SAND2017-3823PE

Sandia National Laboratories

High-Temperature Particle Receivers and Reactors for Concentrating Solar Power and Thermochemical Fuel Production

International Particle Technology Working Group Workshop
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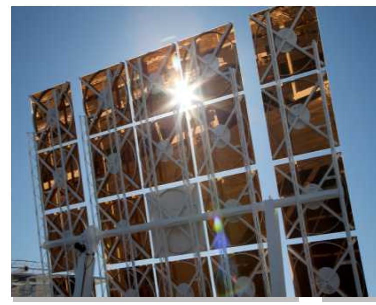

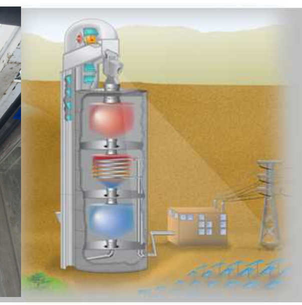


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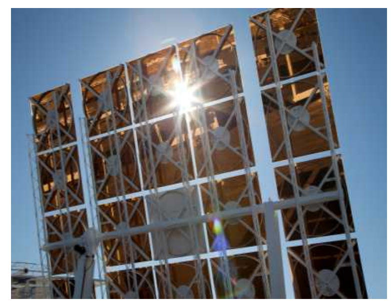
Overview

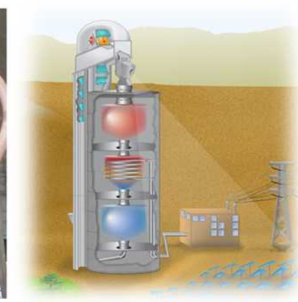
- High-Temperature Falling Particle Receivers for CSP
- Packed Particle Bed Reactor for Solar Thermochemical H2 Production

High-Temperature Falling Particle Receiver for Concentrating Solar Power

Contributors:

- Sandia National Laboratories
- Georgia Institute of Technology
- Bucknell University
- King Saud University
- German Aerospace Center (DLR)





Clifford K. Ho, Principal Investigator

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Concentrating Solar Technologies Dept.

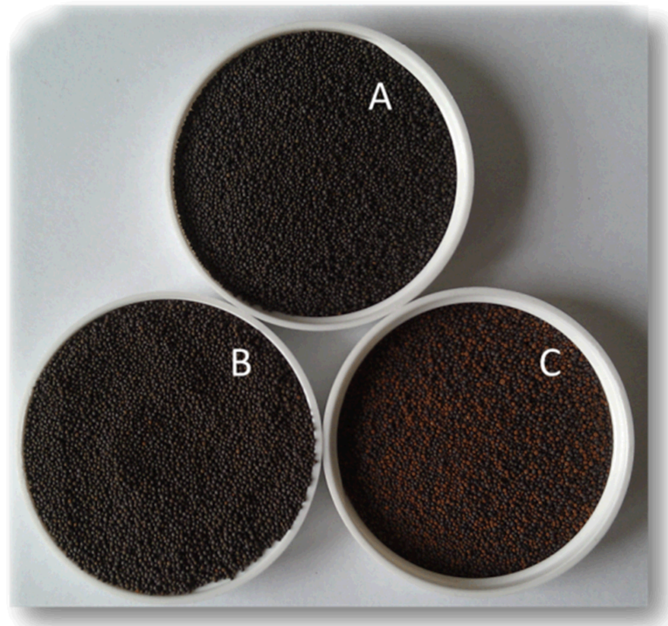
SAND2016-5660 PE

Advantages of Particle Receivers

SolarPACES

- Direct heating and storage of particles
  - Higher temperatures than conventional molten salts
    - Enables more efficient power cycles
  - Higher solar fluxes for increased receiver efficiency
- No freezing or decomposition
  - Reduced costs

⇨ particle Power



CARBO ceramic particles (“proppants”)

History

Particle Receiver Research at Sandia

- 1980's
  - Feasibility study, modeling, bench-scale testing
- 2007 – 2008
  - First on-sun particle receiver test at Sandia
    - Batch run – no continuous operation
    - "Low" temperatures (up to ~300 ˚C)
    - Low thermal efficiency (~50%)
- Goal of current work (2013 – present)
  - Higher temperature (> 700 ˚C particle outlet)
  - Higher thermal efficiency (> 90%)
  - Provide heat and storage for solarized supercritical CO_2 Brayton cycle

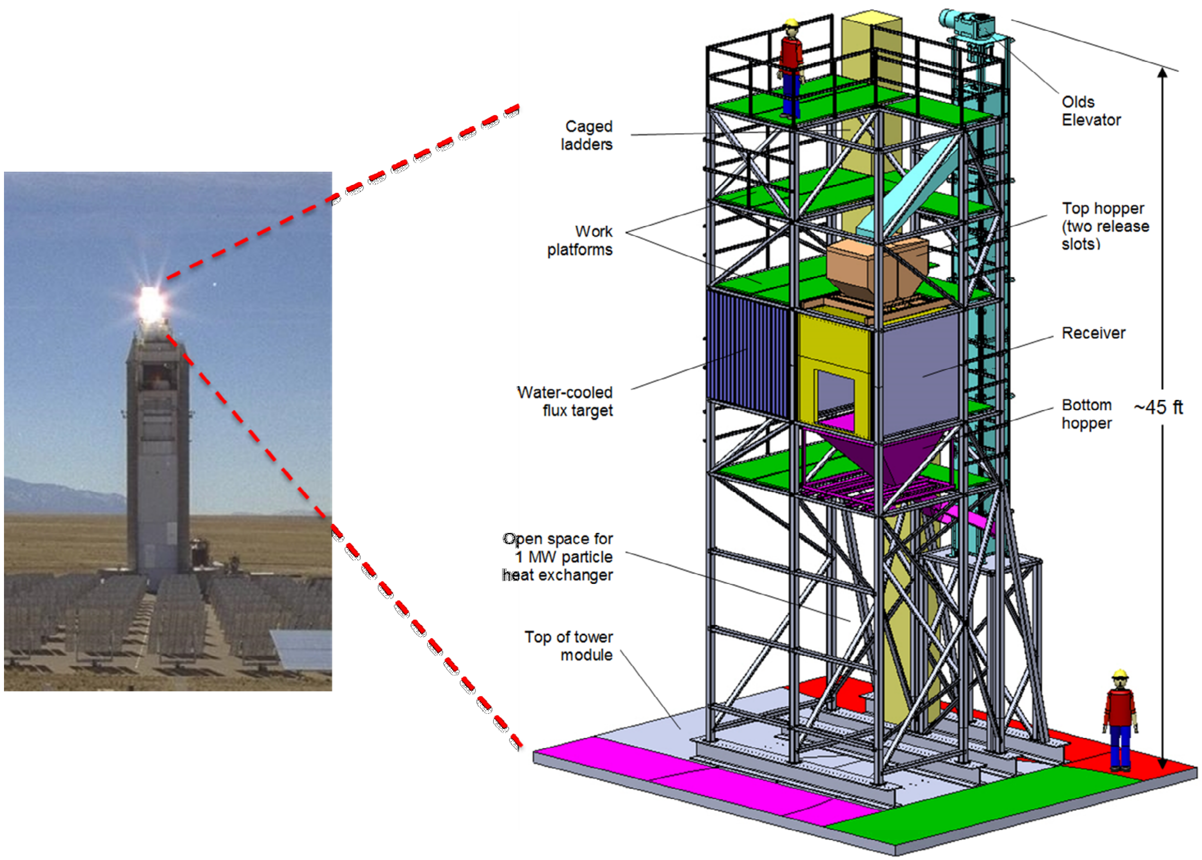
Jill Hruby
Sandia President

Sandia National Laboratories

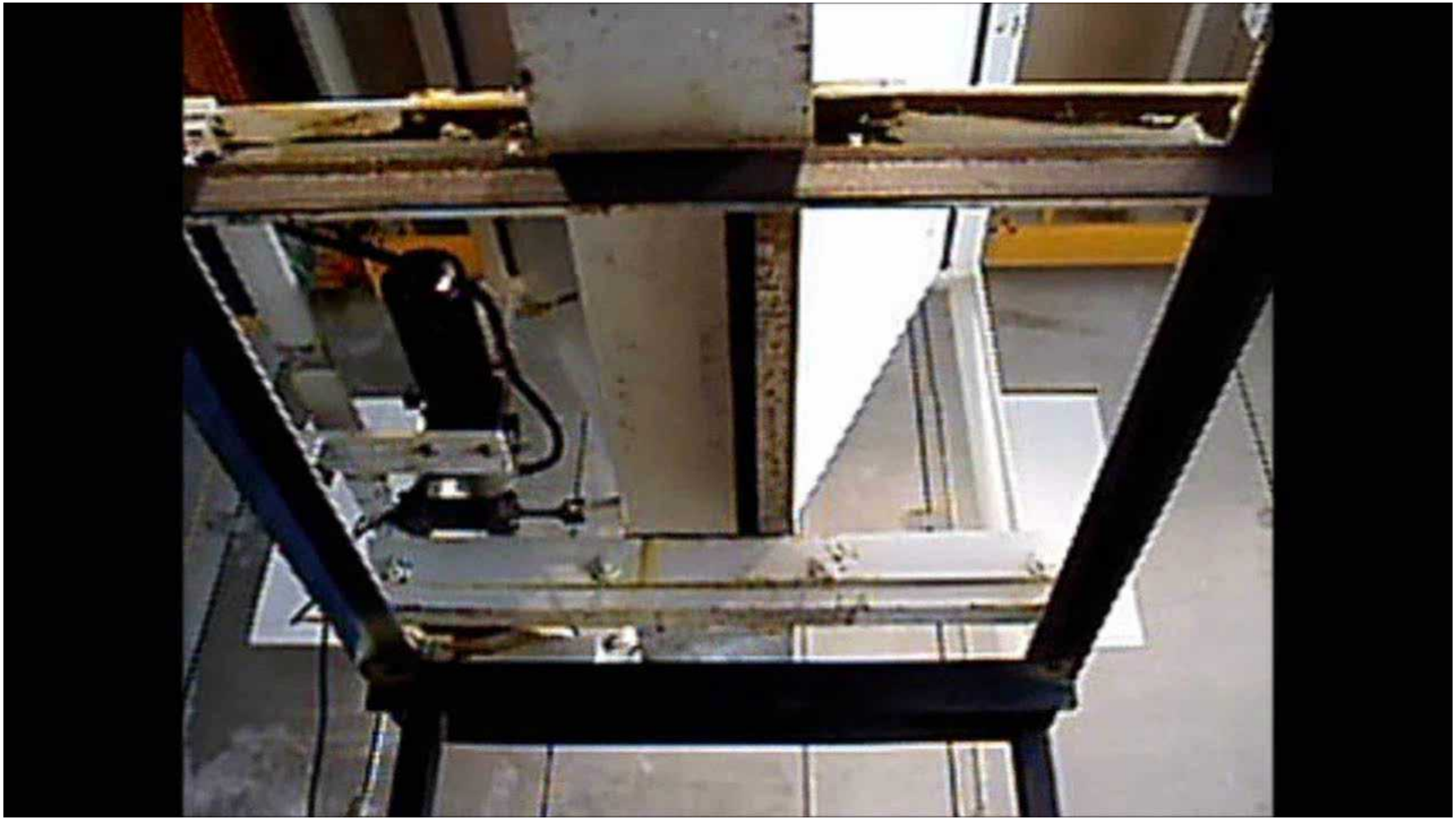
(DOE SunShot Award 2012 - 2016)

