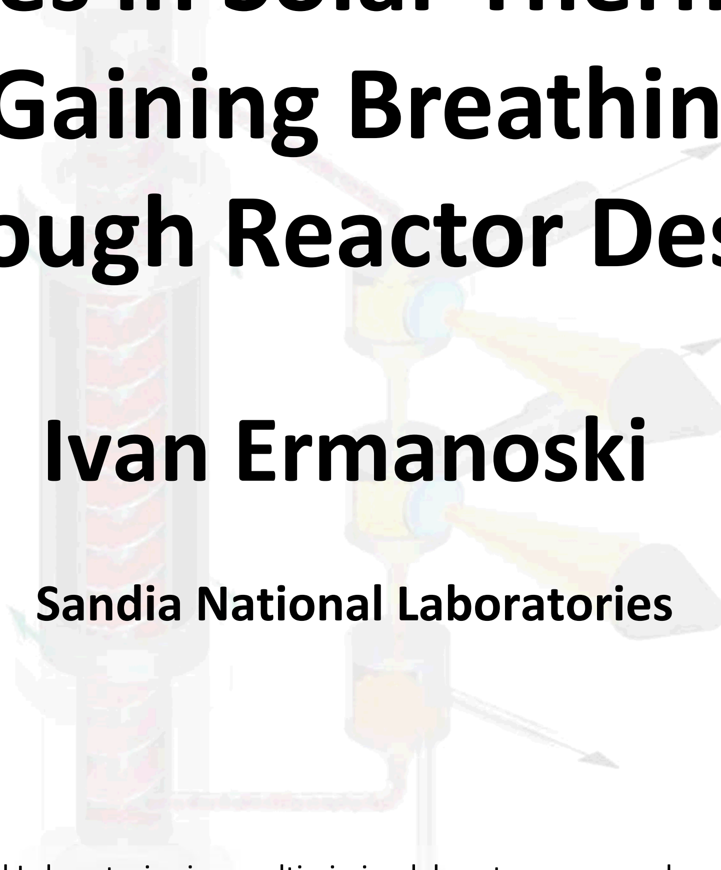
SAND2017-6302C

Metal Oxides in Solar Thermochemical Cycles: Gaining Breathing Room Through Reactor Design



Ivan Ermanoski

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Bucknell University

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Outline

- Materials role and requirements in two-step cycles
- Key efficiency drivers
- Achieving low thermal reduction pressure
- Electrically forcing reduction and water splitting
- Increasing temperature
- Fantasy materials

- **Materials role and requirements in two-step cycles**
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- **Fantasy materials**

Two-Step Thermochemical Fuel Production

A theoretically simple process

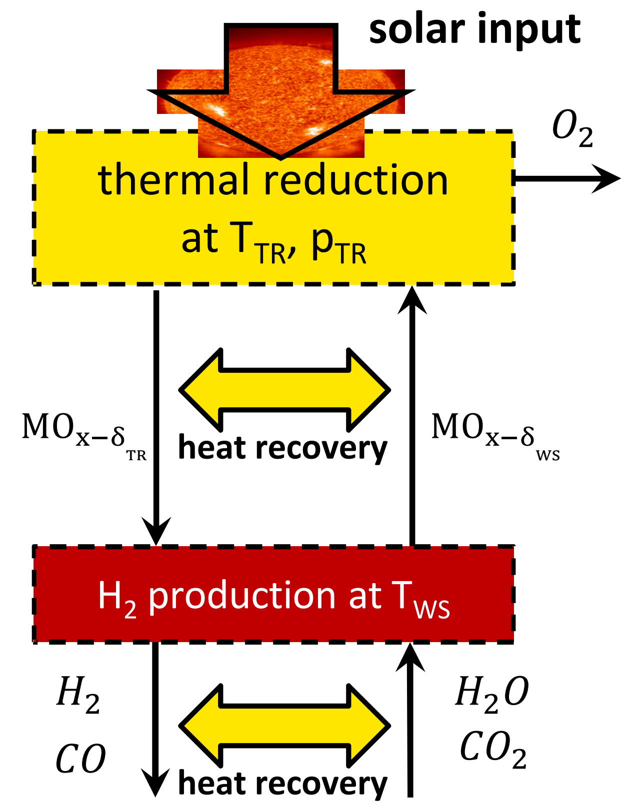
Thermal reduction

$$\frac{1}{\delta_{TR} - \delta_{WS}} MO_{x-\delta_{WS}} \rightarrow \frac{1}{\delta_{TR} - \delta_{WS}} MO_{x-\delta_{TR}} + \frac{1}{2} O_2$$

Water/CO_2 splitting

$$\frac{1}{\delta_{TR} - \delta_{WS}} MO_{x-\delta_{TR}} + H_2O \rightarrow \frac{1}{\delta_{TR} - \delta_{WS}} MO_{x-\delta_{WS}} + H_2$$

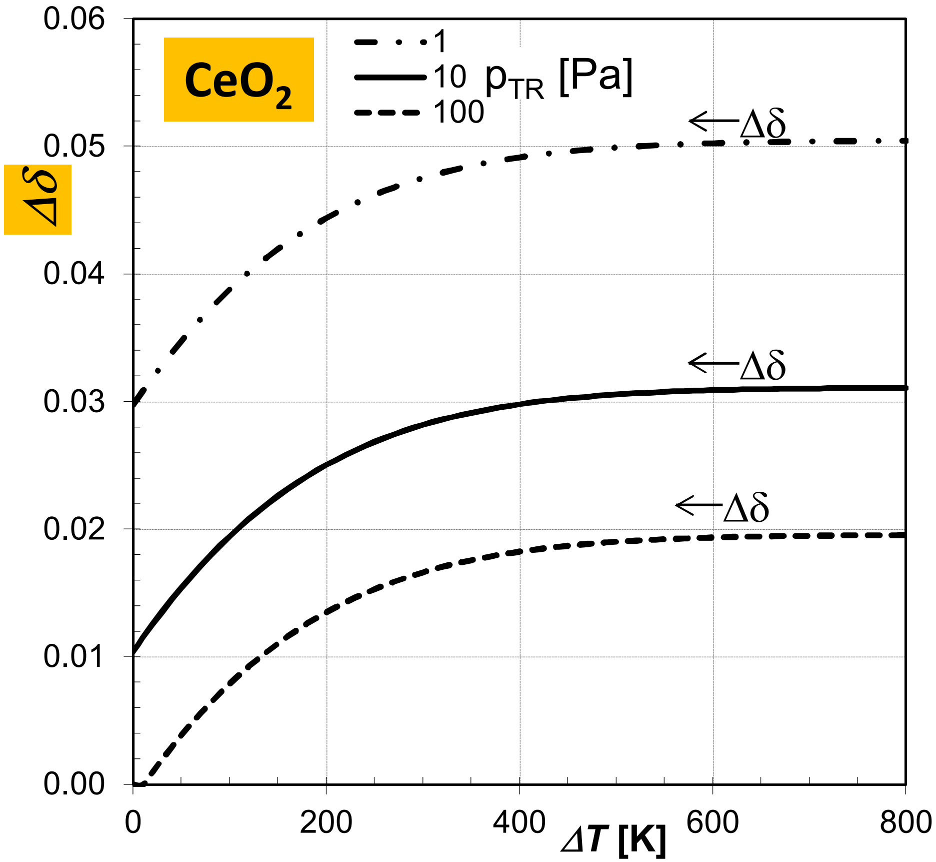
$$\frac{1}{\delta_{TR} - \delta_{WS}} MO_{x-\delta_{TR}} + CO_2 \rightarrow \frac{1}{\delta_{TR} - \delta_{WS}} MO_{x-\delta_{WS}} + CO$$

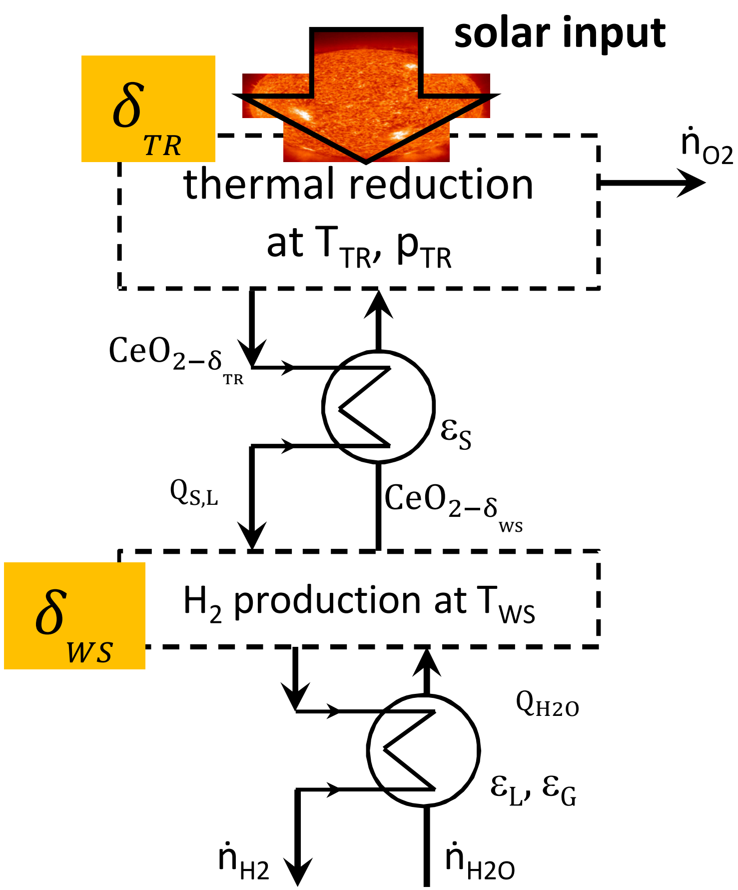


Key Material Requirements: Reactive Oxide

How much CeO_2 per mole H_2?

$\delta_{TR} - \delta_{WS} = \Delta\delta$ T_{TR}=1773K





The reversible oxygen capacity can be very low!

