
- 2500°C Heaters
- Emitter Deposition
- High current density
- High reflectivity (> 98%)
- High efficiency($\geq$ 50%)
- Long term testing



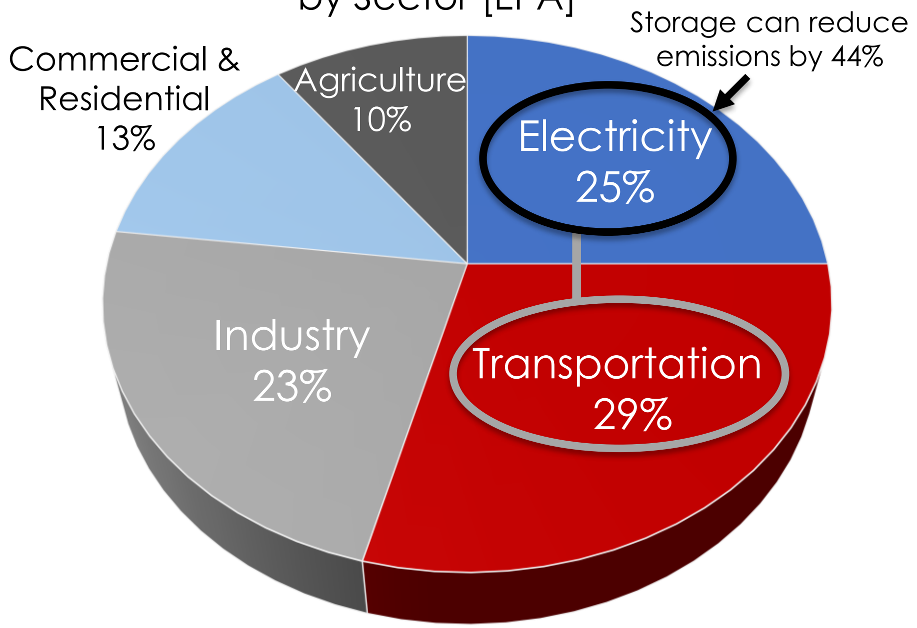
The Problem: Climate Change

- Climate change is the most important problem and an imminent threat to our species' survival
- Cost of renewables has dropped, but penetration onto the grid is limited by the lack of storage



D. Feldman *et al.* NREL/TP-6A20-77324 - https://www.nrel.gov/docs/fy21osti/77324.pdf

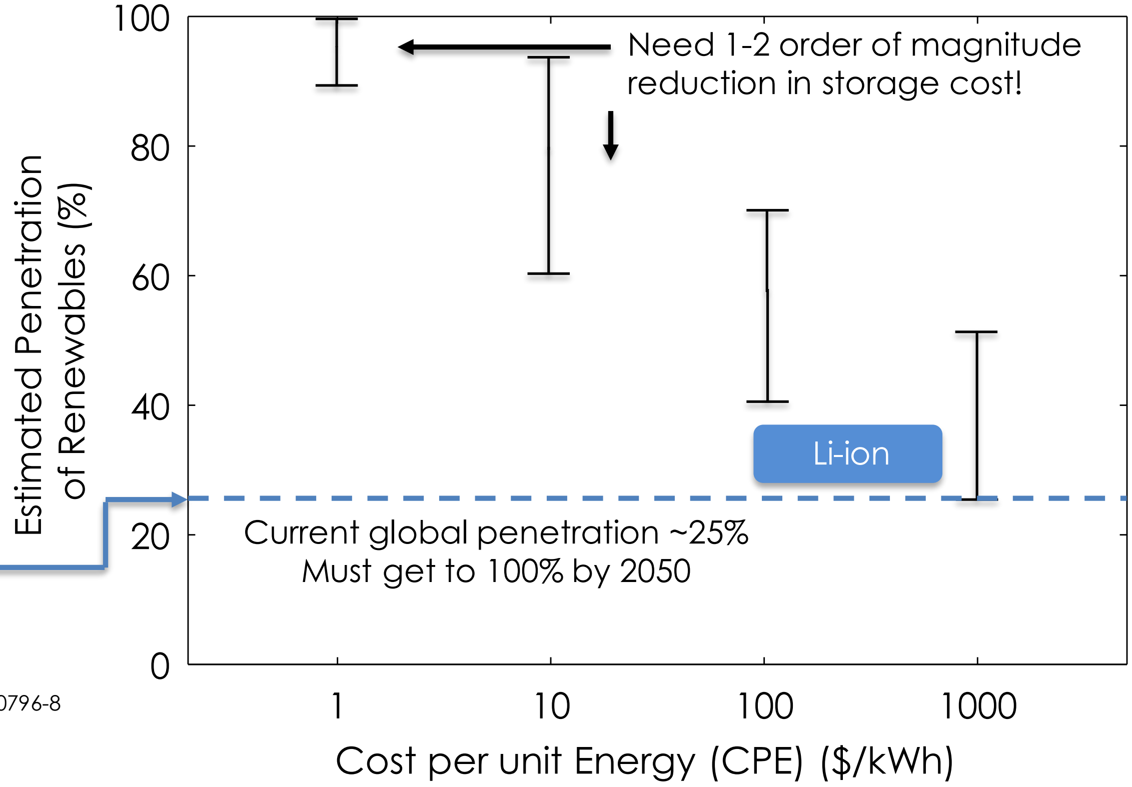
U.S. Greenhouse Gas Emissions by Sector [EPA]



https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Energy Storage is the Key