Collaborators: Georgia Tech, Bucknell U., King Saud University, DLR

- 1 MW_t on-sun demonstration of recirculating free-falling particle receiver system
- Achieved nearly 800 C average particle outlet temperature
- Up to 70 – 80% efficiency



Conventional Linear Particle Release



Zig-Zag Release

Parallel-Line Release Pattern

On-Sun Tower Testing

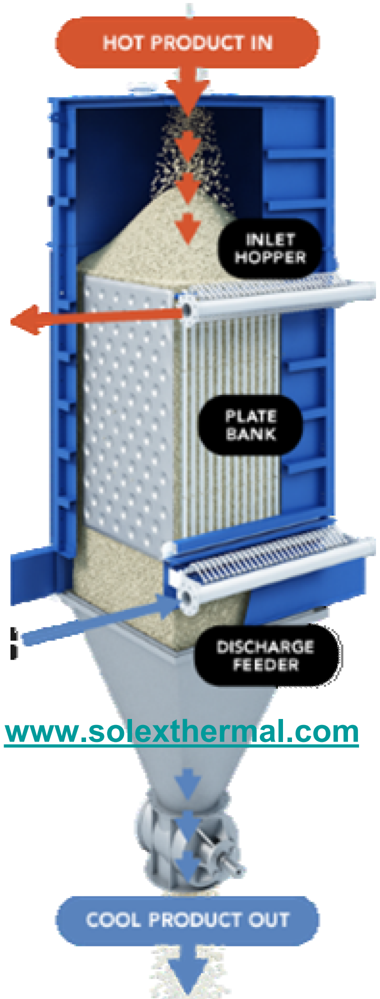
Over 600 suns peak flux on receiver
(July 20, 2015)

On-Sun Tower Testing

Particle Flow Through Mesh Structures
(June 25, 2015)

Particle to Working Fluid Heat Exchanger

- Evaluation of heat transfer coefficients & particle flow



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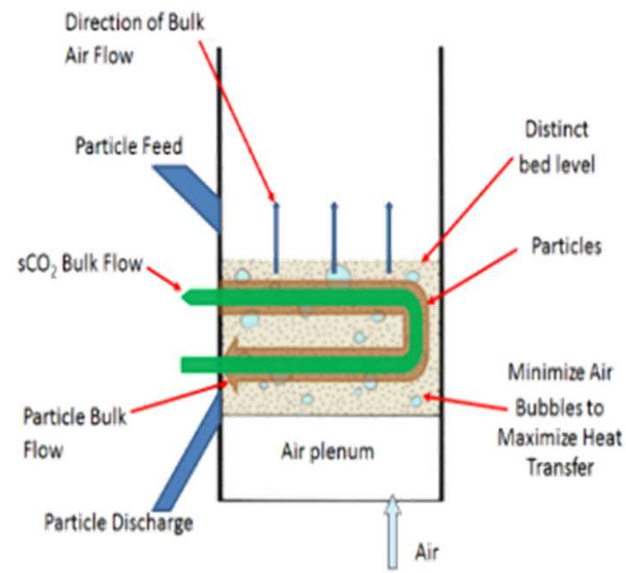
VACUUM PROCESS ENGINEERING

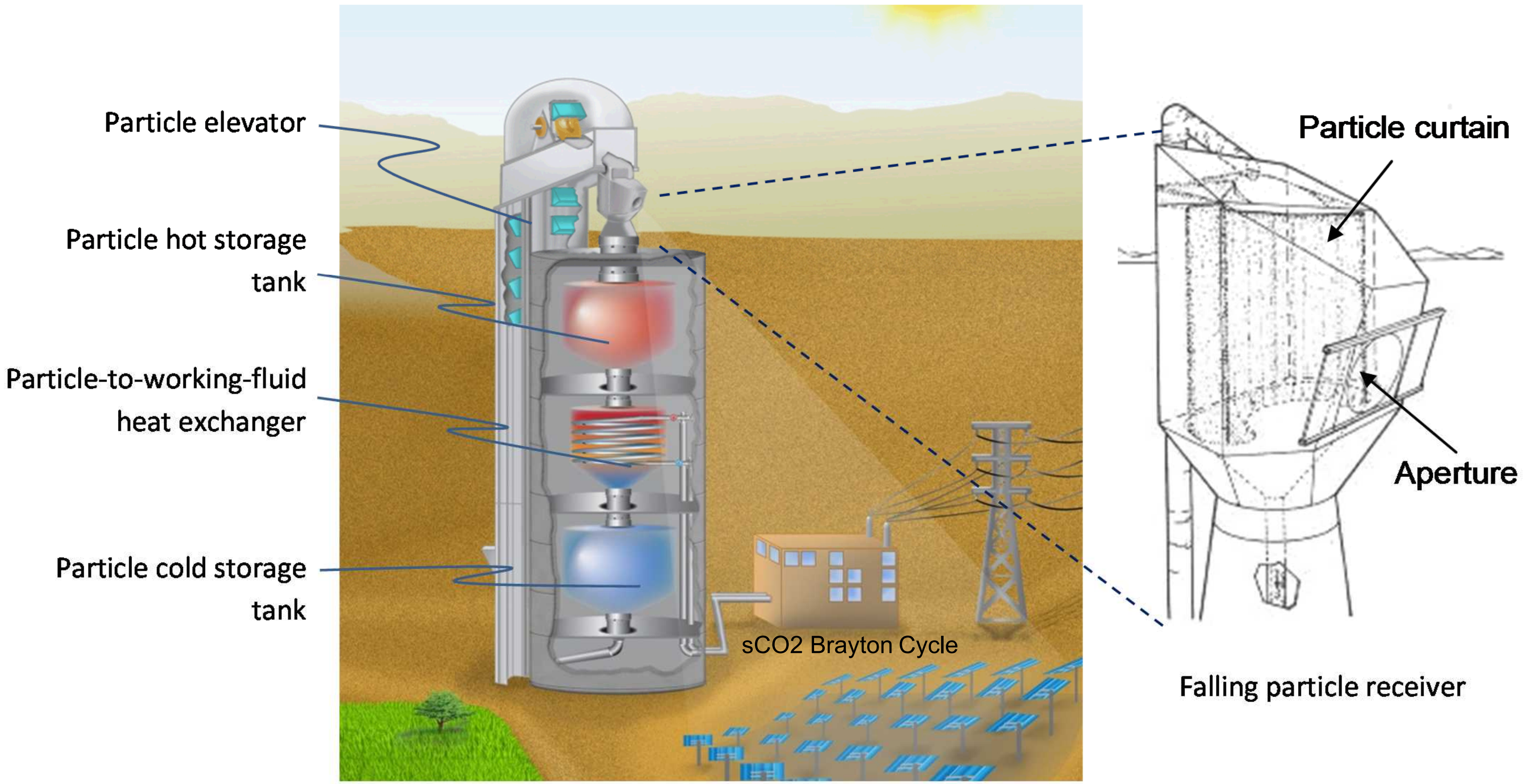
Moving Packed-Bed Shell-and-Tube and Shell-and-Plate Heat Exchanger

B&W the babcock & wilcox company

Fluidized-Bed Heat Exchanger



Solarized Supercritical CO_2 Brayton Cycle with Particle Heating & Storage



Packed Particle Bed Reactor for Solar-Thermochemical H_2 Production

Ivan Ermanoski

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Acknowledgements

Team:

Sandia National Laboratories (SNL)

German Aerospace Center (DLR)

Arizona State University (ASU)

Colorado School of Mines

Funding:

U.S. Department of Energy (DOE)

Office of Energy Efficiency & Renewable Energy (EERE)

Fuel Cell Technologies Office (FCTO)

Two-Step Thermochemical Fuel Production

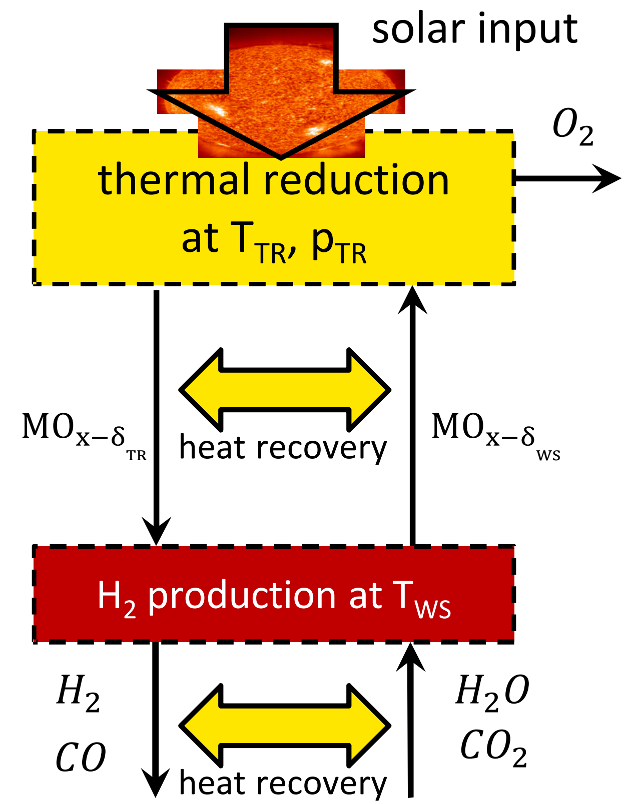
Thermal reduction

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

Water/CO_2 splitting

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

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



A theoretically simple process.

Requires low p_{O2}.

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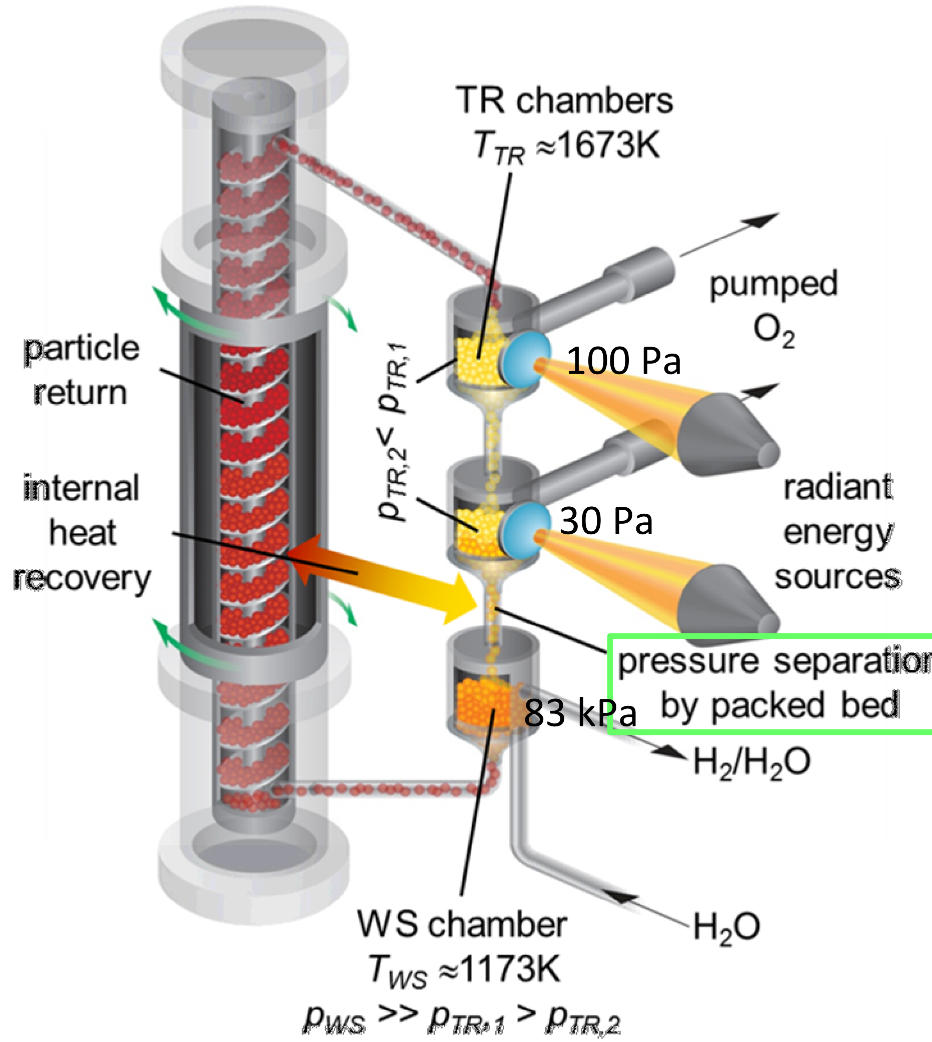
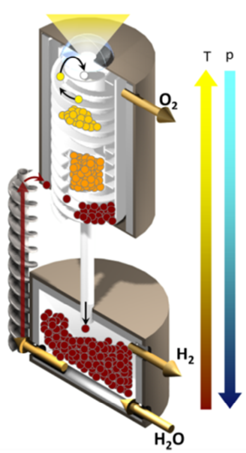
Cascading Pressure Reactor