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Key Material Requirements: Reactive Oxide

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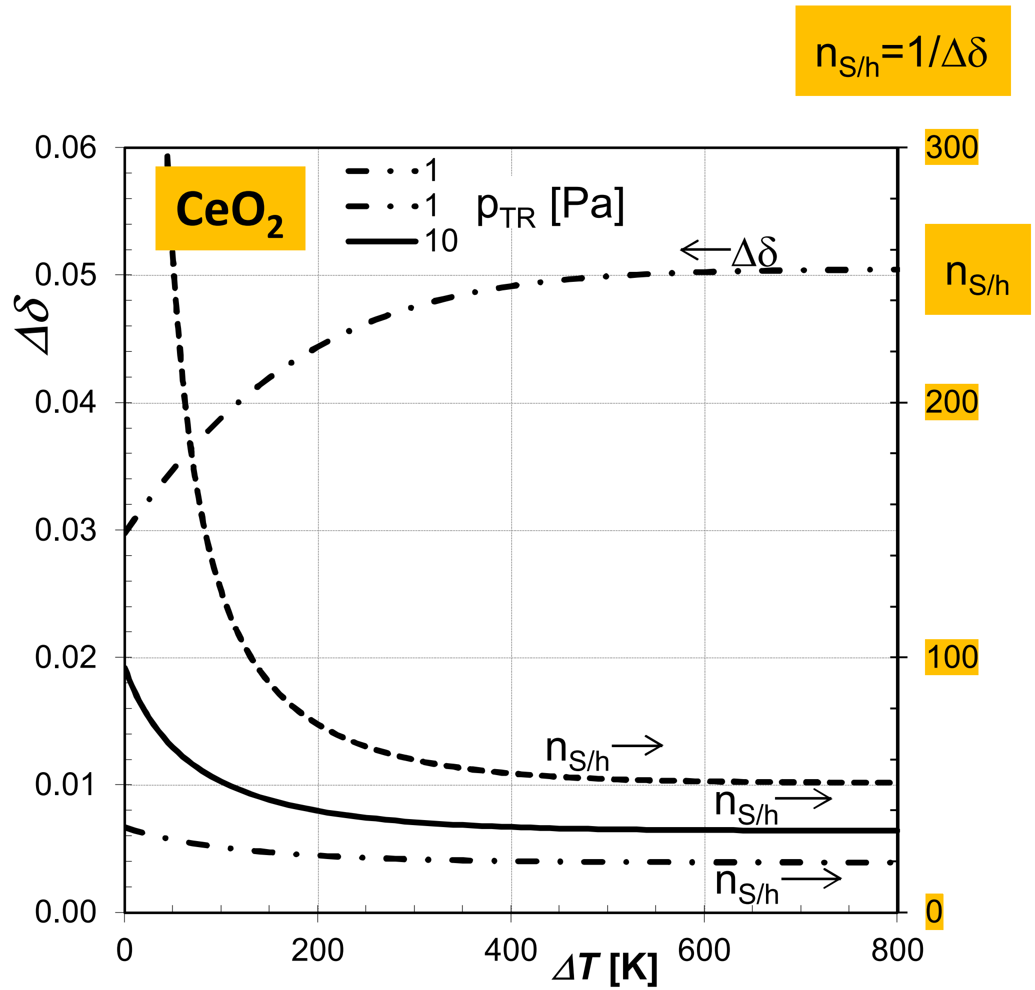
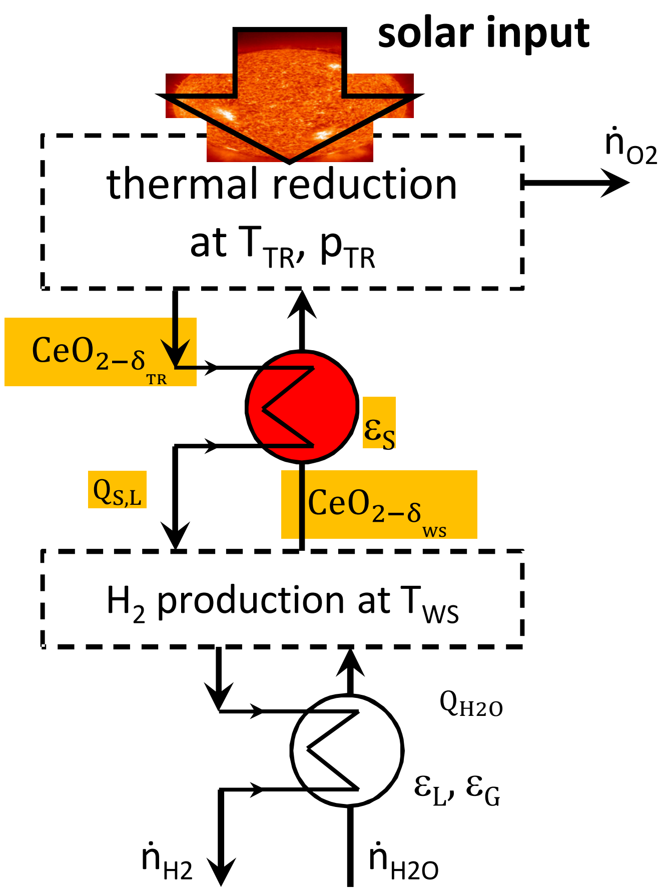
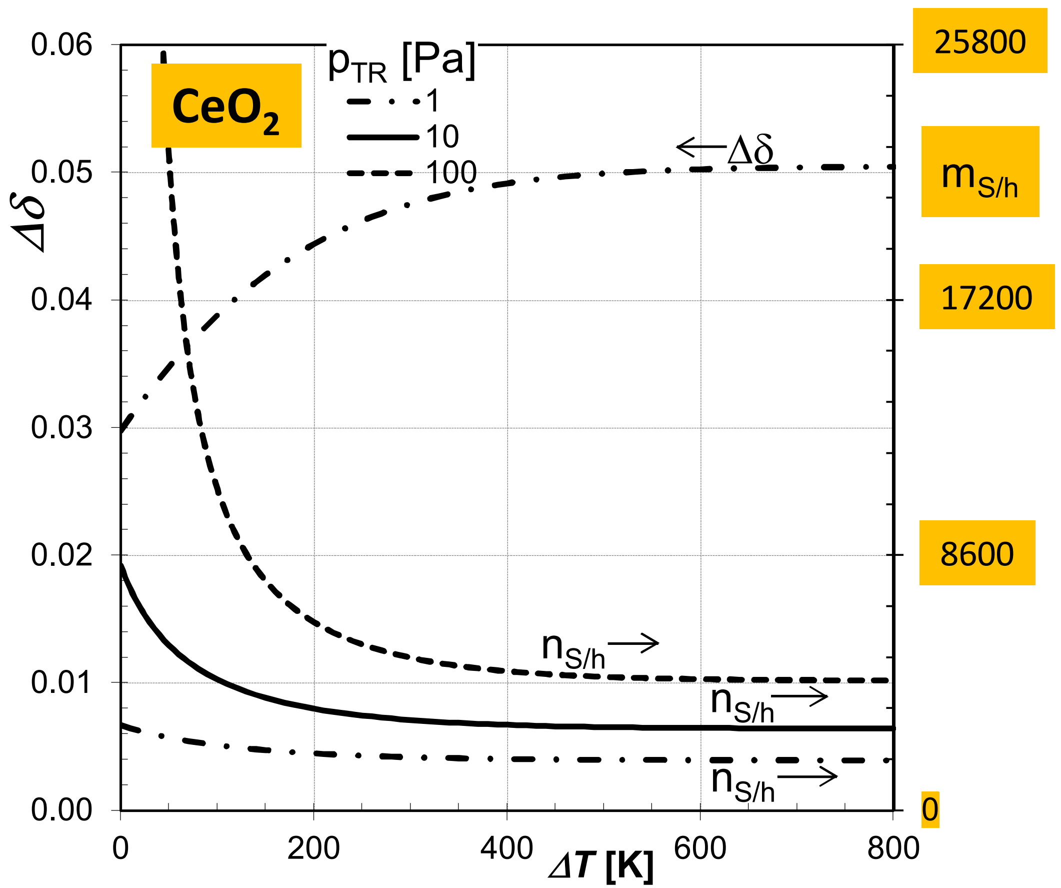


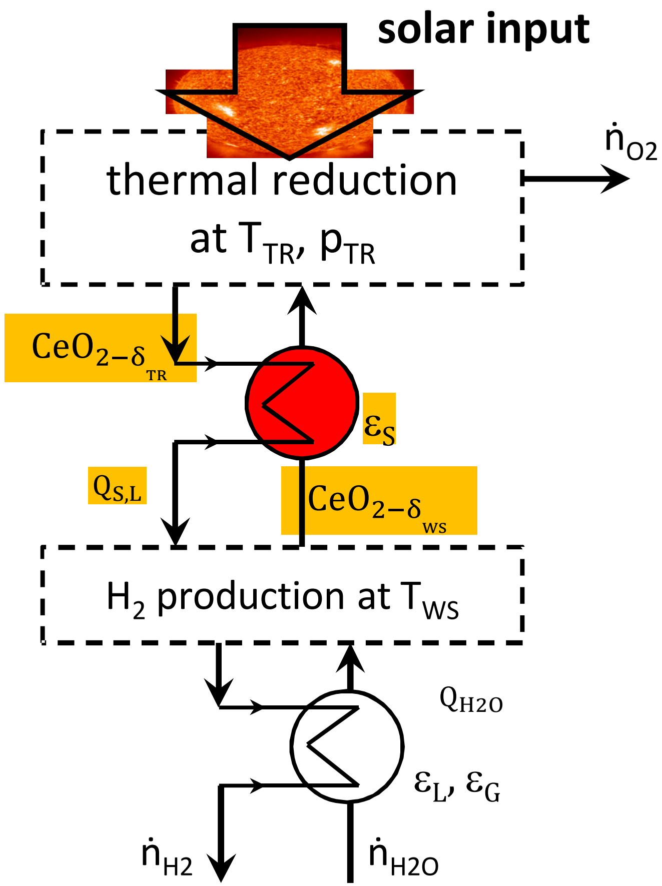


A low reversible oxygen capacity leads to a very high oxide/H_2 ratio and excessive oxide mass flow and heat recovery requirements

Key Material Requirements: Reactive Oxide

How much CeO_2 per mole H_2?

