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

International Particle Technology Working Group Workshop
Riyadh, Saudi Arabia
April 19 – 20, 2017

Clifford K. Ho and Ivan Ermanoski

Sandia National Laboratories

Albuquerque, New Mexico, USA

ckho@sandia.gov

iermano@sandia.gov

SAND2017-3823 PE

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview

- High-Temperature Falling Particle Receivers for CSP
- Packed Particle Bed Reactor for Solar Thermochemical Hydrogen Production
- Thermochemical particle storage with reduction/oxidation of metal oxides

High-Temperature Falling Particle Receiver for Concentrating Solar Power

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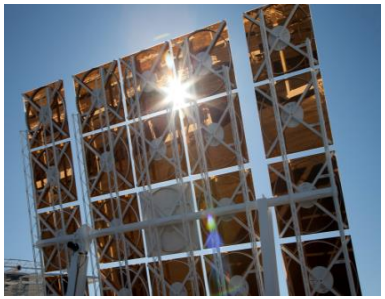

Contributors:

- 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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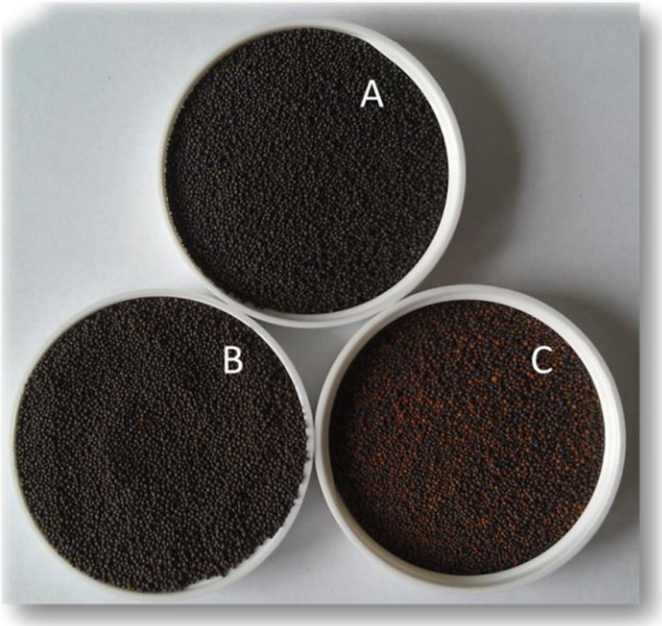
Concentrating Solar Technologies Dept.

SAND2016-5660 PE

Advantages of Particle Receivers

- 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
  - Particle characterization
- 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