An improvement of an earlier moving packed bed concept

- Direct solar absorption by reactive particles
- Internal heat recovery between T_{TR} and T_{WS}
- Continuous on-sun operation
- Temperature and product separation
- Pressure separation by particle bed
- Non-monolithic oxide
- Reaction kinetics decoupled from reactor operation

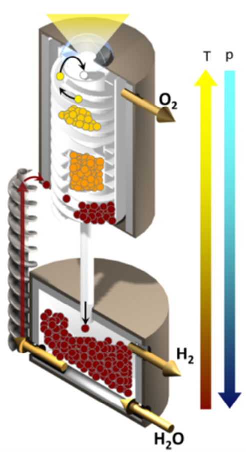


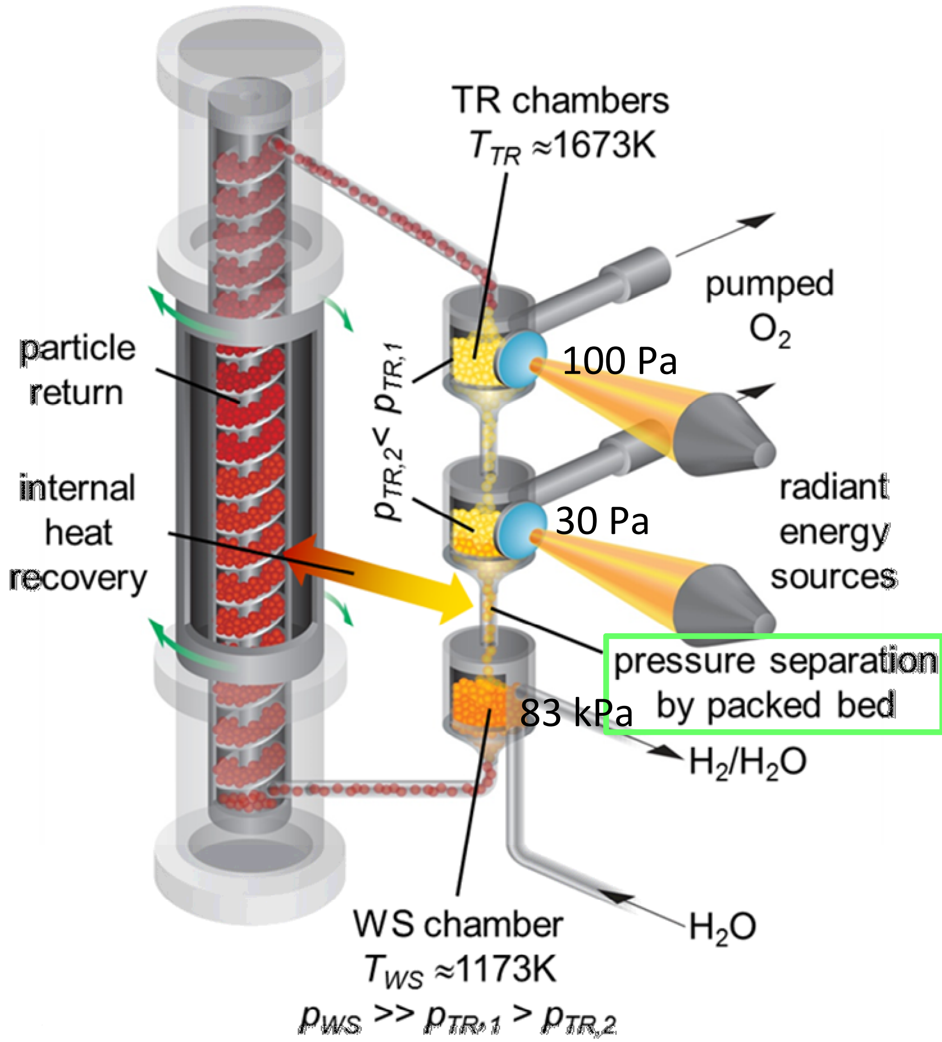
- Thermal reduction pressure (0.1-10Pa)
- Decreased solid-solid heat recovery requirement
- Decreased pump work requirement
- Compatibility with MW-scale plant



Cascading Pressure Reactor

- Direct solar absorption by reactive particles
- Pressure separation by particle bed





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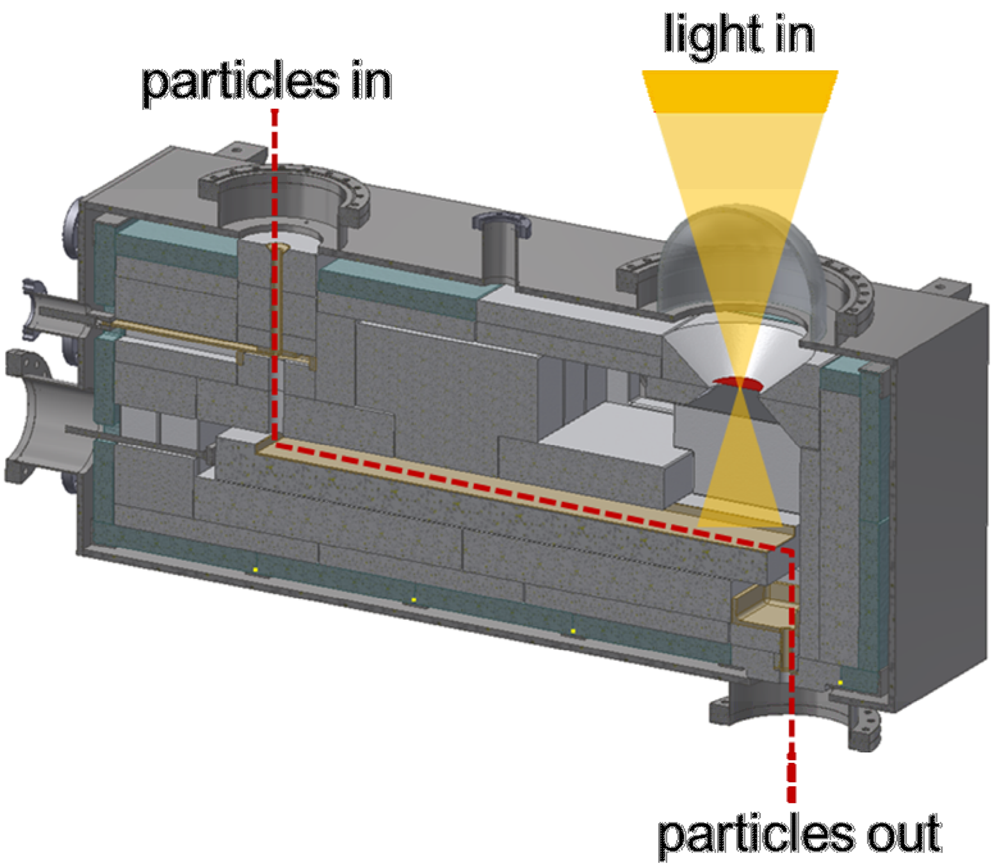
Slip-Stick Receiver

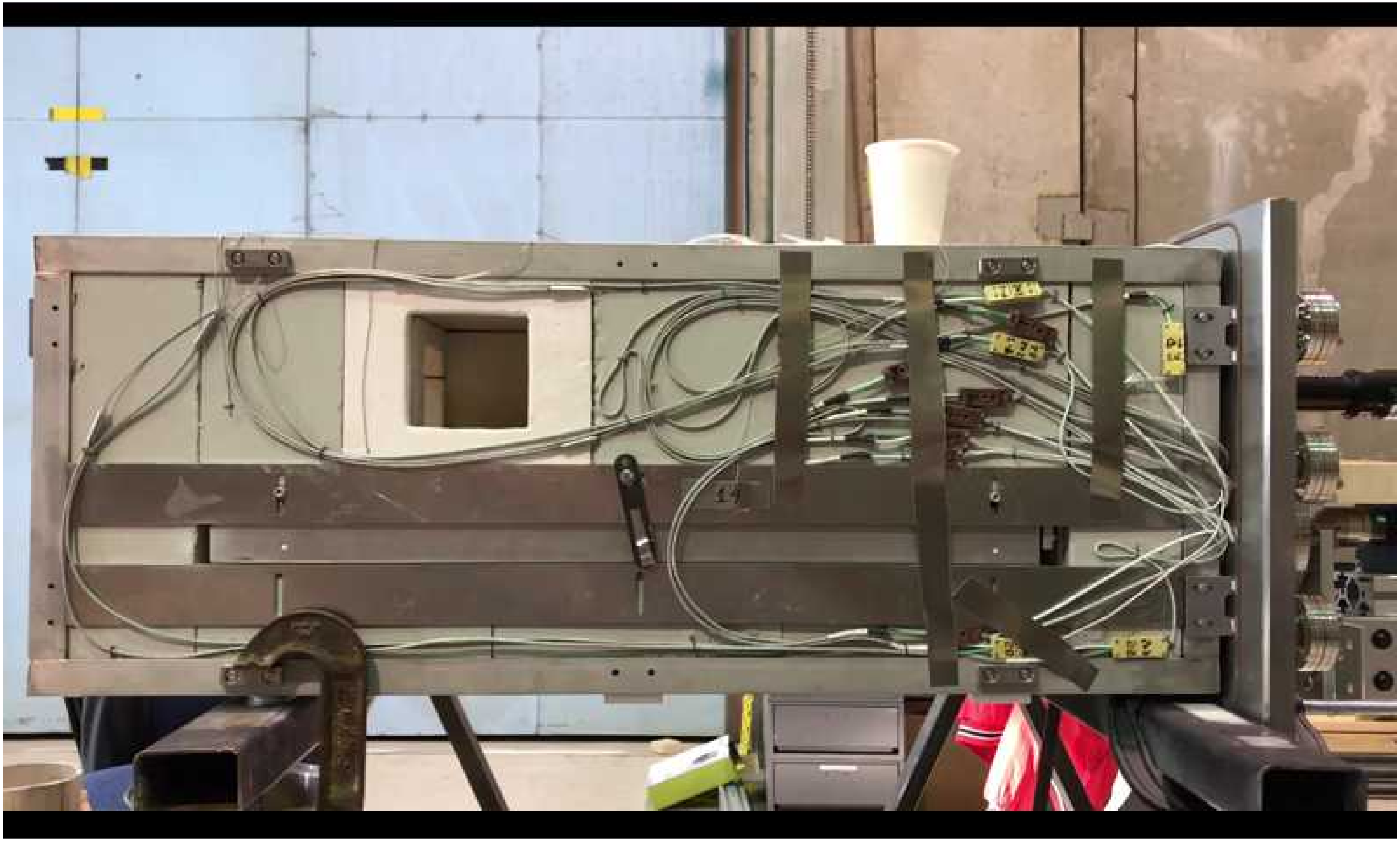


Operation:

- Rough vacuum (10^{-4} atm)
- High temperature (1500 °C)
- Refractory insulation keeps wall T<100°C
- Designed with "lift-off" dome

- Particle gate controls the flow rate onto the slip-stick plate
- Slip-stick plate motion pattern controls forward velocity/residence time

Slip-Stick Receiver Operation



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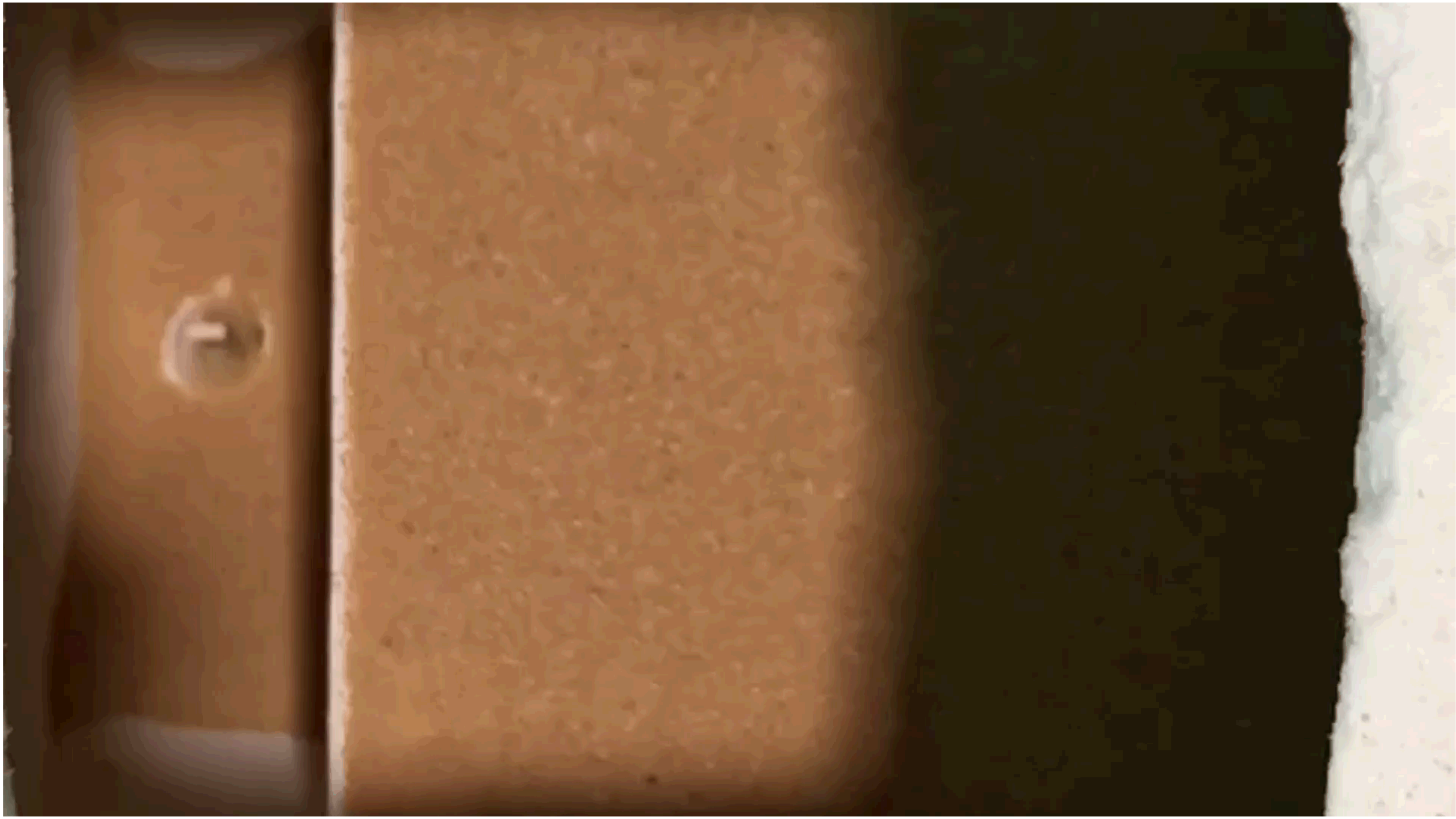
Slip-Stick Receiver Operation



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Slip-Stick Receiver Operation

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Slip-Stick Receiver Operation

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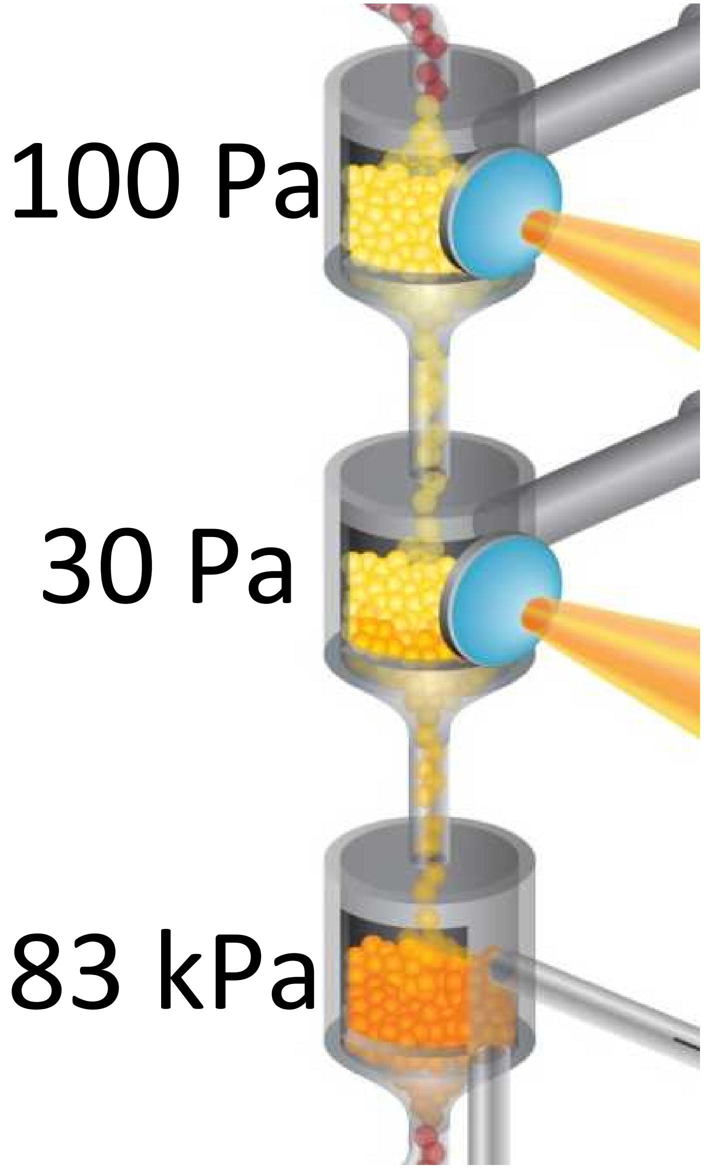
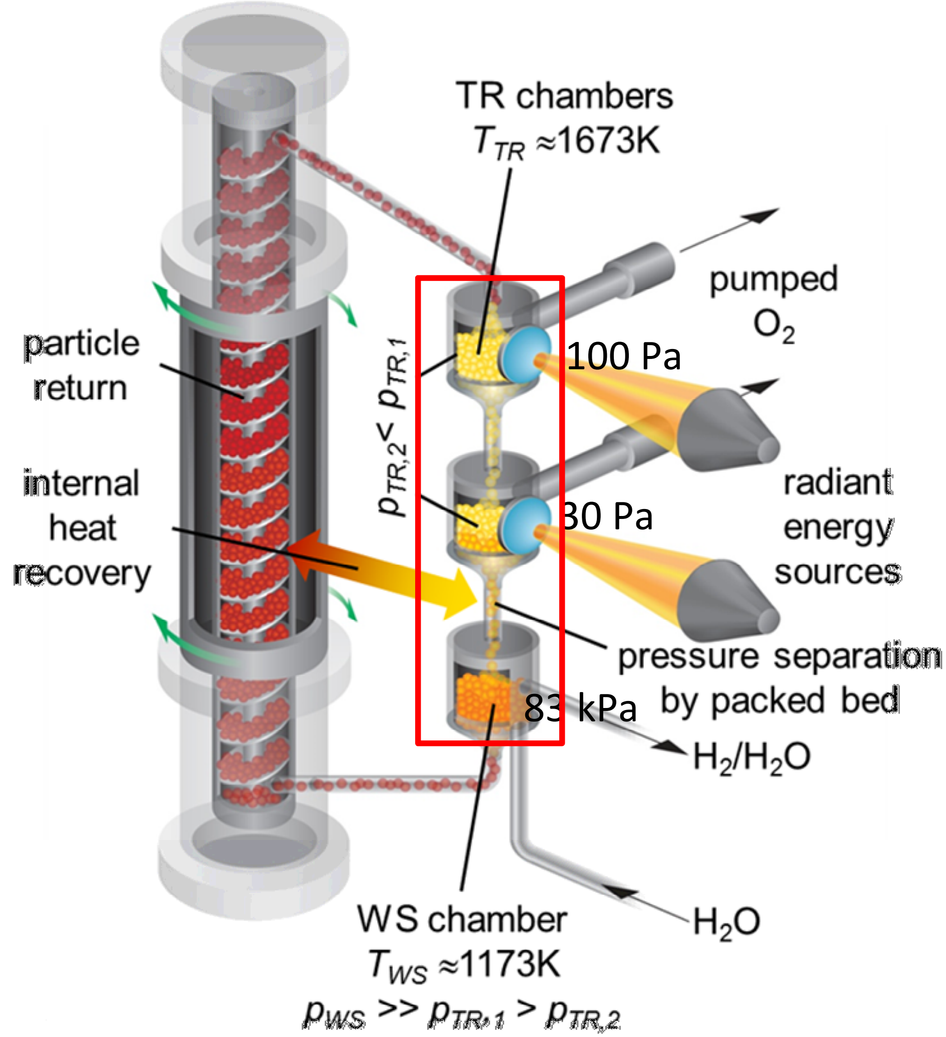
Pressure Separation by Moving Packed Bed