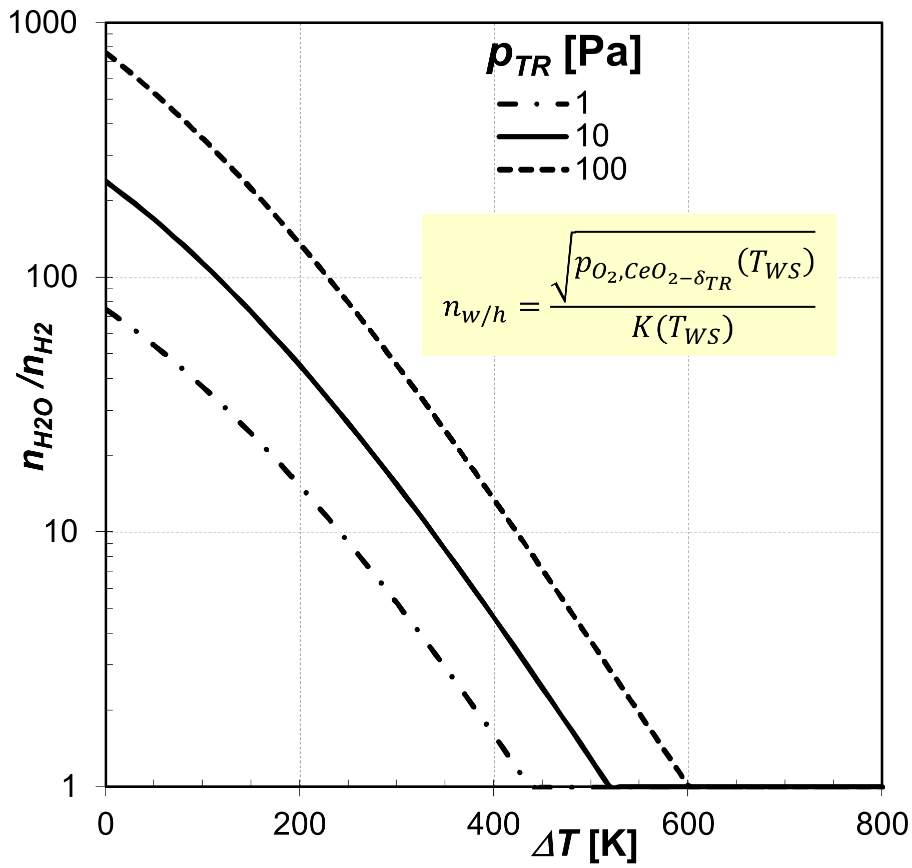


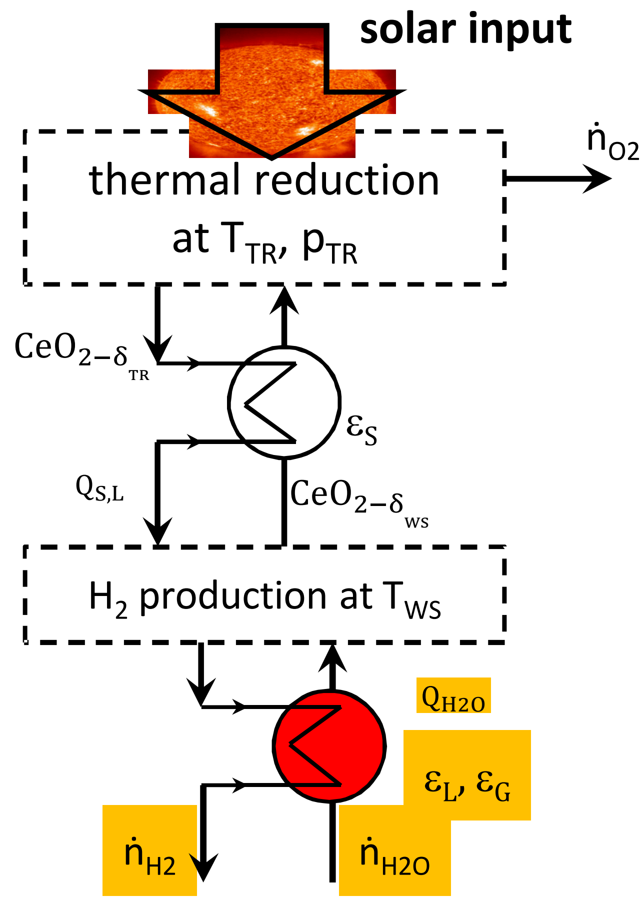


A low reversible oxygen capacity leads to a very high oxide/H_2 ratio and excessive oxide mass flow and heat recovery requirements

Key Material Requirements: Steam

How much steam per mole H_2?





Low ΔT or high reduction pressure leads to a high steam/H_2 ratio

- **Materials role and requirements in two-step cycles**
- **Key efficiency drivers**
- **Achieving low thermal reduction pressure**
- **Electrically forcing reduction and water splitting**
- **Increasing temperature**
- **Fantasy materials**

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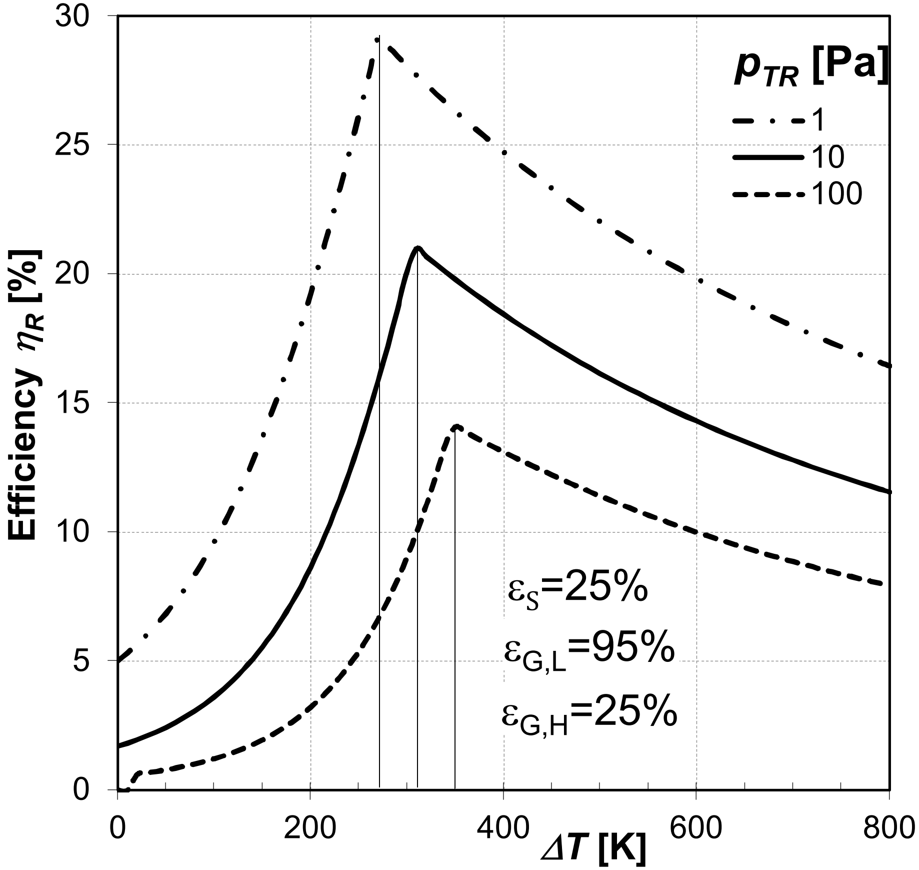
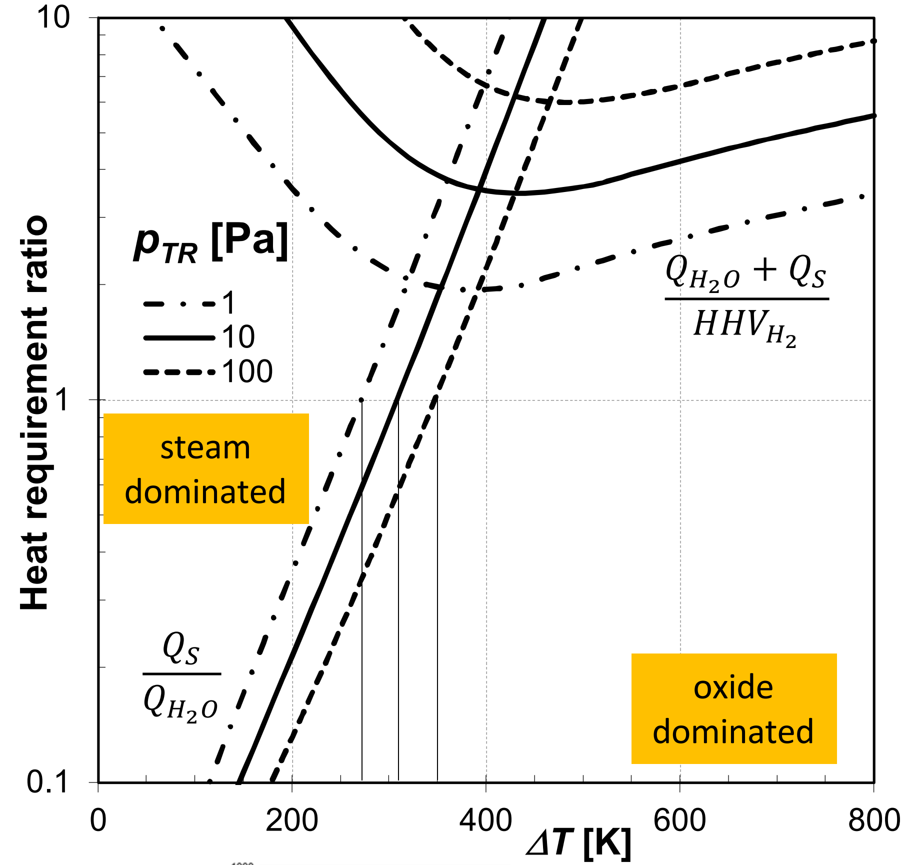
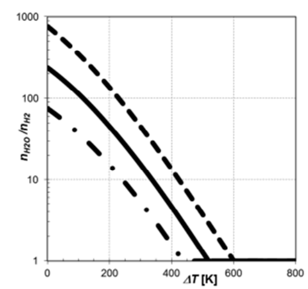
Maximizing Efficiency: Solid/Steam Heating Balance and a Low Reduction Pressure