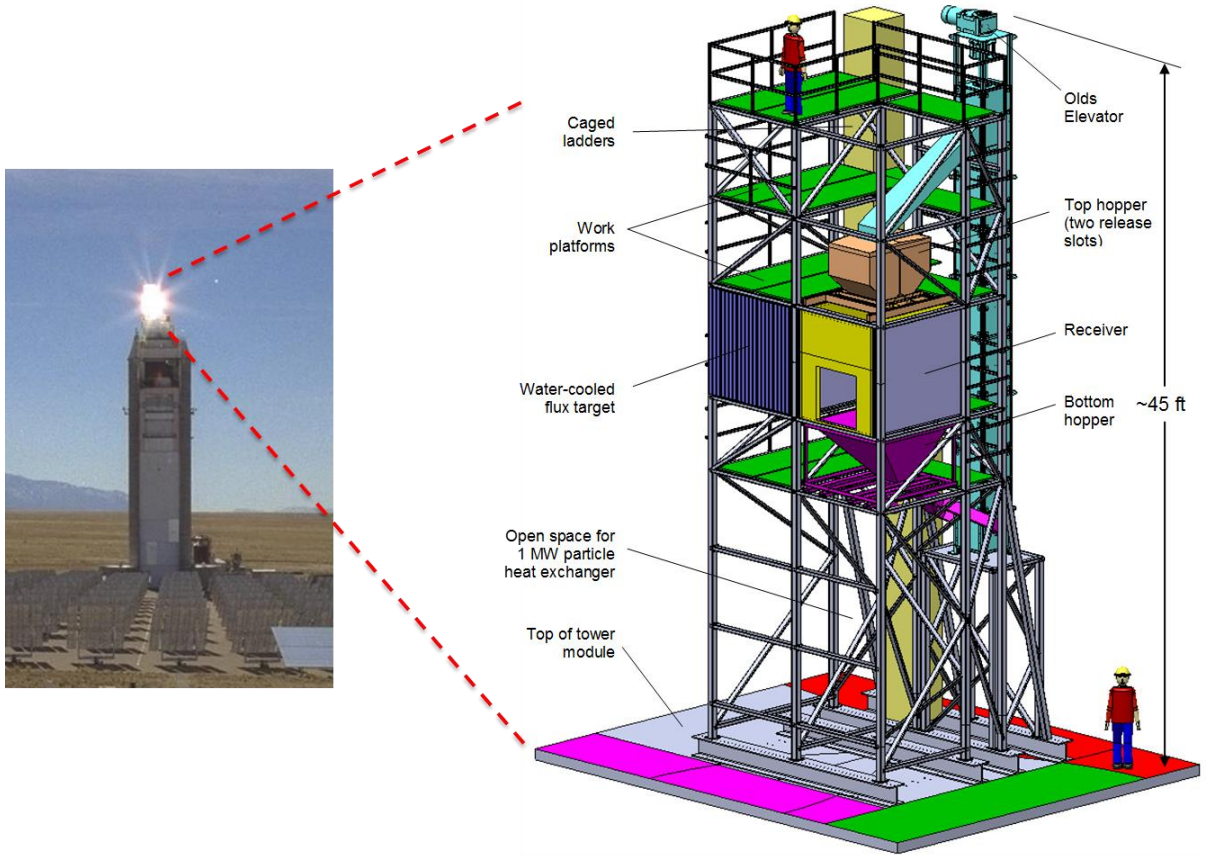
Jill Hruby
Sandia President

Sandia National Laboratories