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Gas Permeation: Detailed Approach

$$\frac{\mathrm{d}p}{\mathrm{d}\boldsymbol{l}} = -\frac{\dot{m}_g}{A(l)}\frac{RT}{pMD_p}\frac{1-\phi}{\phi^3}\left[\frac{150(1-\phi)\mu}{f_c\,(Kn)D_p} + 1.75\frac{\dot{m}_g}{A(l)}\right]$$

Ergun equation with Knudsen correction

$$f_c = [1+\alpha(Kn)Kn]\left[1+\frac{4Kn}{1-bKn}\right]$$

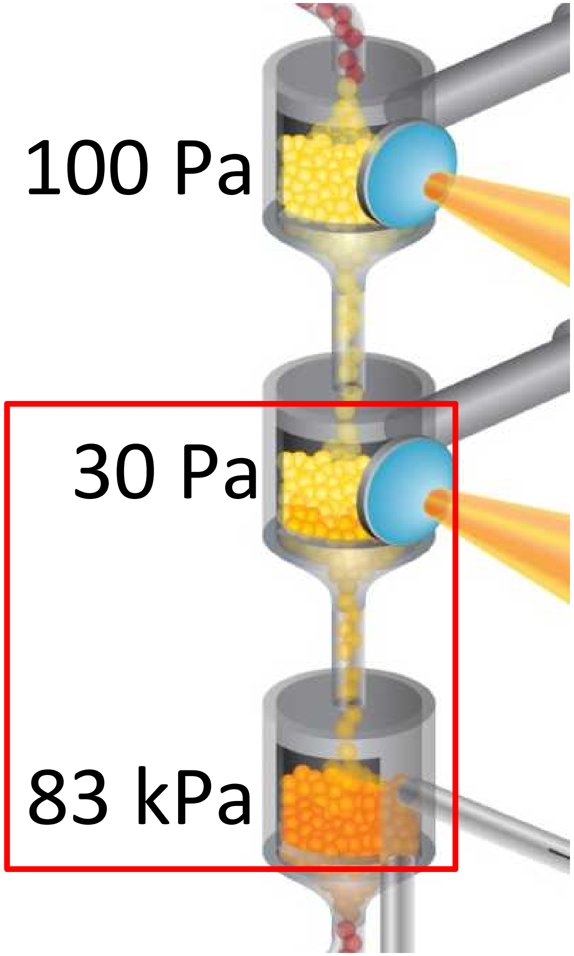
Knudsen correction factor

$$Kn = \frac{\lambda}{D_p} \qquad \lambda = \frac{k_B T}{\sqrt{2}\pi d^2 p}$$

$$\alpha(Kn) = \alpha_0 \frac{2}{\pi} tan^{-1}\left(\alpha_1 Kn^{\beta}\right)$$

$$\alpha_0 \equiv \alpha_{Kn\to\infty} = \frac{64}{3\pi\left(1-\frac{4}{b}\right)}$$

Must use full equations because of substantial pressure drops



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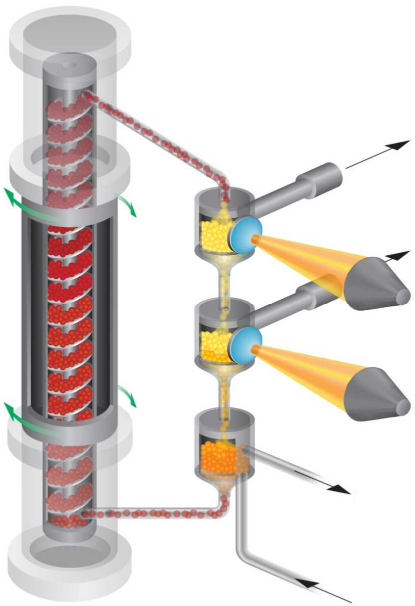
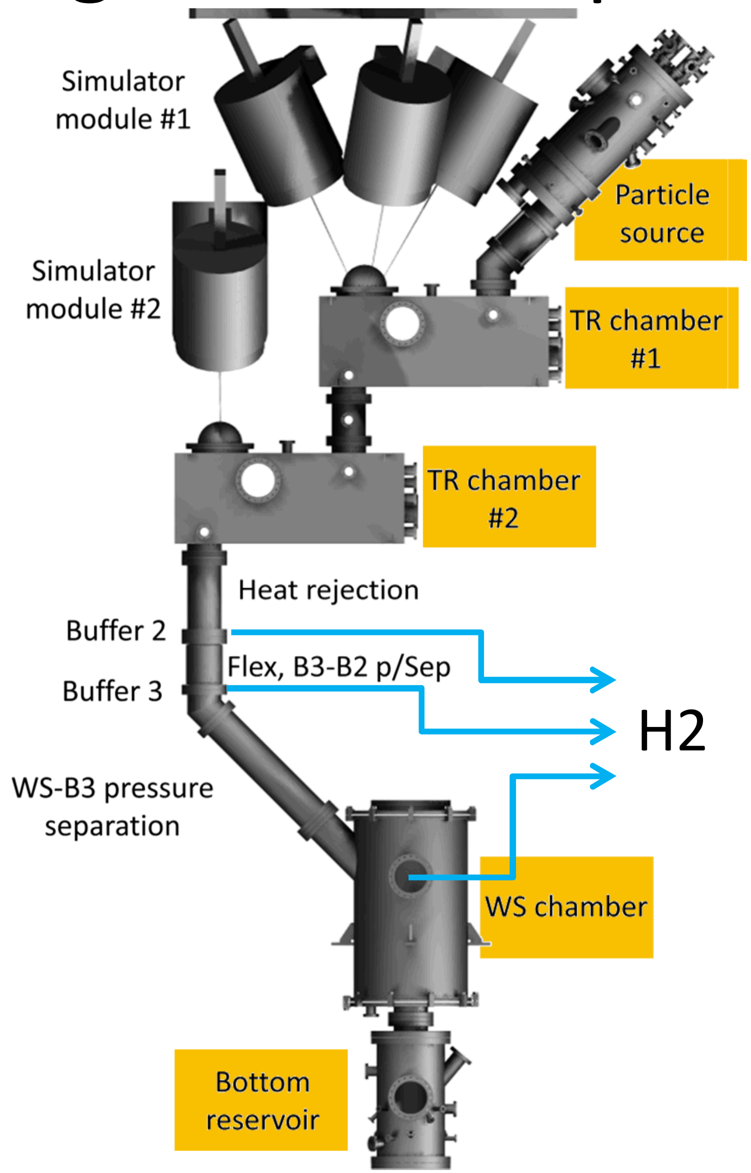
Staging Pressure Separation

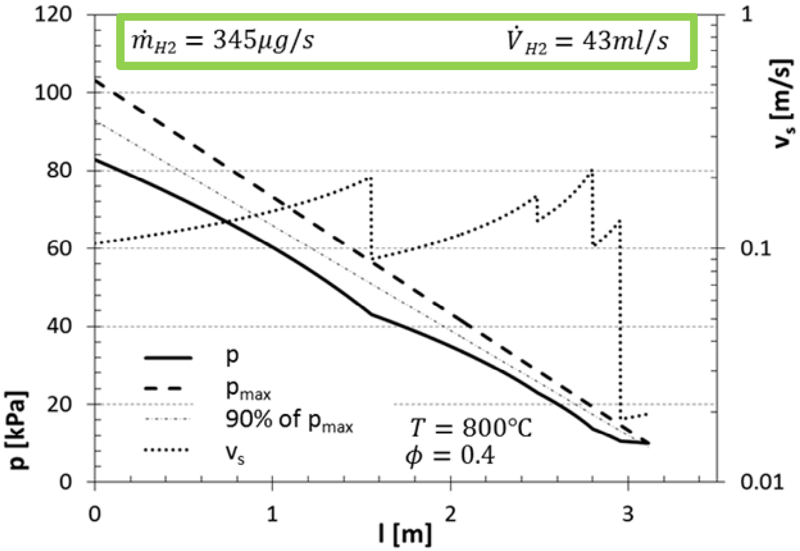


Concept



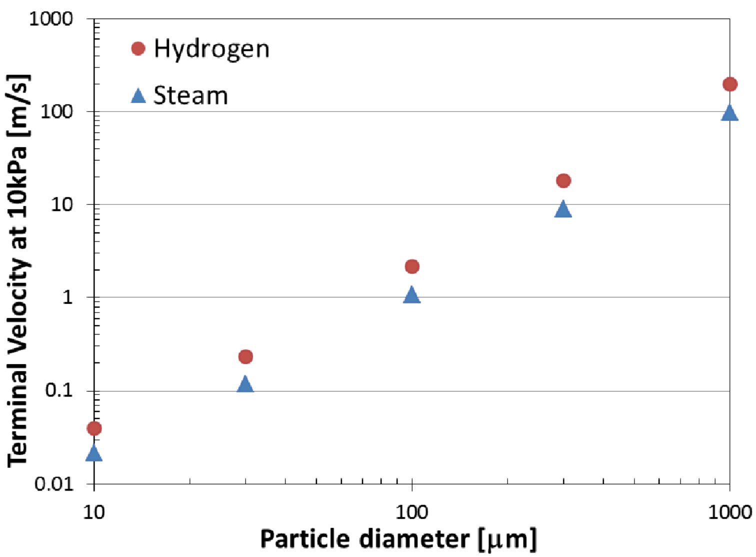
Prototype

H_2 Permeation: WS to Buffer 3



83 kPa→10 kPa H_2
T=800°C
ϕ=0.4
D_p=300 μm

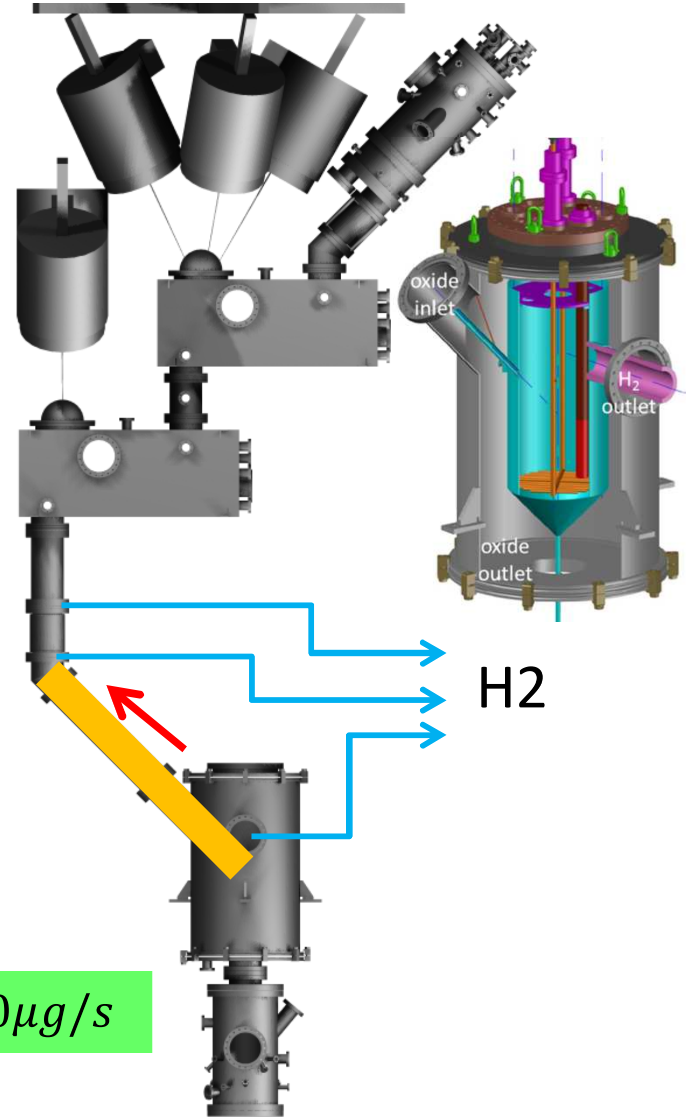
ID_i=15 mm
ID_f=50 mm
incline=45°



$$v_t = \frac{C(\rho_{solid} - \rho_{gas})D_p}{18}$$

$$C = 1 + A \cdot Kn$$

$$A = \alpha + \beta e^{\frac{-\gamma}{Kn}}$$



$$\dot{m}_{H_2,prod} = 400\mu g/s$$

H_2 permeation vastly decreased by including buffer stage.