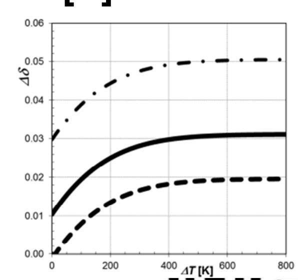




Efficiency is the highest when:

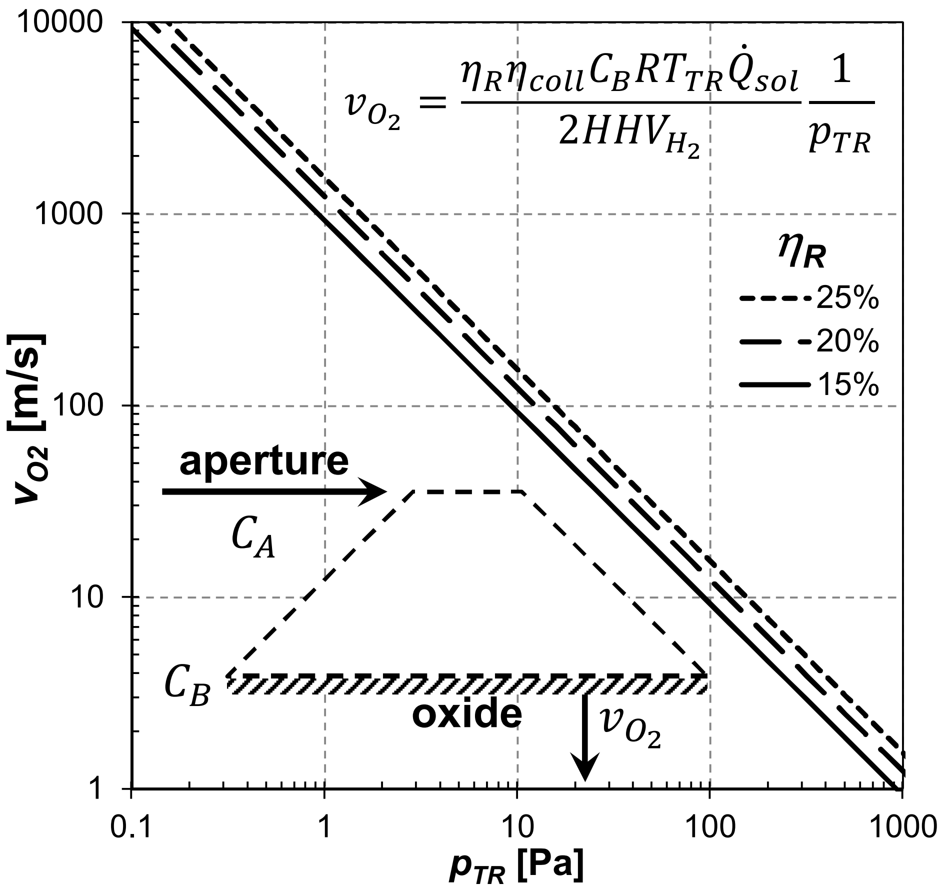
- Oxide and steam heating loads are roughly equal
- Thermal reduction pressure is low

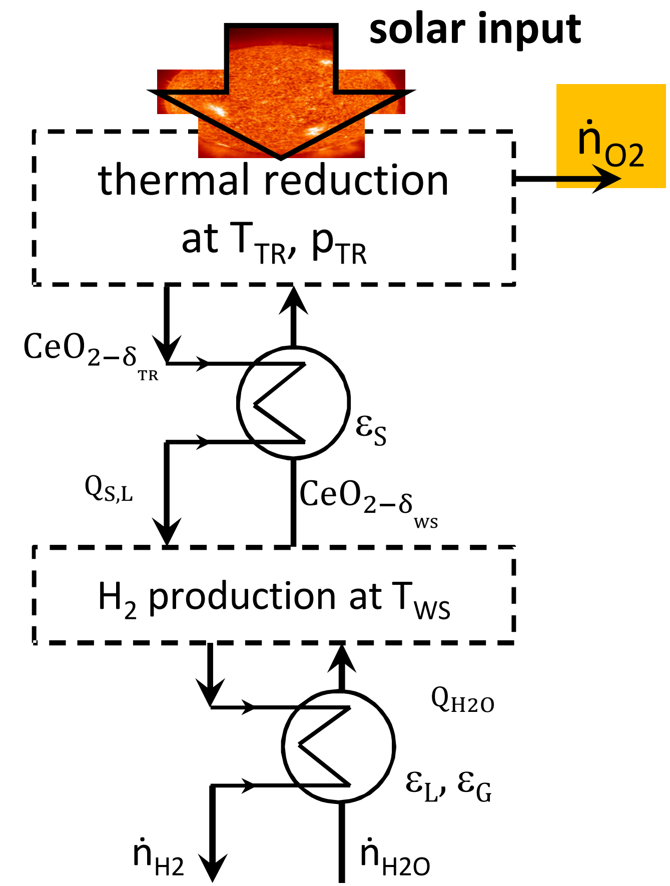




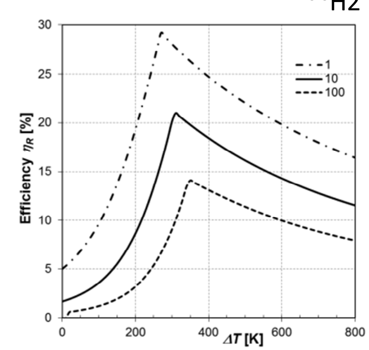
O_2 Pressure Limits: Flow Volume and Speed

Is 1Pa accessible?





At low pressure required flow volumes and velocities are astronomical!



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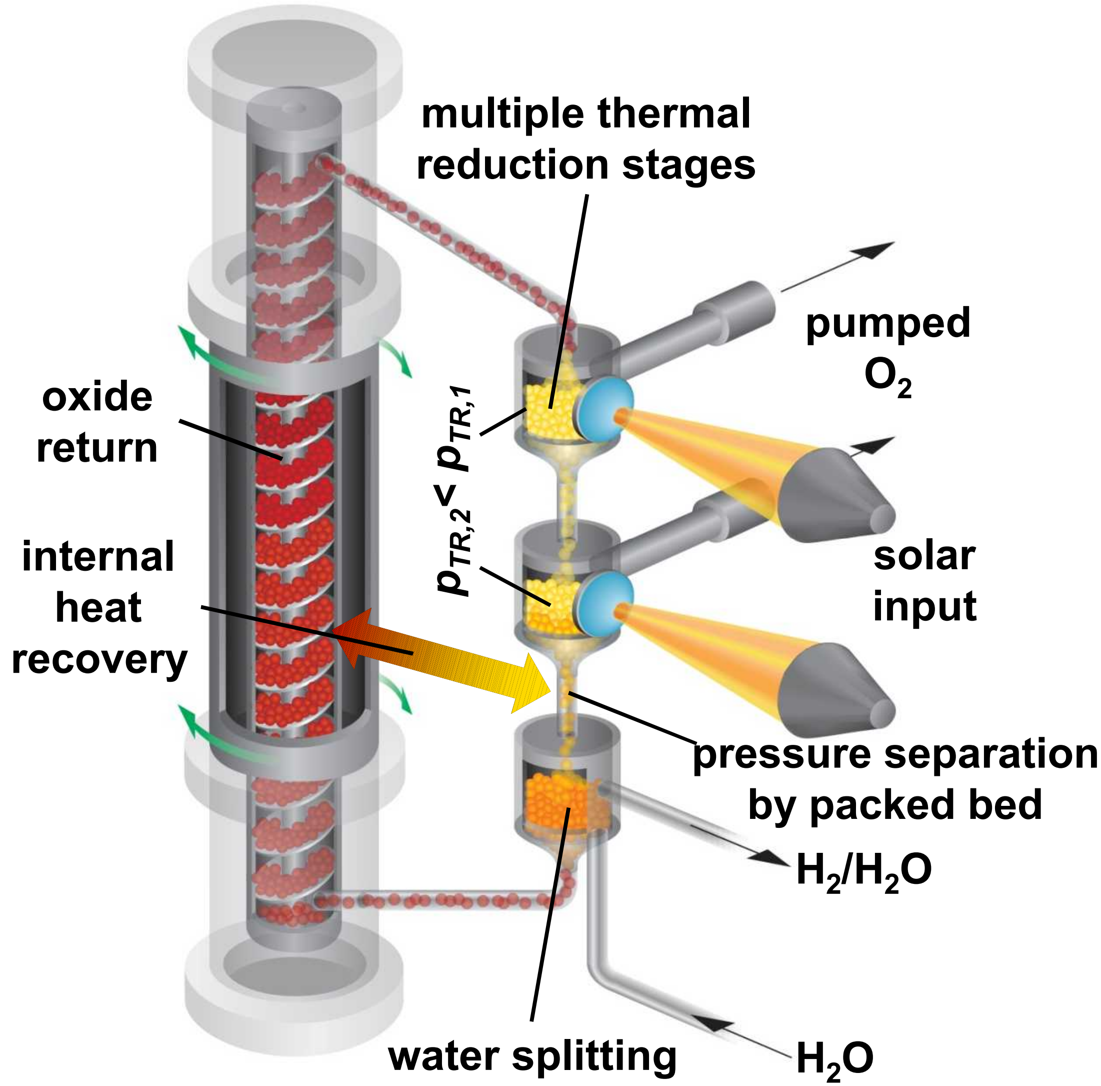
Staged Reduction Reactor for Low Pressure