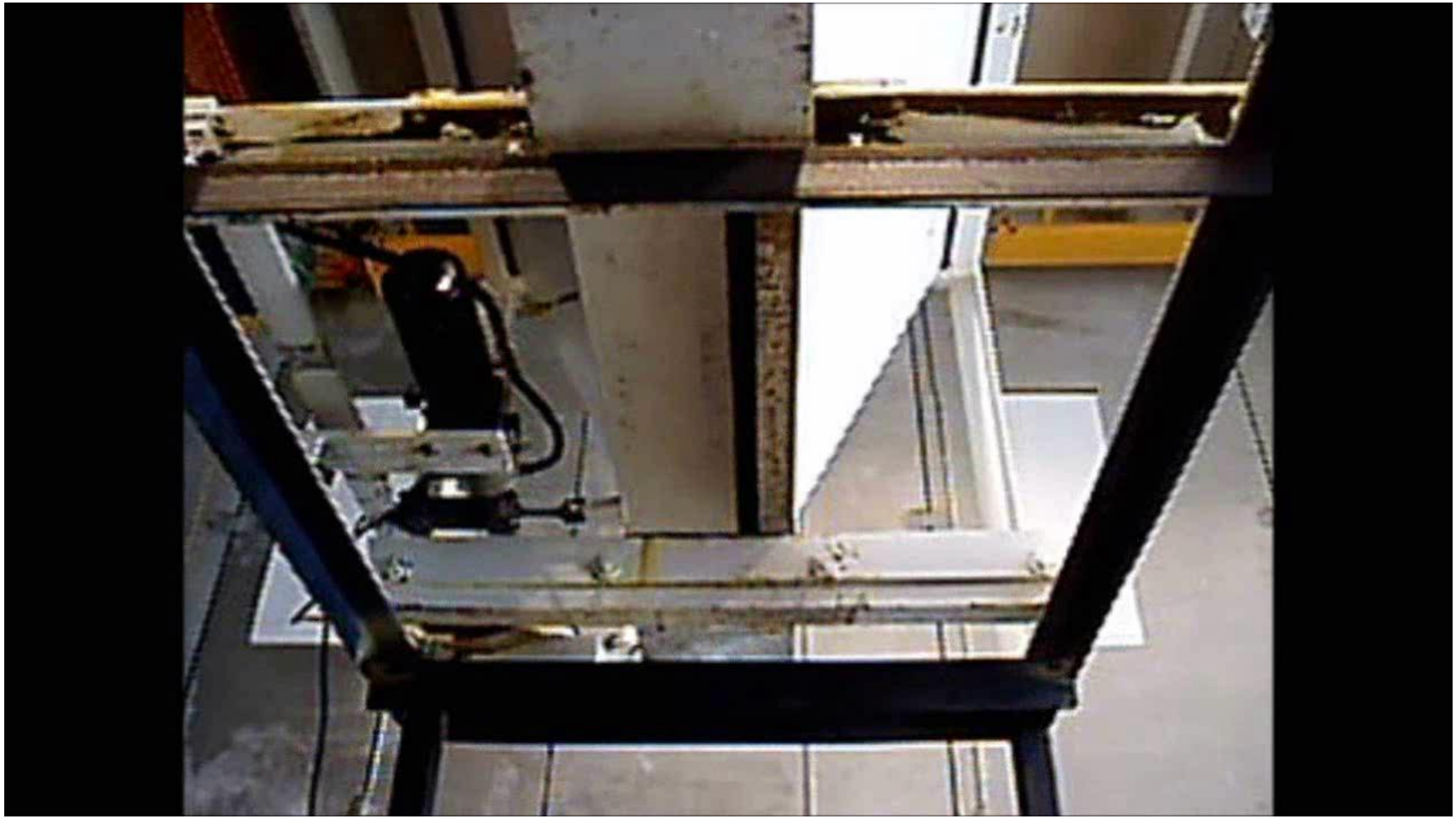
(DOE SunShot Award 2012 - 2016)