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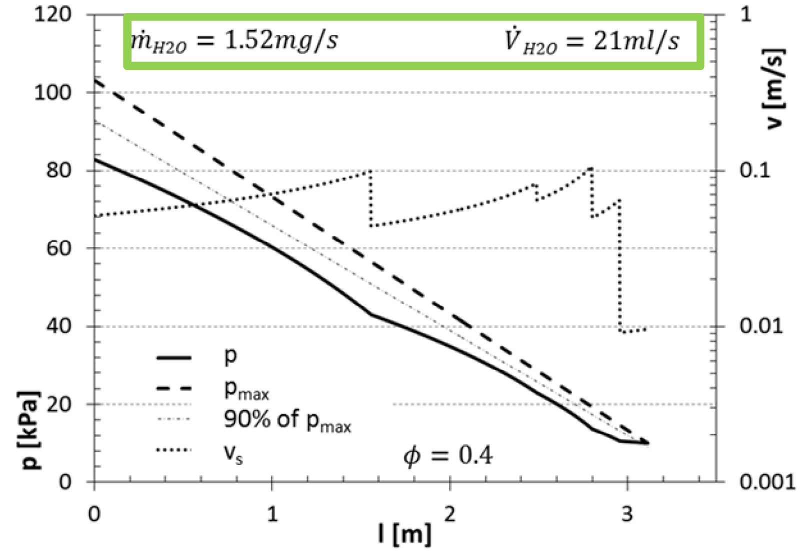
H_2O Permeation: WS to Buffer 3



83 kPa→10 kPa H_2O
T=800°C
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D_p=300 μm

ID_i=15 mm
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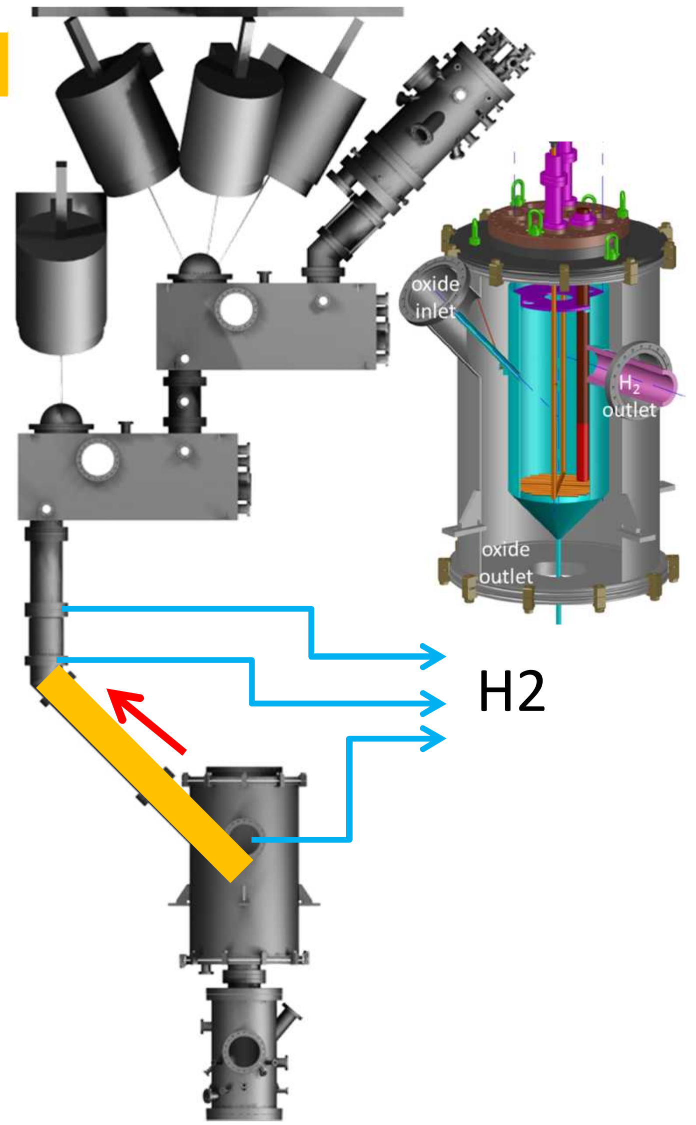

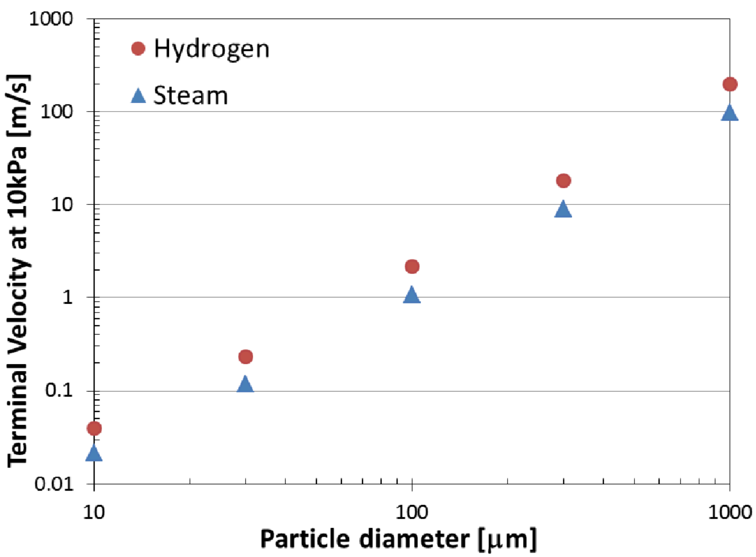

$$v_t = \frac{C(\rho_{solid} - \rho_{gas})D_p}{18}$$

$$C = 1 + A \cdot Kn$$

$$A = \alpha + \beta e^{\frac{-\gamma}{Kn}}$$

H_2 and H_2O pressure profiles are virtually identical.

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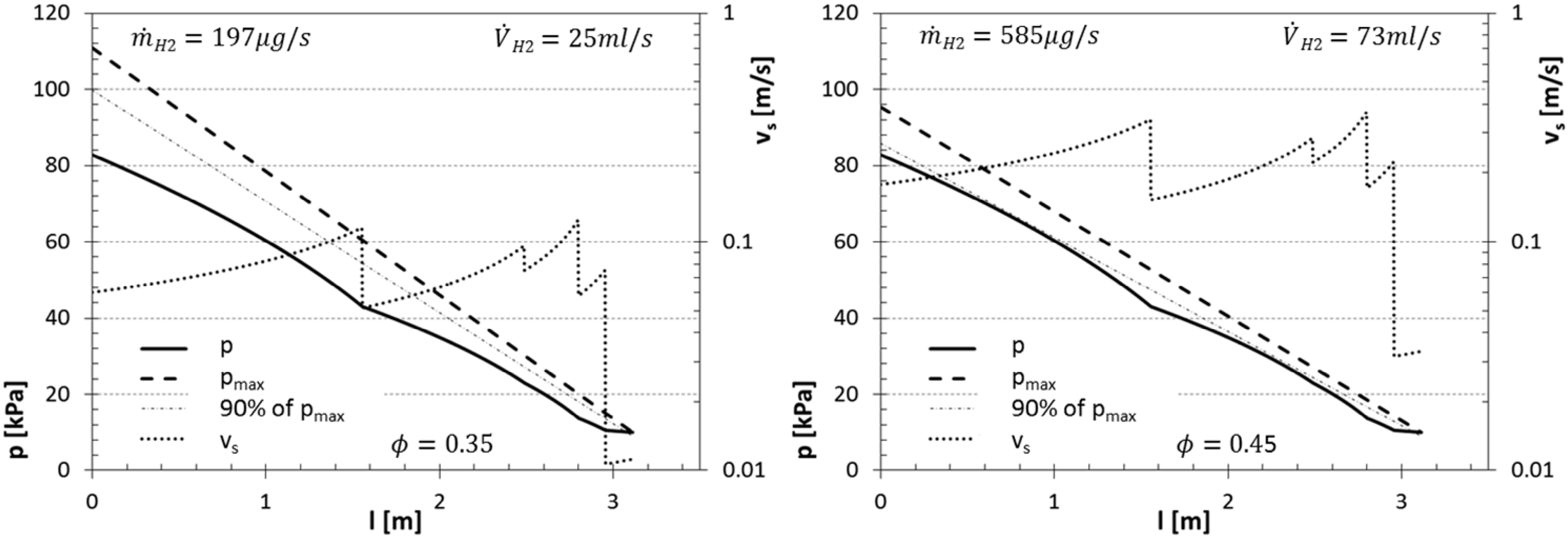
Permeation vs. Void Fraction



Nominal ϕ=0.4

Void fraction affects pressure separation capacity. Adequate total pressure margins are required.