Incrementally pumping O_2 reduces the overall flow volume and velocity

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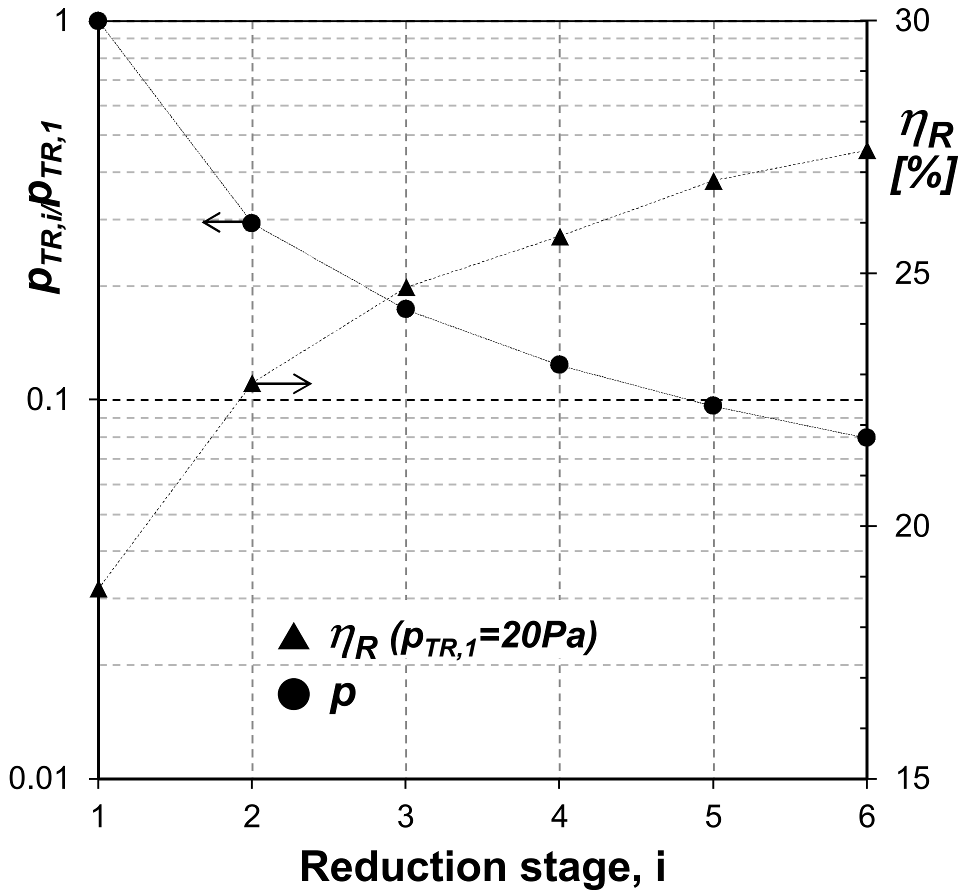
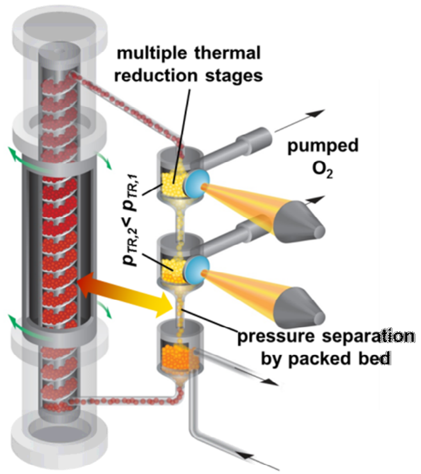
Staged Reduction for Low Pressure





$$p_{TR,i} = \dot{n}_{ox} R T_{TR} \frac{\delta_{TR,i} - \delta_{TR,i-1}}{2\dot{V}_{O_2}}$$

Efficiency is the highest when:

- **10x pressure decrease possible with as few as 5 chambers**
- **Decreased pump work and size**

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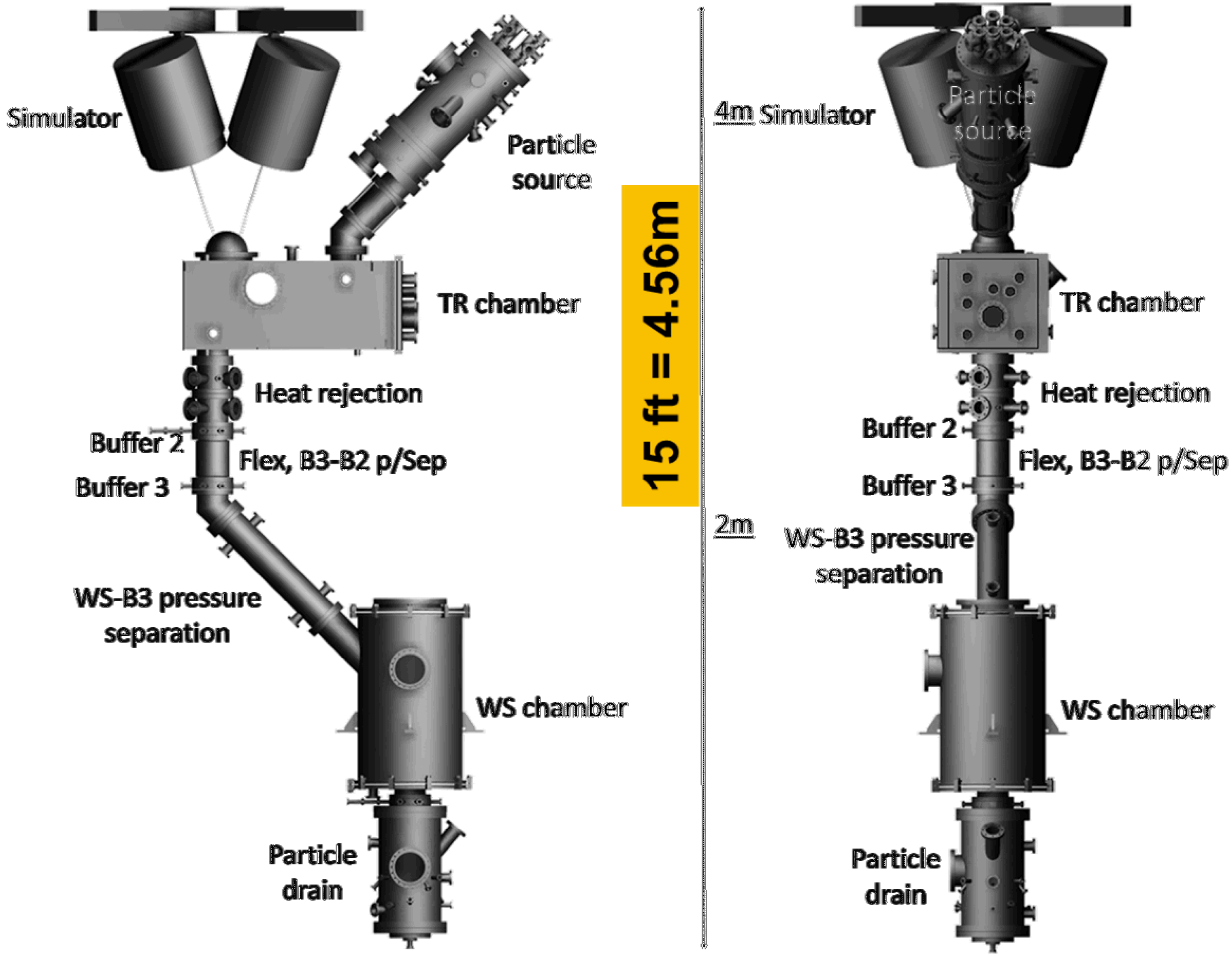
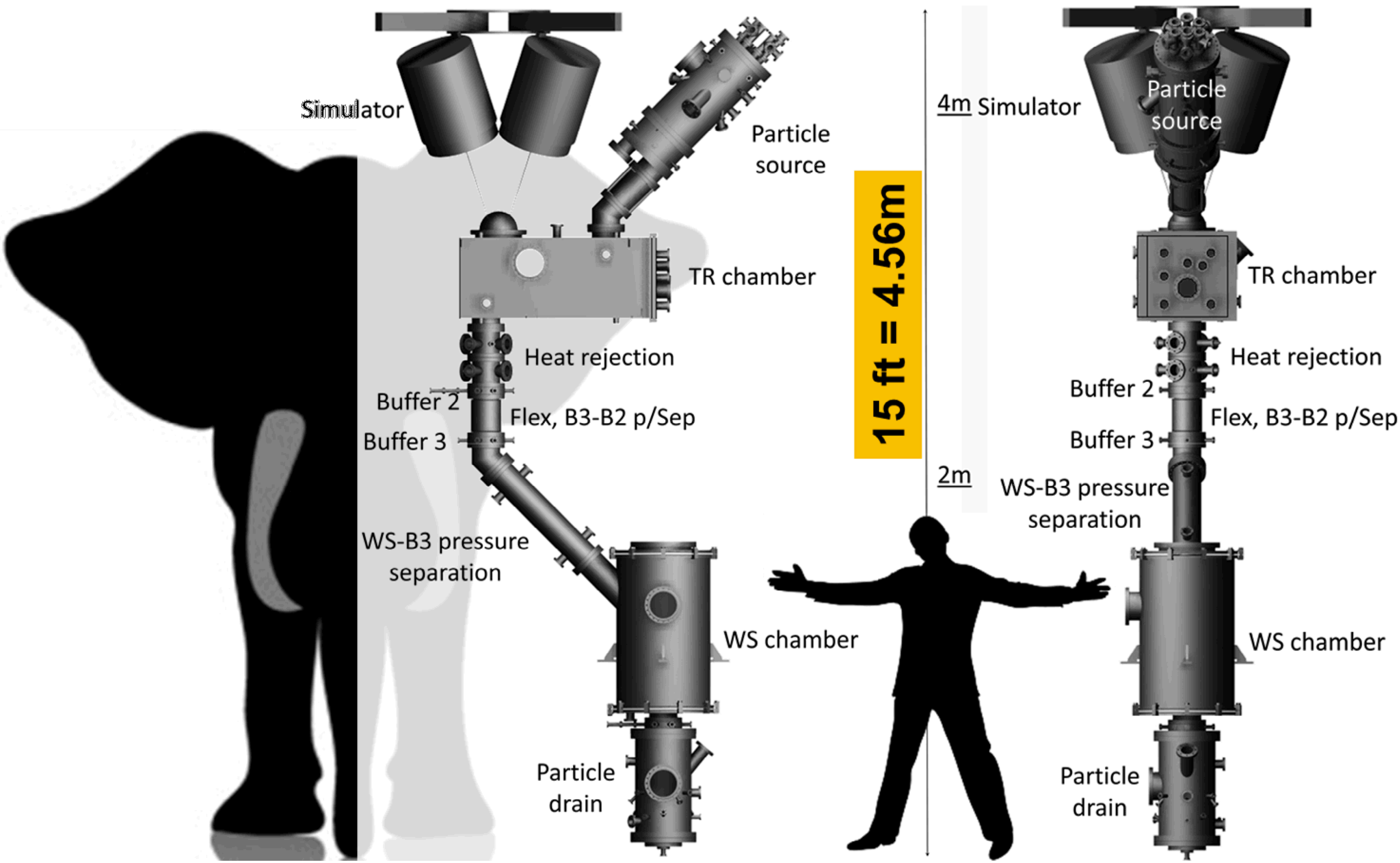
Vacuum and Staged Reduction in Practice