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



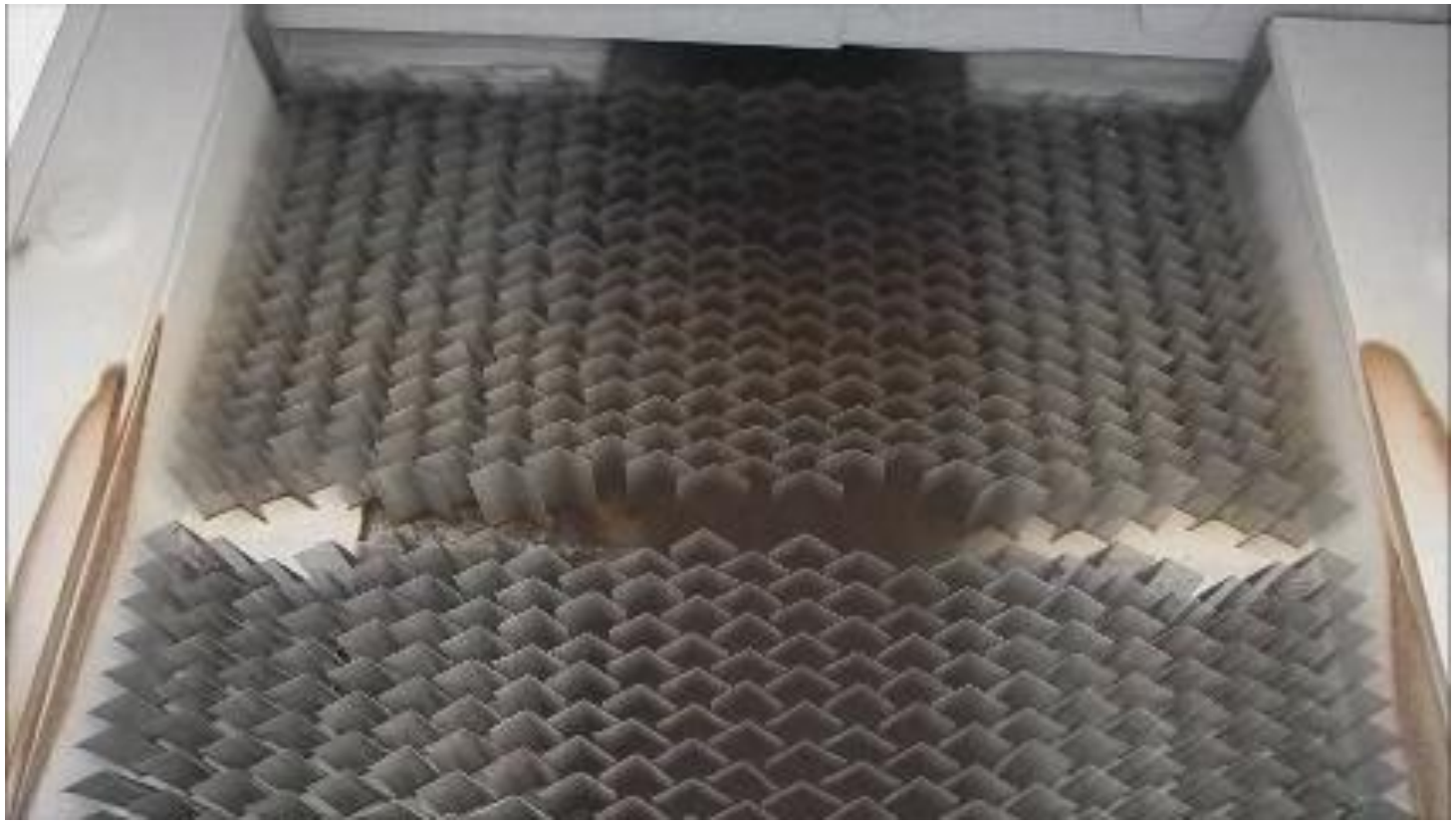
Zig-Zag Release

Parallel-Line Release Pattern

On-Sun Tower Testing

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

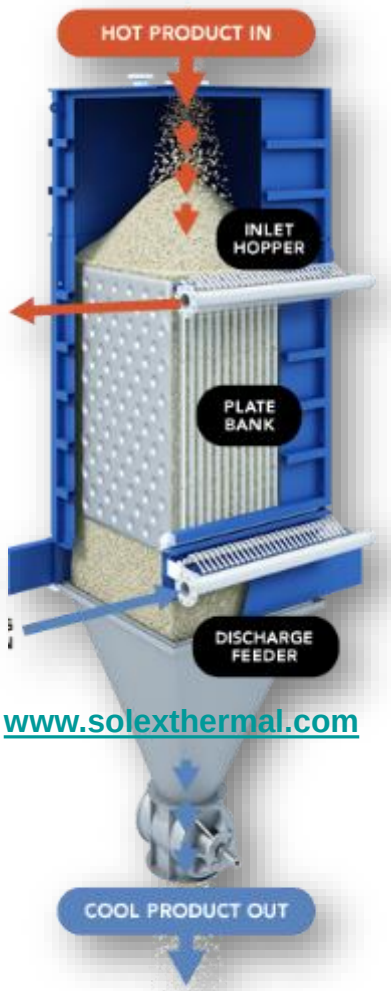
On-Sun Tower Testing



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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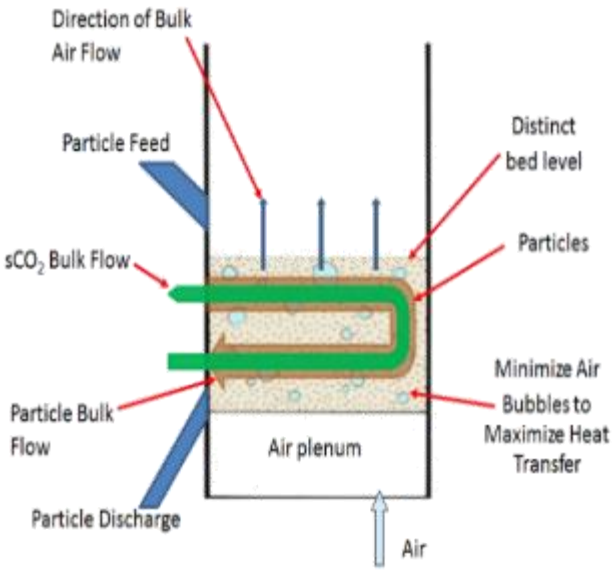
SOLEX THERMAL SCIENCE