- The studies listed below all reach the same conclusions
- Renewable penetration onto the grid is limited without storage
- Current penetration (~25%)
- Need order of magnitude cost reductions to achieve a > 80-90% renewable grid
- The current state of the art (Li-ion) will never get there



Estimates based on:

N. Sepulveda et al., Nat. Energy - DOI: https://doi.org/10.1038/s41560-021-00796-8

P. Albertus et al., Joule - DOI: https://doi.org/10.1016/j.joule.2019.11.009

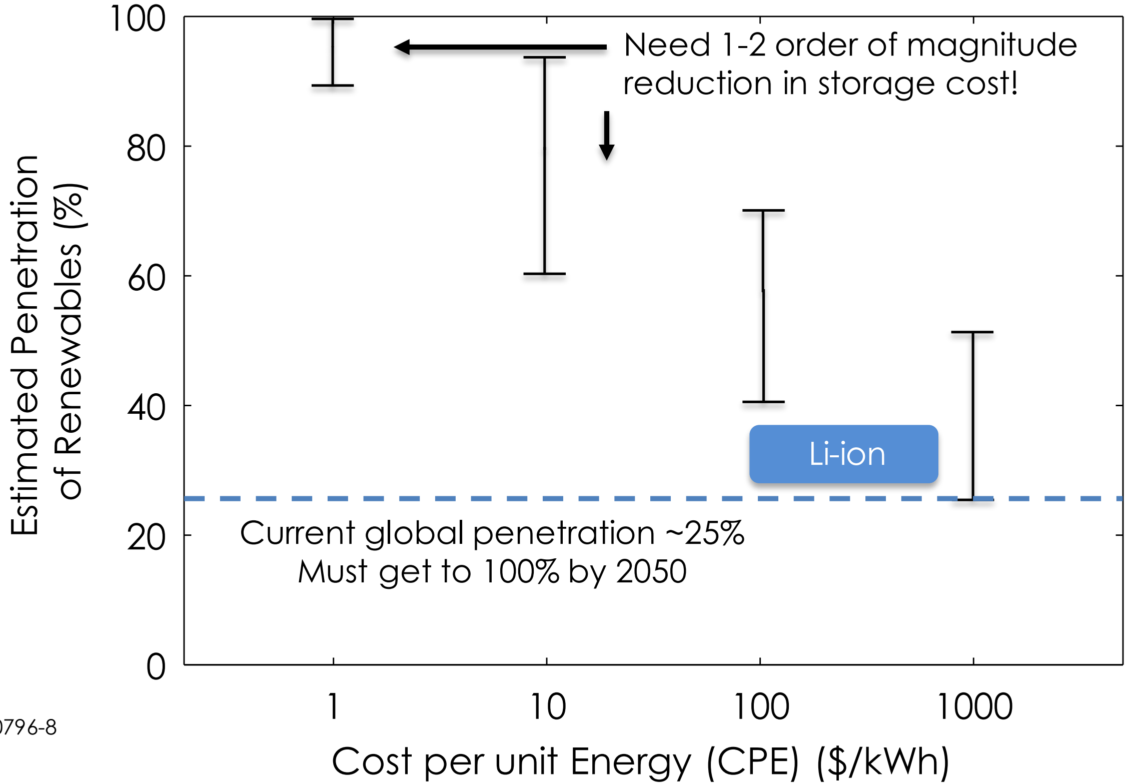
M. Ziegler et al., Joule - DOI: https://doi.org/10.1016/j.joule.2019.06.012

Energy Storage is the Key

- There are 4 important parameters that determine the cost effectiveness of storage:
- Cost per unit energy (CPE)
  - CPE = CAPEX of components that scale with amount of energy stored (e.g., 10 hrs of storage at 100 MW)
- Cost per unit power (CPP)
  - CPP = CAPEX of components that scale with the rate of charging/discharging (e.g., a 100 MW battery)
- Roundtrip efficiency (RTE)
  - RTE = amount of electricity discharged (output) divided by the amount of electricity used to charge (input)
- Lifetime
  - How long the system lasts before needing replacement

Studies below conclude:

1. <u>CPE is most important</u>
2. RTE must be > 35% to make $ from arbitrage
3. **Need CPE < $20/kWh**



Estimates based on:

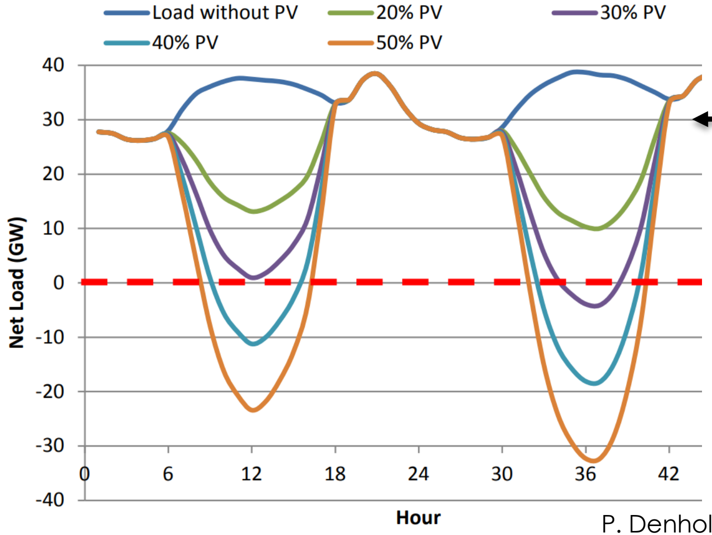
N. Sepulveda et al., Nat. Energy - DOI: https://doi.org/10.1038/s41560-021-00796-8

P. Albertus et al., Joule - DOI: https://doi.org/10.1016/j.joule.2019.11.009

M. Ziegler et al., Joule - DOI: https://doi.org/10.1016/j.joule.2019.06.012

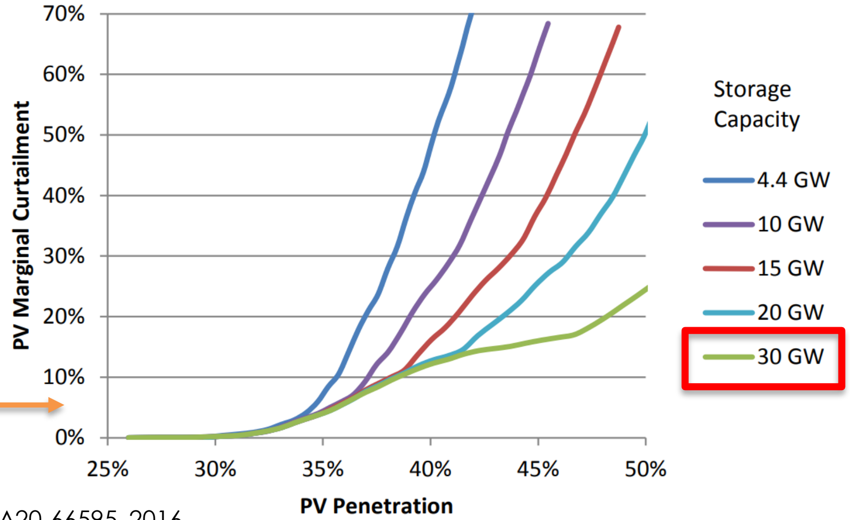
We need lots of storage!

- How much storage do we need?
- Storage needed ≅ generation capacity
- Global electricity production ~ 9TW
- <u>California's load is ~ 30 GW</u>
- <u>> 30 GW of storage is needed</u> to even reach 50% penetration
- We need as much storage as generation for decarbonization



CA Net Load is ~ 30 GW

Storage Needed ~ 30 GW



P. Denholm, R. Margolis, NREL/TP-6A20-66595, 2016

Current state of the art

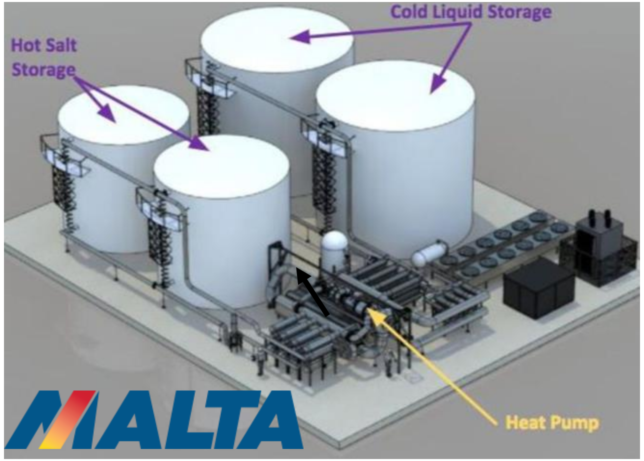
Li-ion Batteries
[$150-350/kWh]

Too expensive
Target < $20/kWh

Pumped Hydro
[$50-100/kWh]

Too expensive &
Geographically limited

Pumped Heat Storage
[$35-50/kWh]
Under development



Not cheap enough
Slow ramp

Current state of the art

Any technology that relies on a turbine will have a response time on the order of minutes to 1 hr

When the sun goes down, fossil turbines have to turn on quickly to compensate for solar turning off

To achieve high penetration and stabilize the grid we need storage that can respond in seconds

<u>Thermal batteries can respond in seconds!</u>