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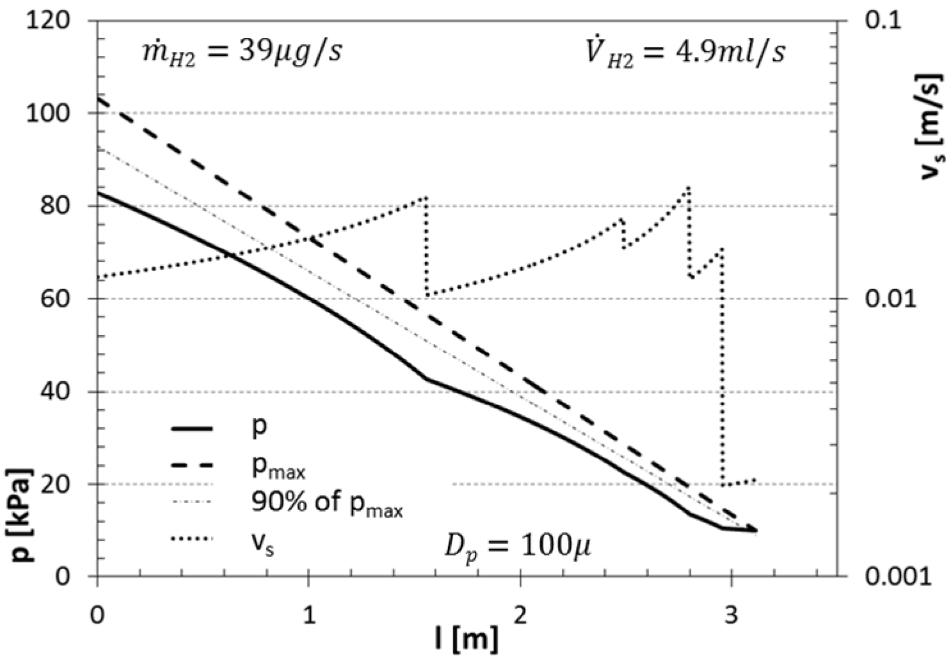
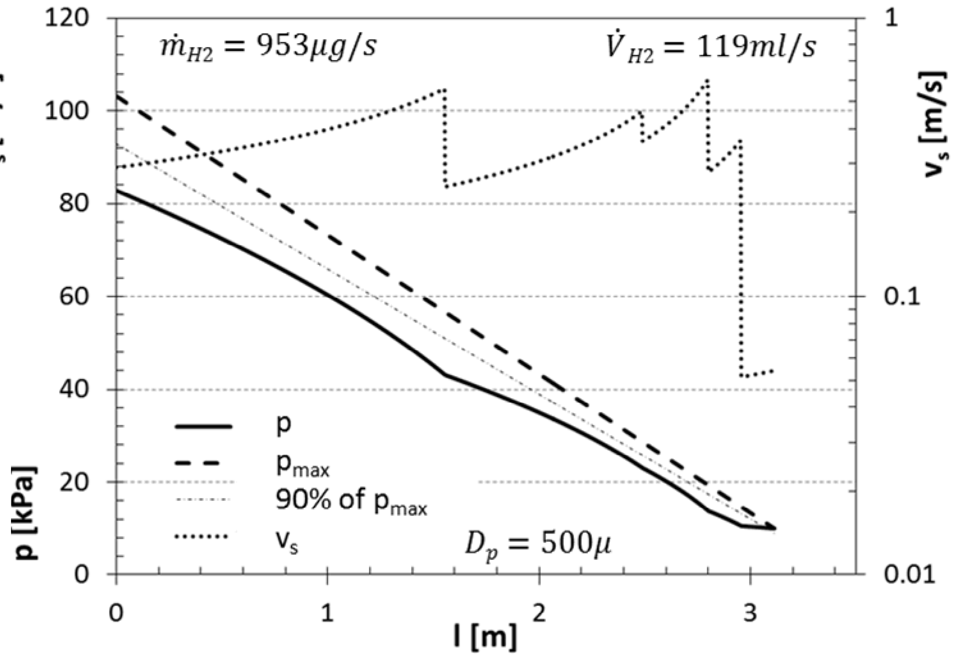
Permeation vs. Particle Size





Nominal D_p=300 μm

Particle size affects permeation significantly, but is not of qualitative importance.

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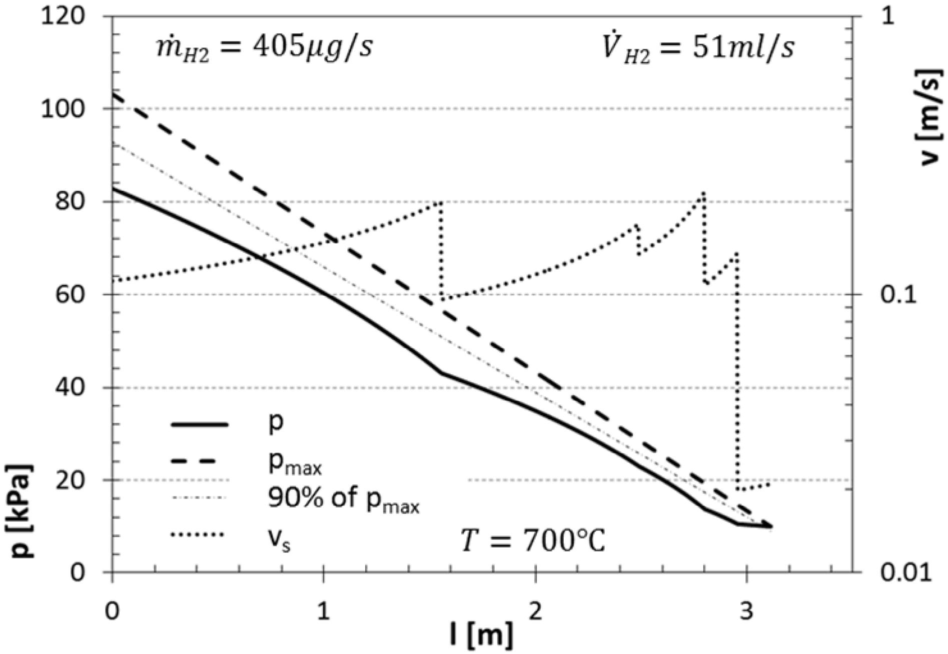
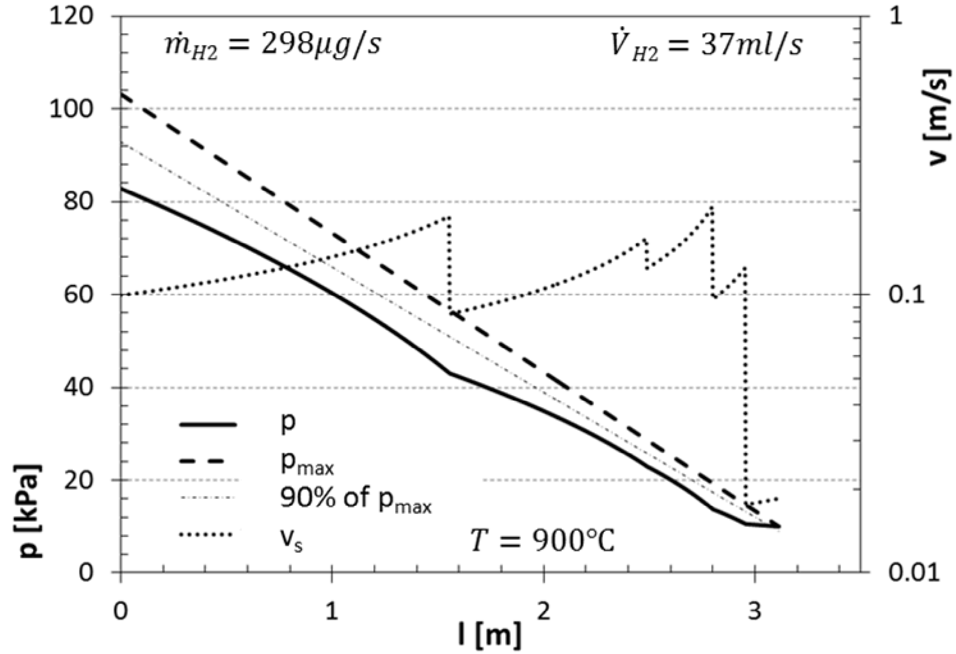
Permeation vs. Temperature

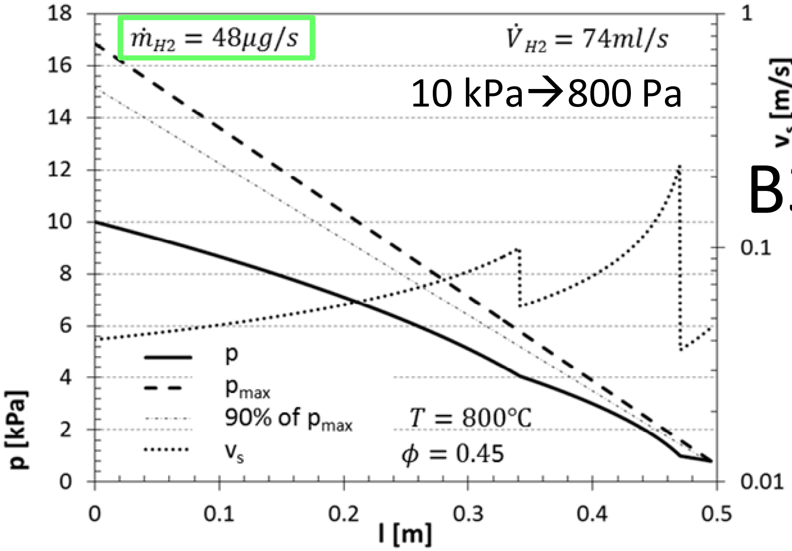




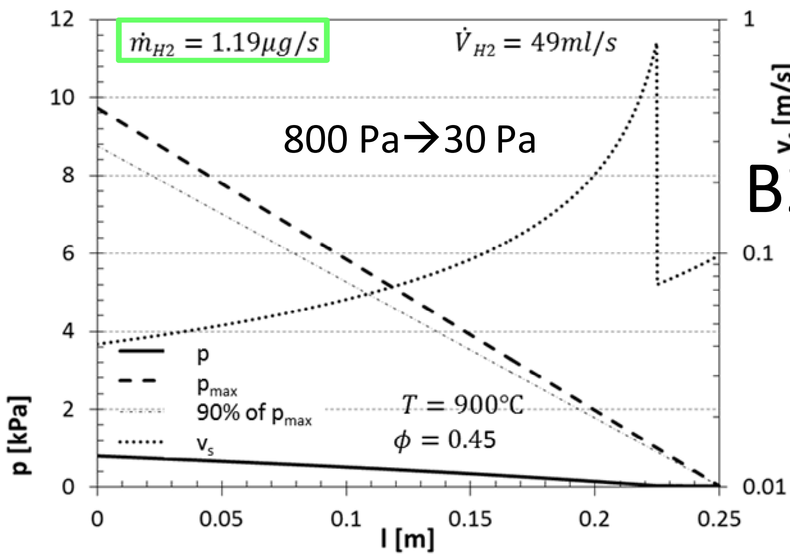
Nominal T=800°C

Temperature variations are of negligible importance.