VPE VACUUM PROCESS ENGINEERING

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

B&W thebabcock&wilcoxcompany

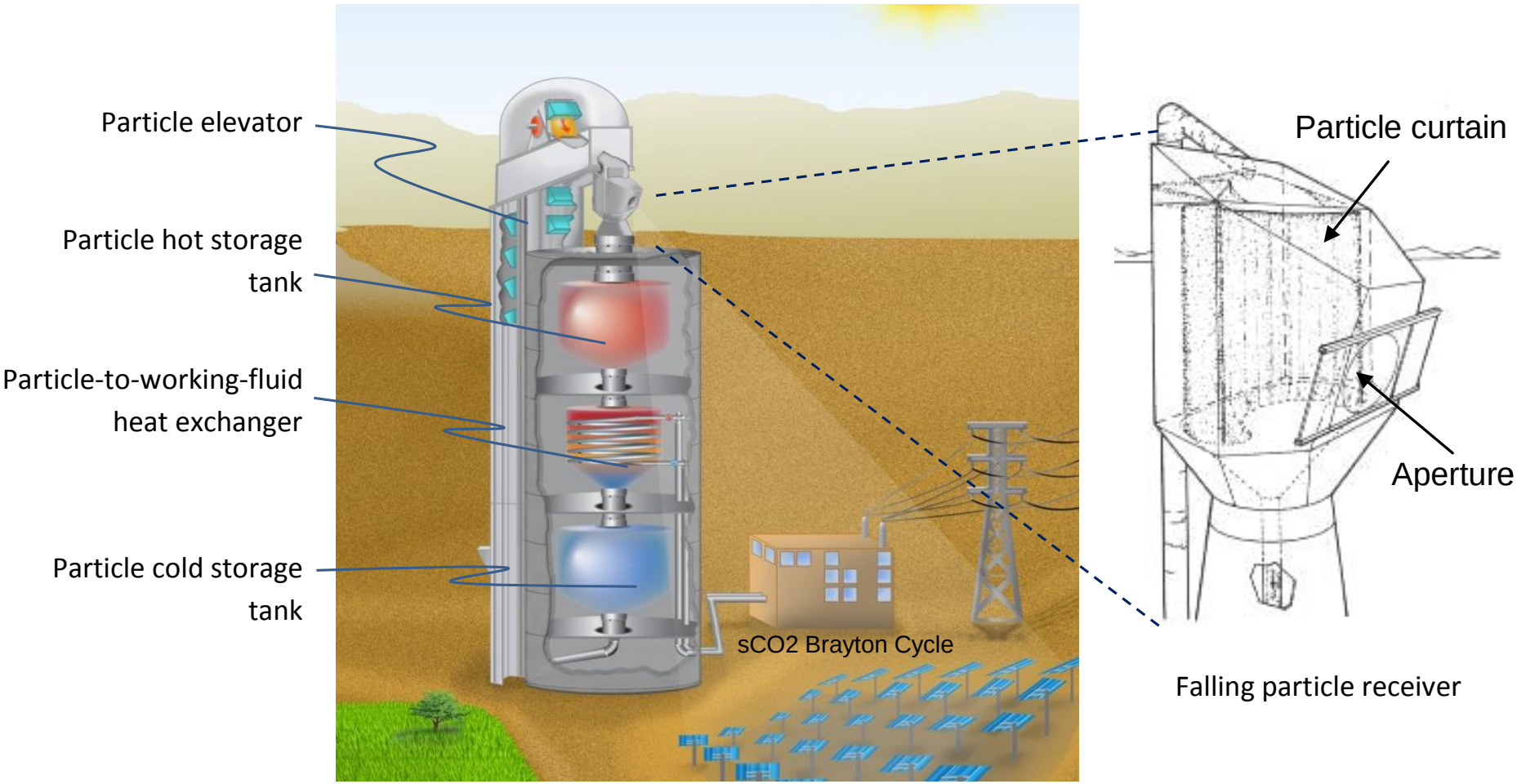
Fluidized-Bed Heat Exchanger



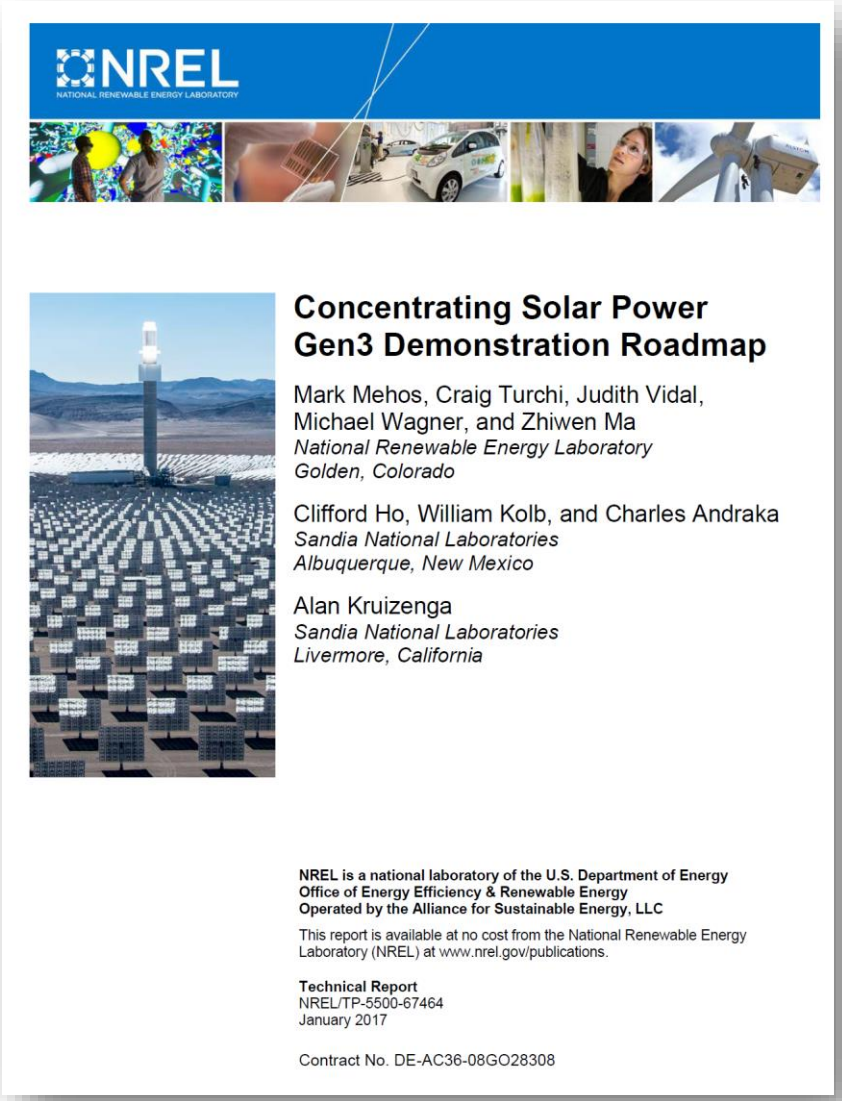
Moving Packed Bed
Parallel Plate Heat Exchanger Tests

Figure 4: Snapshots of cold-flow feeder testing for the 77- (top) and 72-degree (bottom) feeder angles with a slide gate position of 38 mm, which corresponds to a superficial particle velocity of 3.5 mm/s

Solarized Supercritical CO_2 Brayton Cycle with Particle Heating & Storage



U.S. DOE Gen 3 CSP Roadmap and Funding Opportunity



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Concentrating Solar Power Gen3 Demonstration Roadmap

Mark Mehos, Craig Turchi, Judith Vidal, Michael Wagner, and Zhiwen Ma
National Renewable Energy Laboratory
Golden, Colorado