Vacuum and Staged Reduction in Practice



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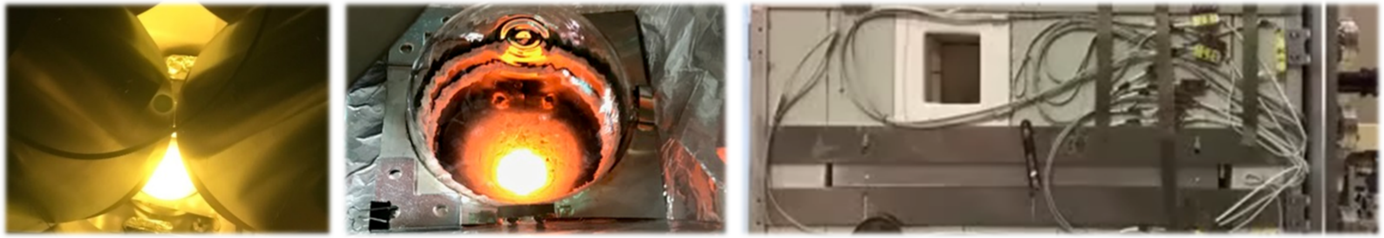
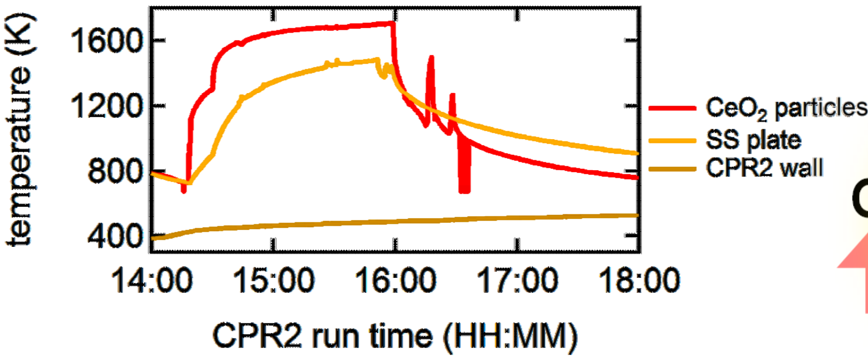
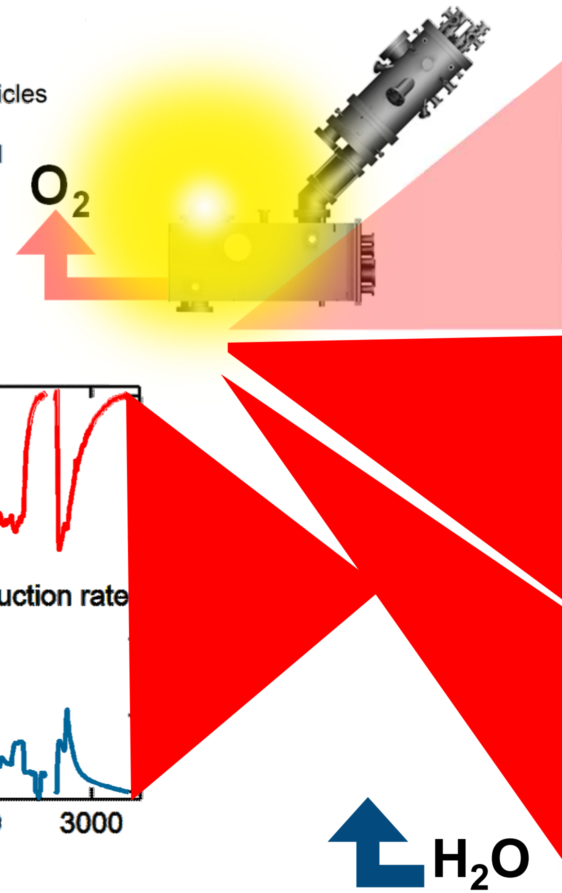
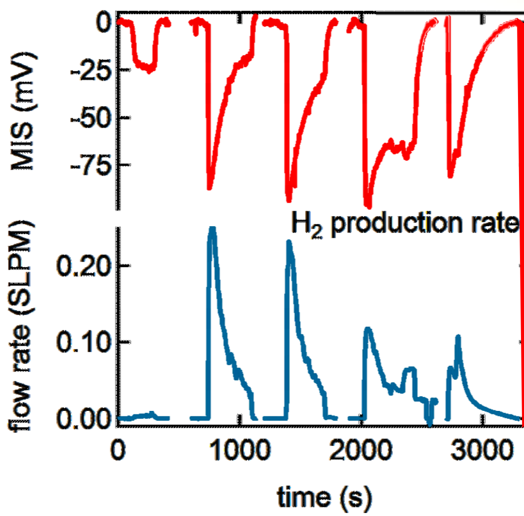
Vacuum and Staged Reduction in Practice









T_R~1700 K

0.25 SLPM peak H_2 rate

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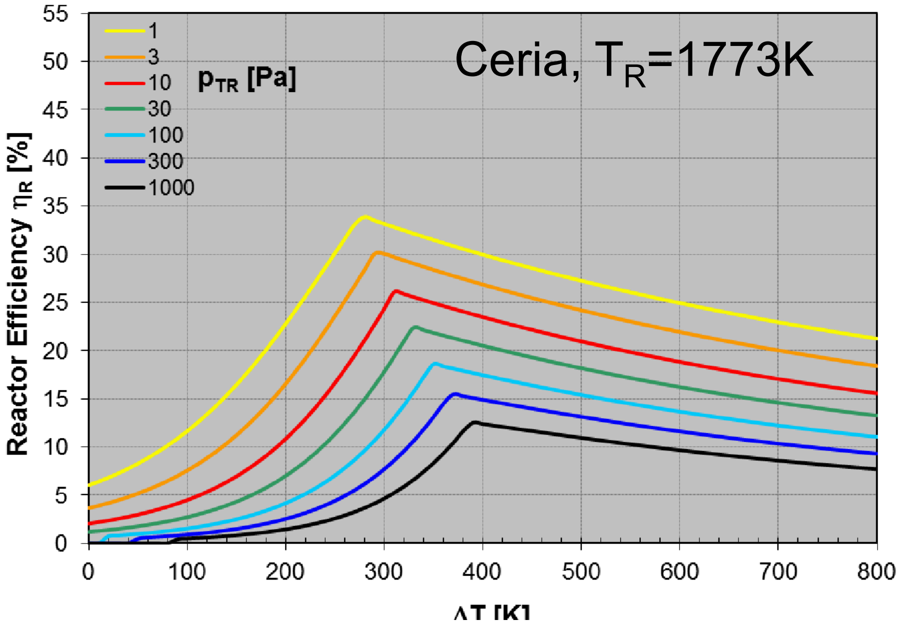
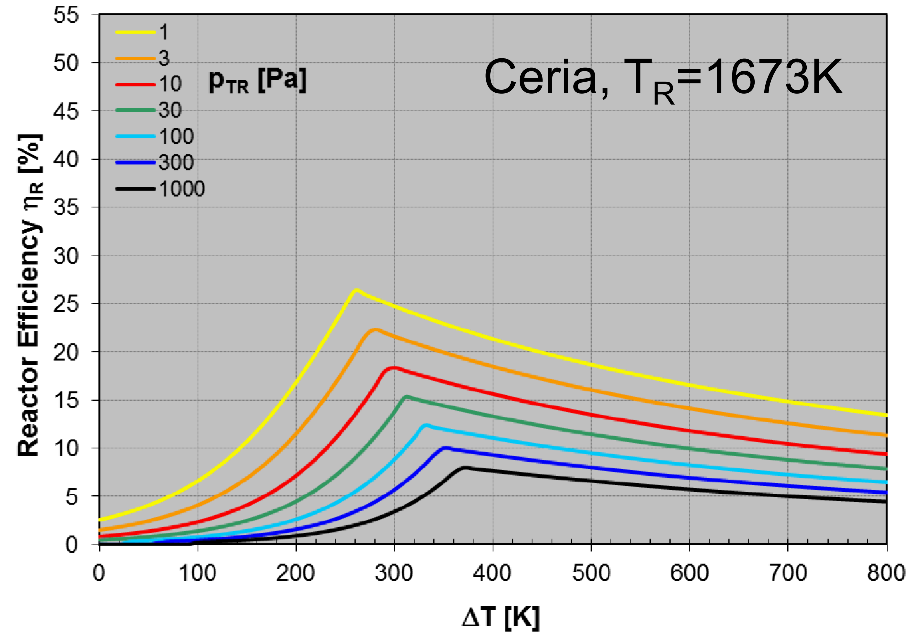
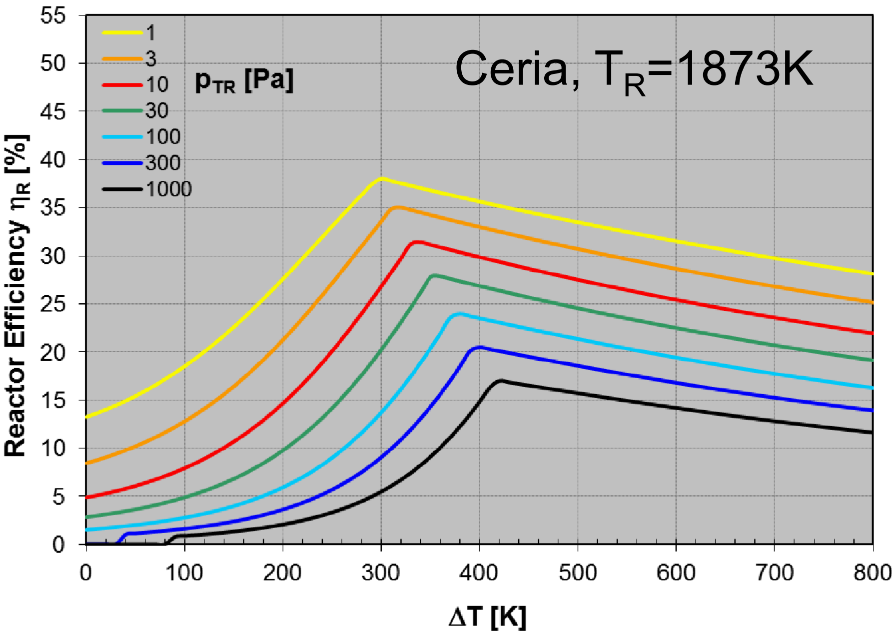
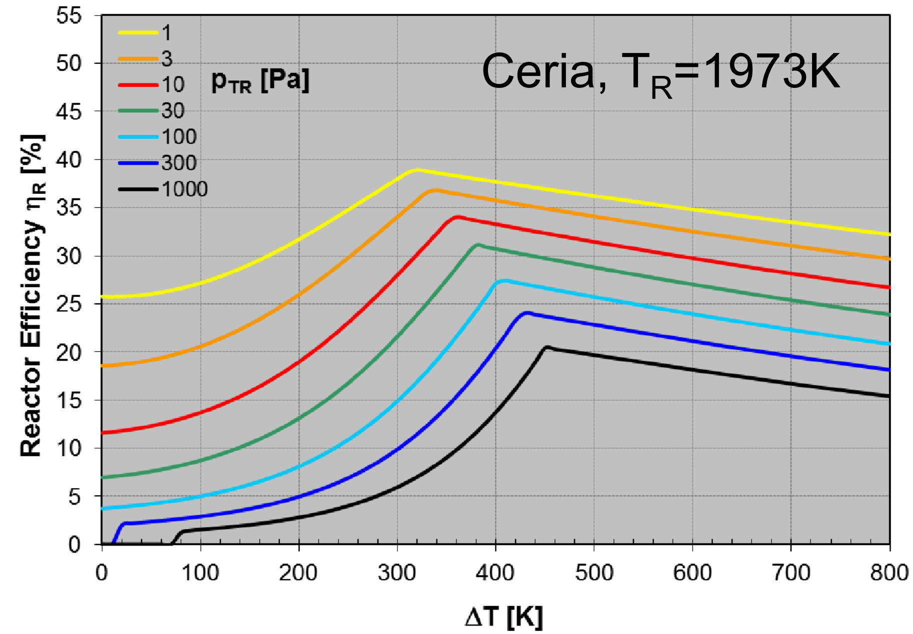
Playing With Reduction Temperature