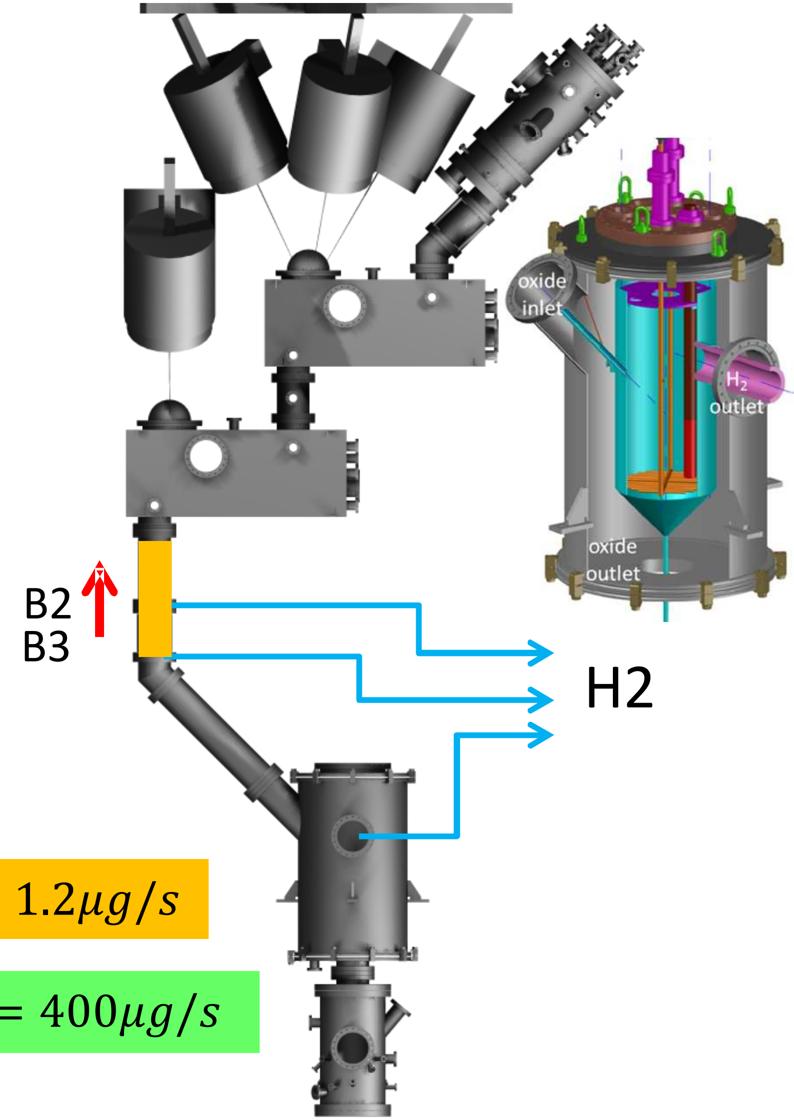
Buffer 3 to TR Chamber Permeation



B3→B2



B2→TR



$$\dot{m}_{H_2,loss} = 1.2\mu g/s$$

$$\dot{m}_{H_2,prod} = 400\mu g/s$$

H_2 loss almost completely eliminated

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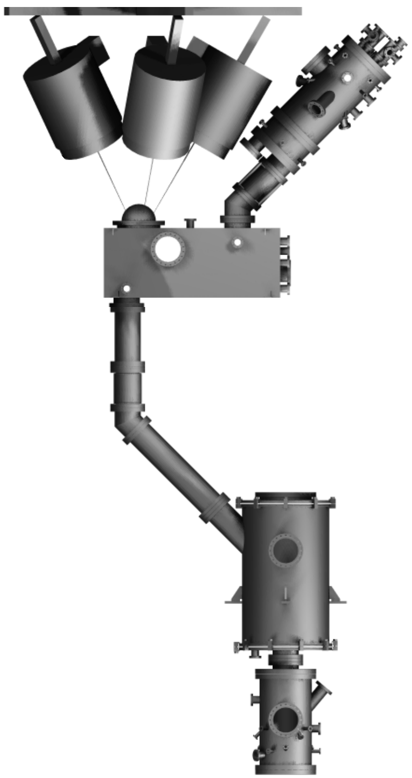
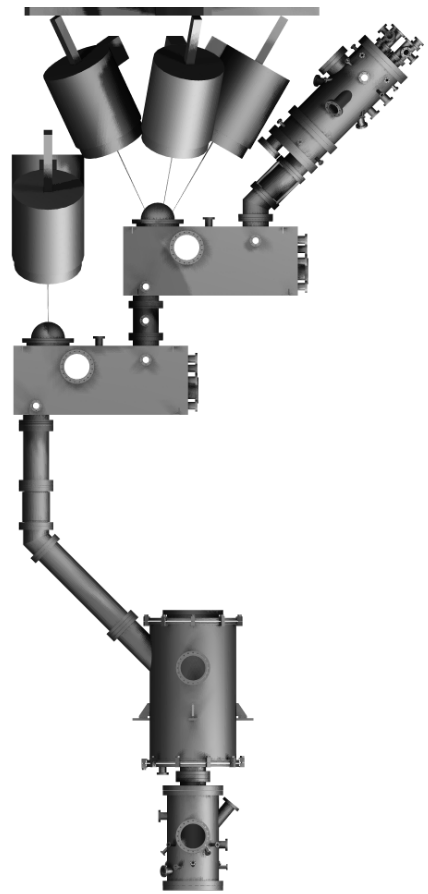
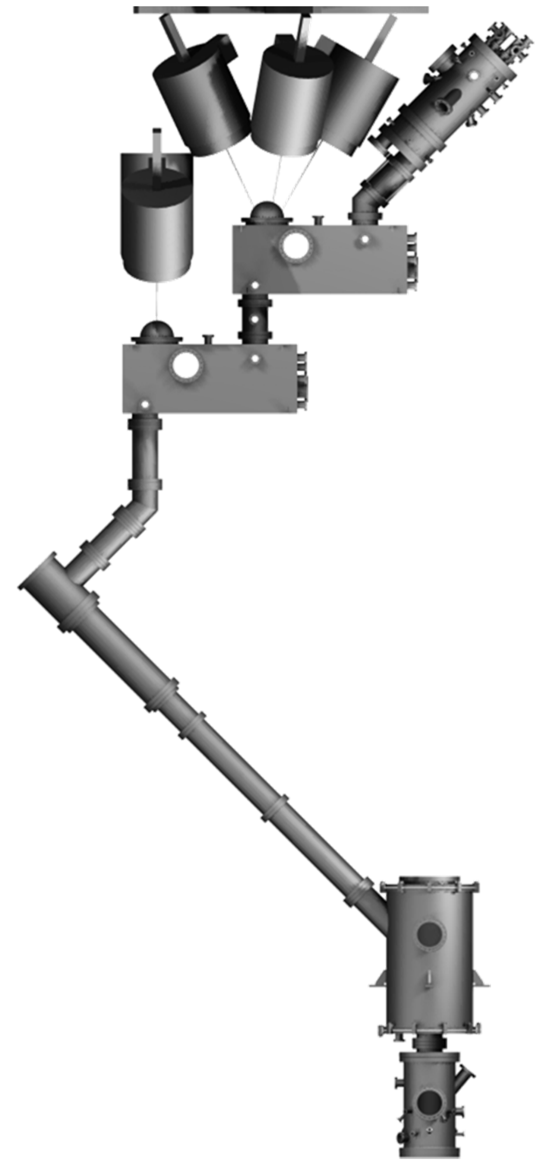
Staged Testing



Single TR Chamber
~20 kPa Oxidation



Cascading TR Chambers
~20 kPa Oxidation



Cascading TR Chambers
Ambient Pressure Oxidation

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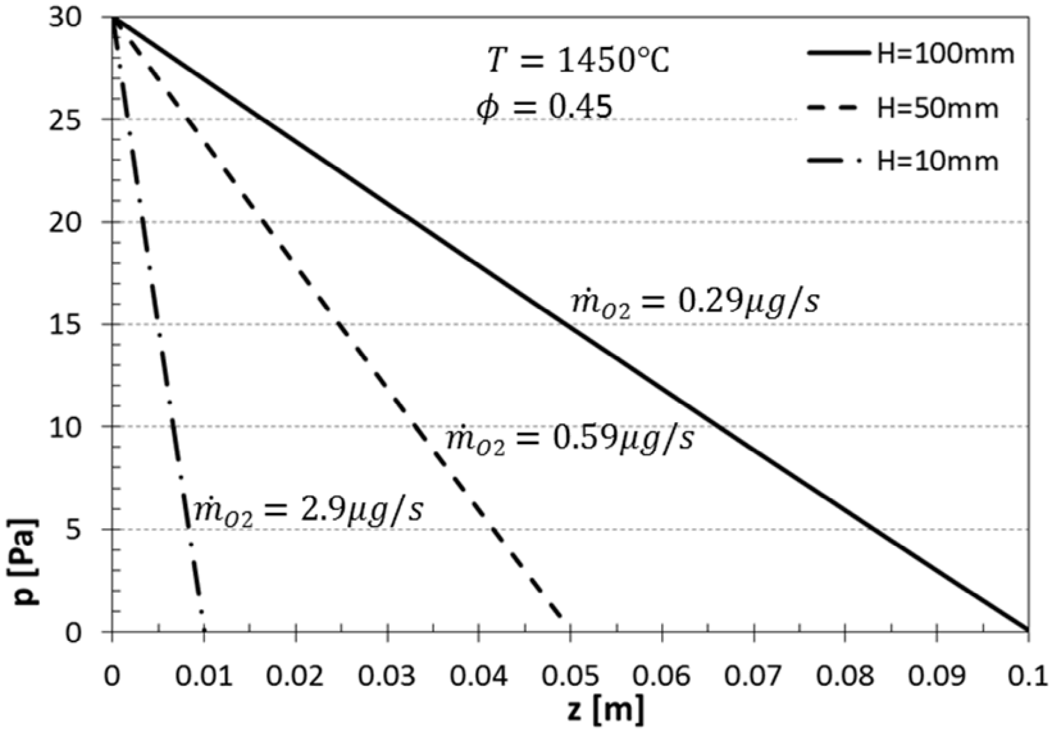
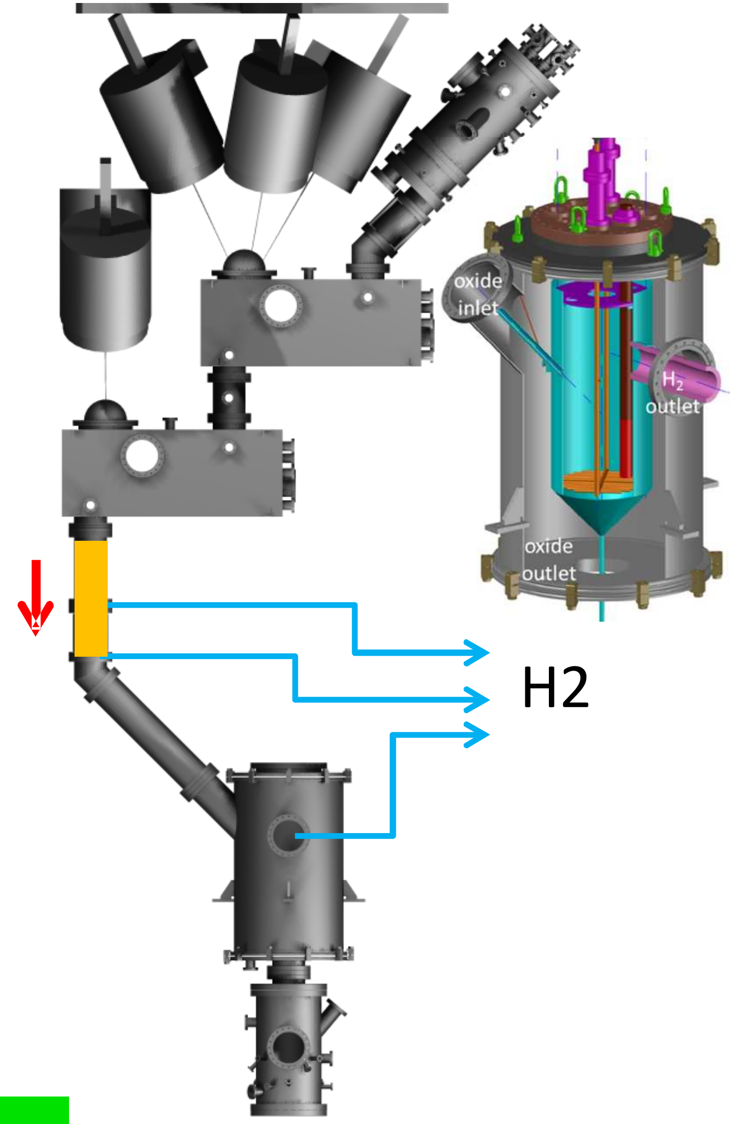
Thank you

Ivan Ermanoski iermano@sandia.gov

O_2 Permeation *From* TR Chamber





$$\dot{m}_{O_2,TR2} = 677\mu g/s$$

Oxide reoxidation is of negligible importance