Clifford Ho, William Kolb, and Charles Andraka
Sandia National Laboratories
Albuquerque, New Mexico

Alan Kruizenga
Sandia National Laboratories
Livermore, California

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

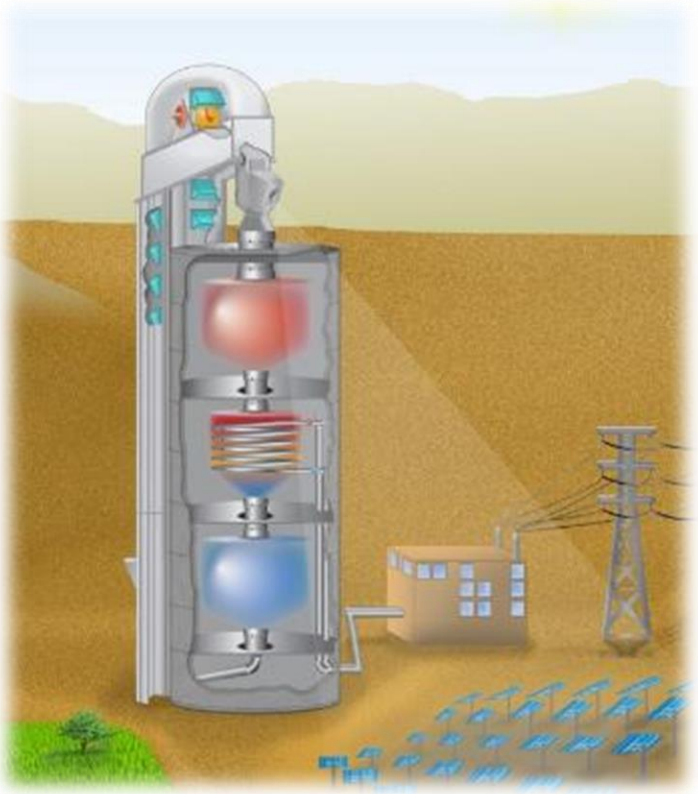
Technical Report
NREL/TP-5500-67464
January 2017

Contract No. DE-AC36-08GO28308

- Goal is to develop 10 MW_e demonstration of solarized supercritical CO_2 Brayton cycle
- Identifies 3 technology pathways
  - High-Temperature Molten Salt
  - Particle Receiver
  - Gas Receiver
- Identifies and prioritizes gaps and research needs

Technology Gaps – Particle Receiver Pathway

- Particles
- Particle Loss
- Receiver and Feed Bin
- Particle Storage
- Particle Heat Exchanger
- Particle Lift and Conveyance



Integration of multiple components and system-like demonstration will be important for Gen 3 FOA
Cost share will be necessary