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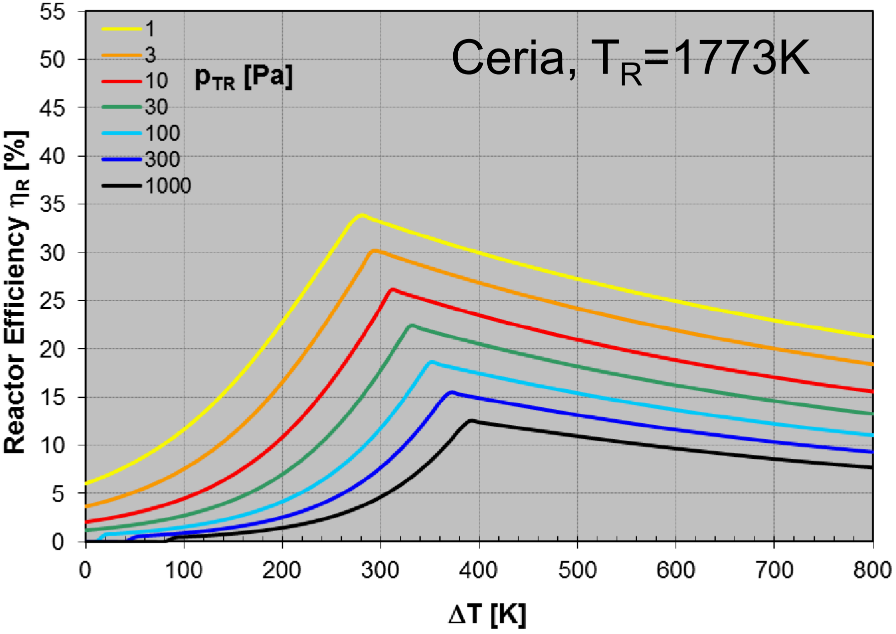
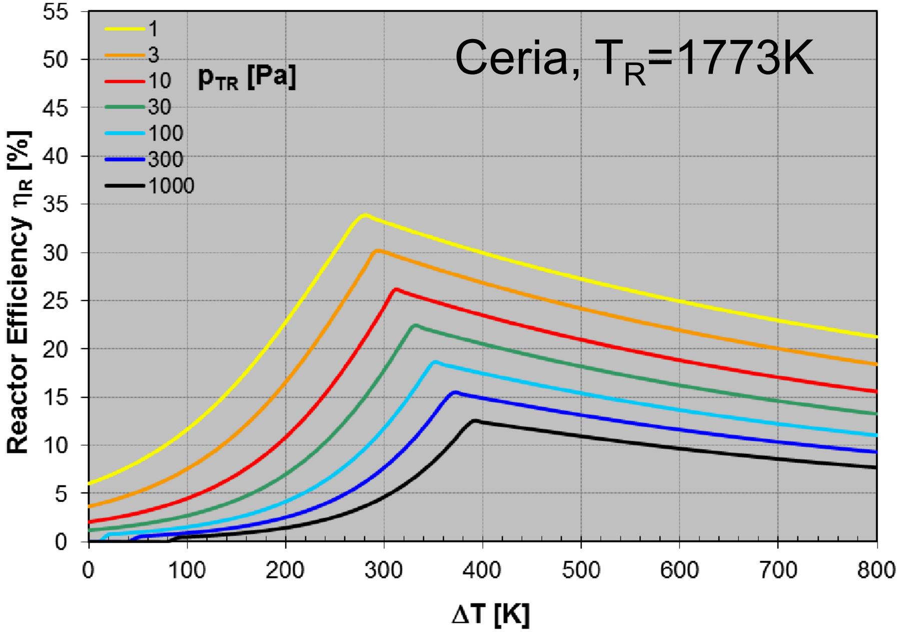
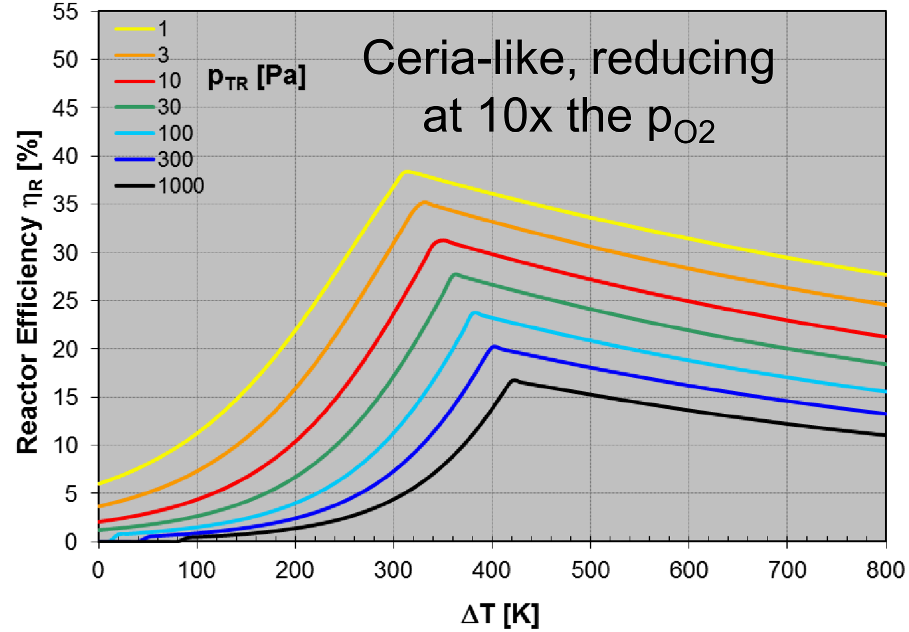
Playing With Materials Properties

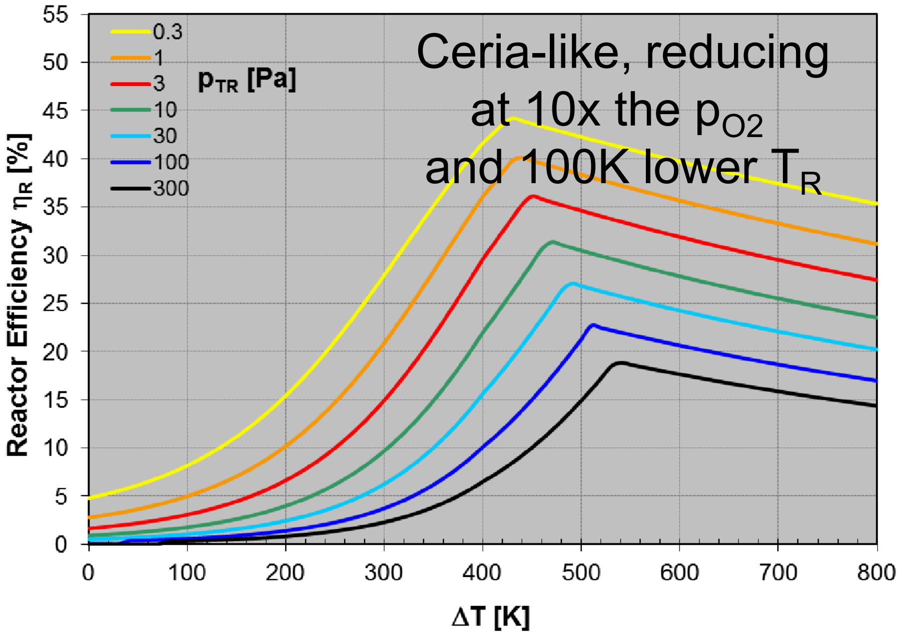


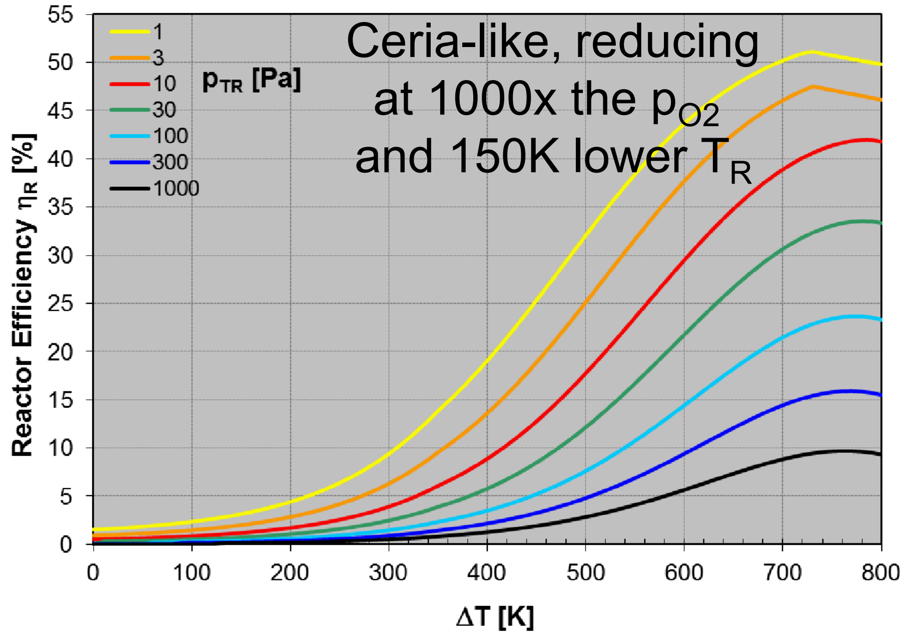
Family of efficiency curves for a CeO_2 reactor.

Playing With Materials Properties

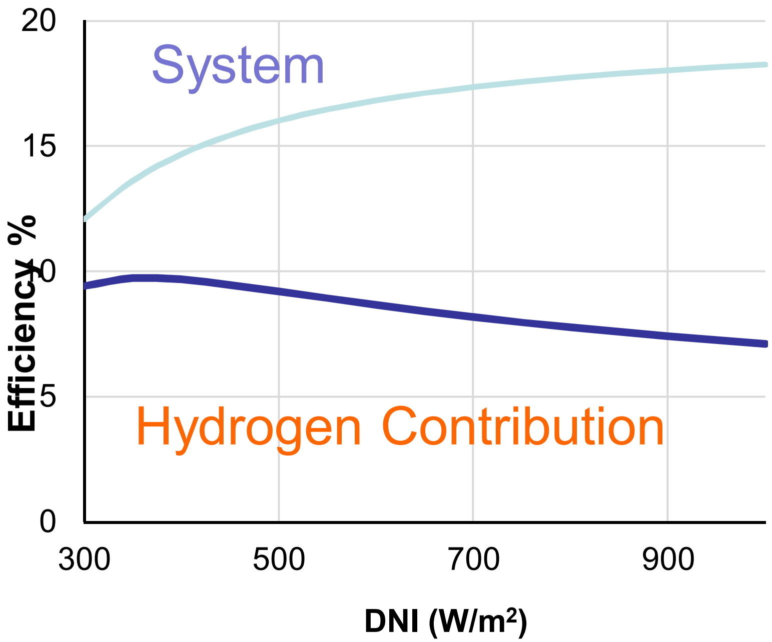


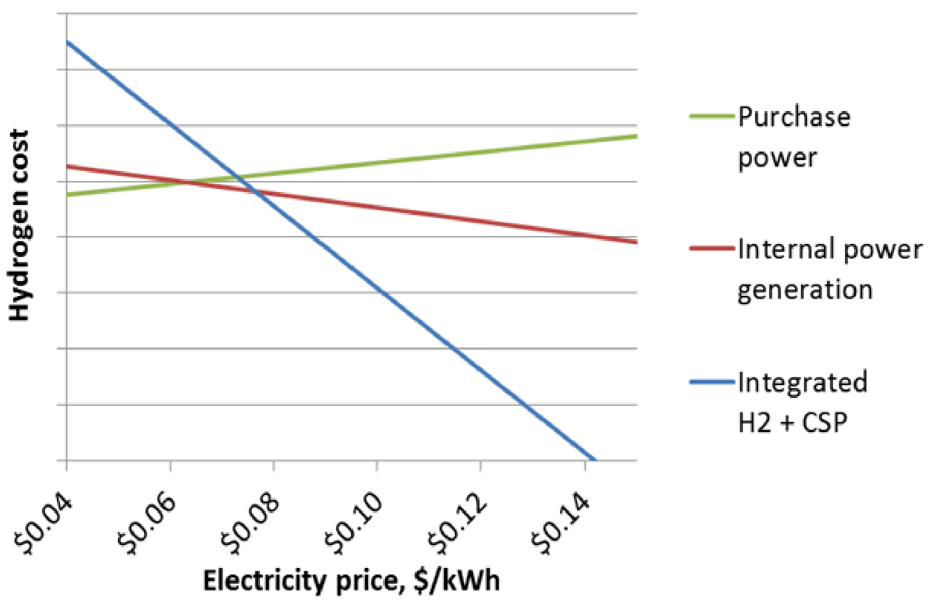






Cogeneration

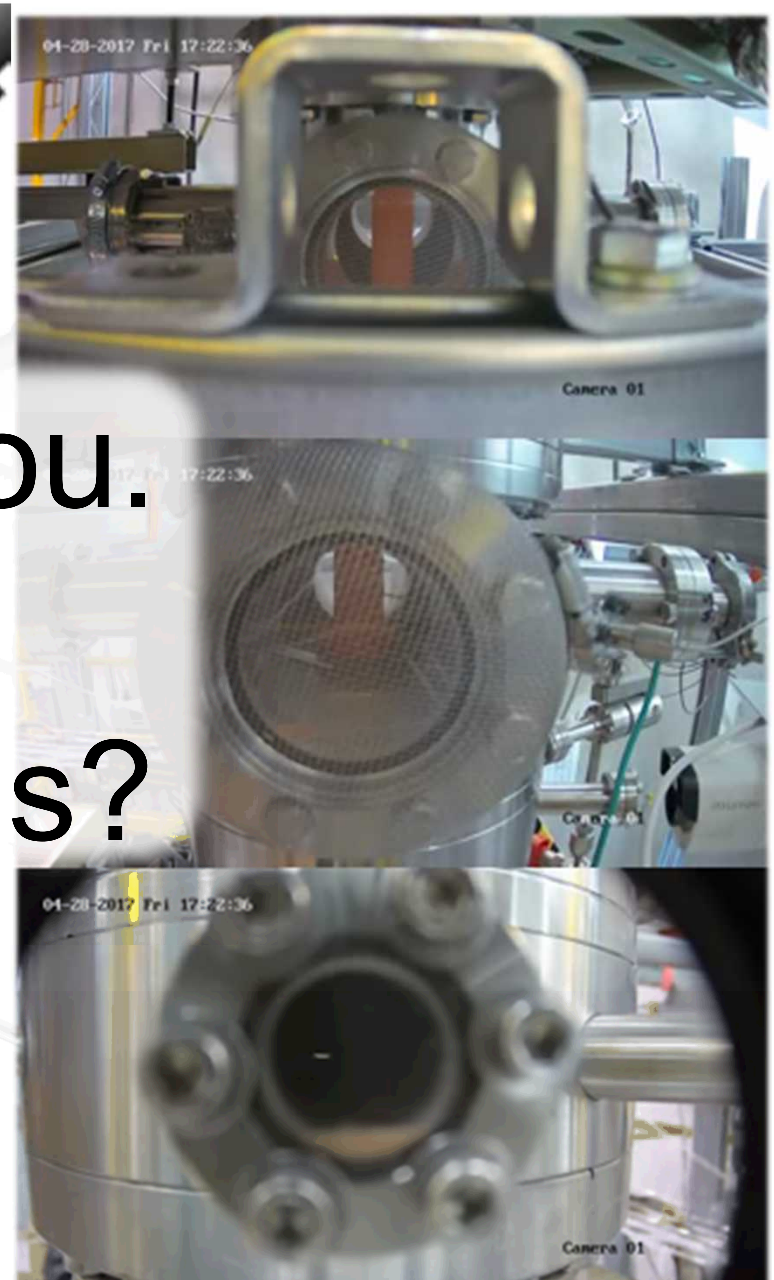




- Electricity production from waste heat can offset H_2 cost.
  - Ratio of H_2:Electricity dependent on DNI
  - System efficiency is more complex
  - Impact of high-temperature waste heat amplified by integration with CSP

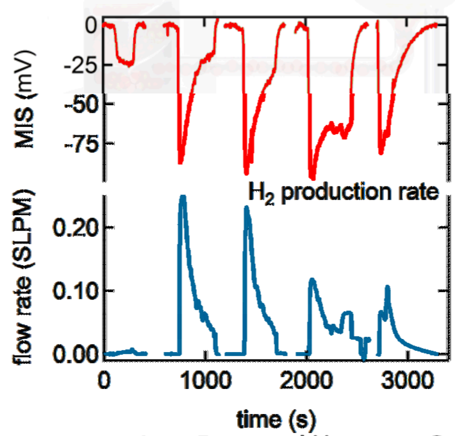
Summary/Interesting questions

- **Materials with low $\Delta\delta$ pose a mass flow challenge**
- **Optimal ΔT can be found to maximize efficiency**
- **Thermal reduction pressure limited by O_2 flow**
- **A >10x pressure decrease feasible in staged reduction**
- **Best results by combining ΔT_{opt}, staged pumping and advanced reactive oxides**
- **Future advances in receiver technology for higher T_R?**
- **Advanced materials?**
- **Cogeneration?**



Thank You.

Questions?



Ivan Ermanoski iermano@sandia.gov