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

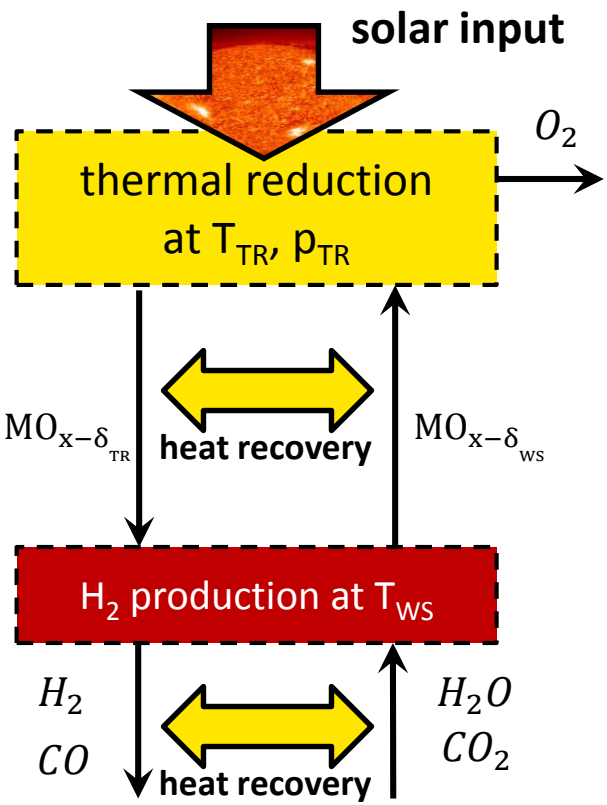
Thermal reduction

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

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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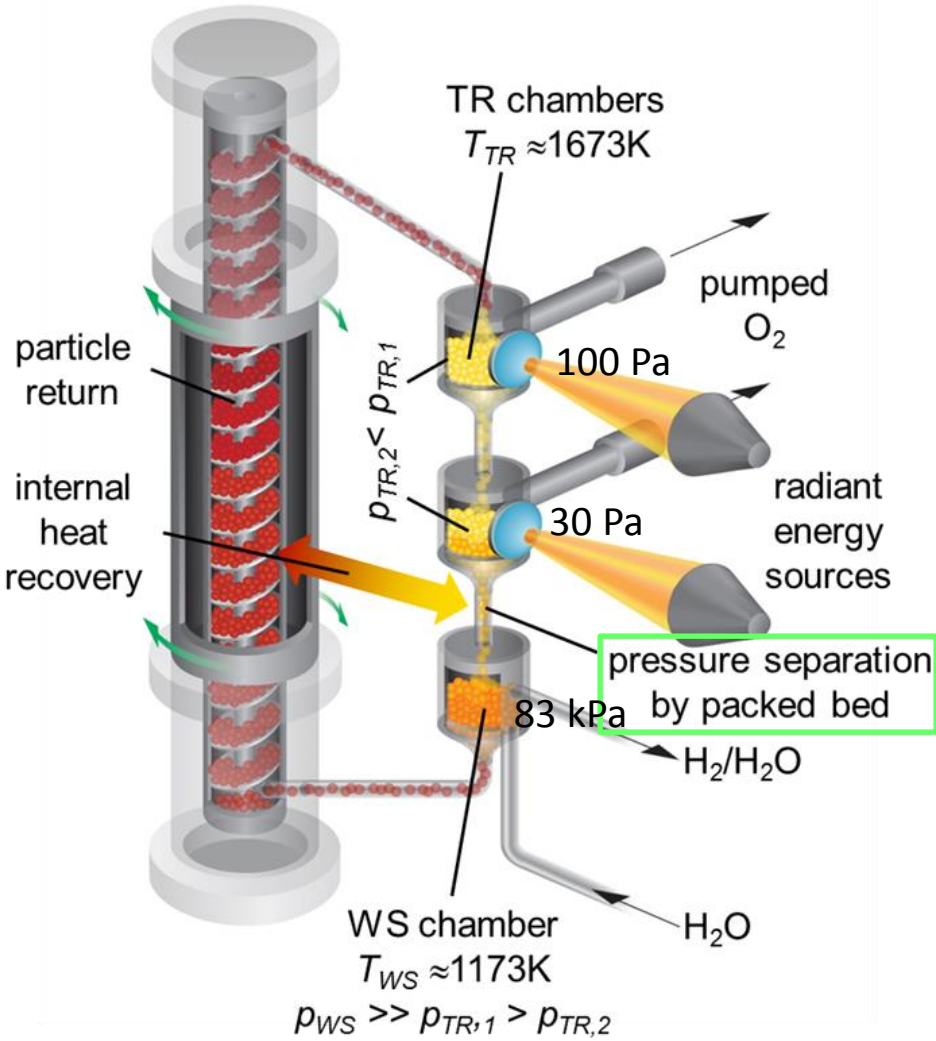
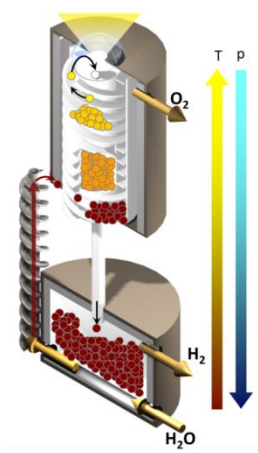
Cascading Pressure Reactor

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





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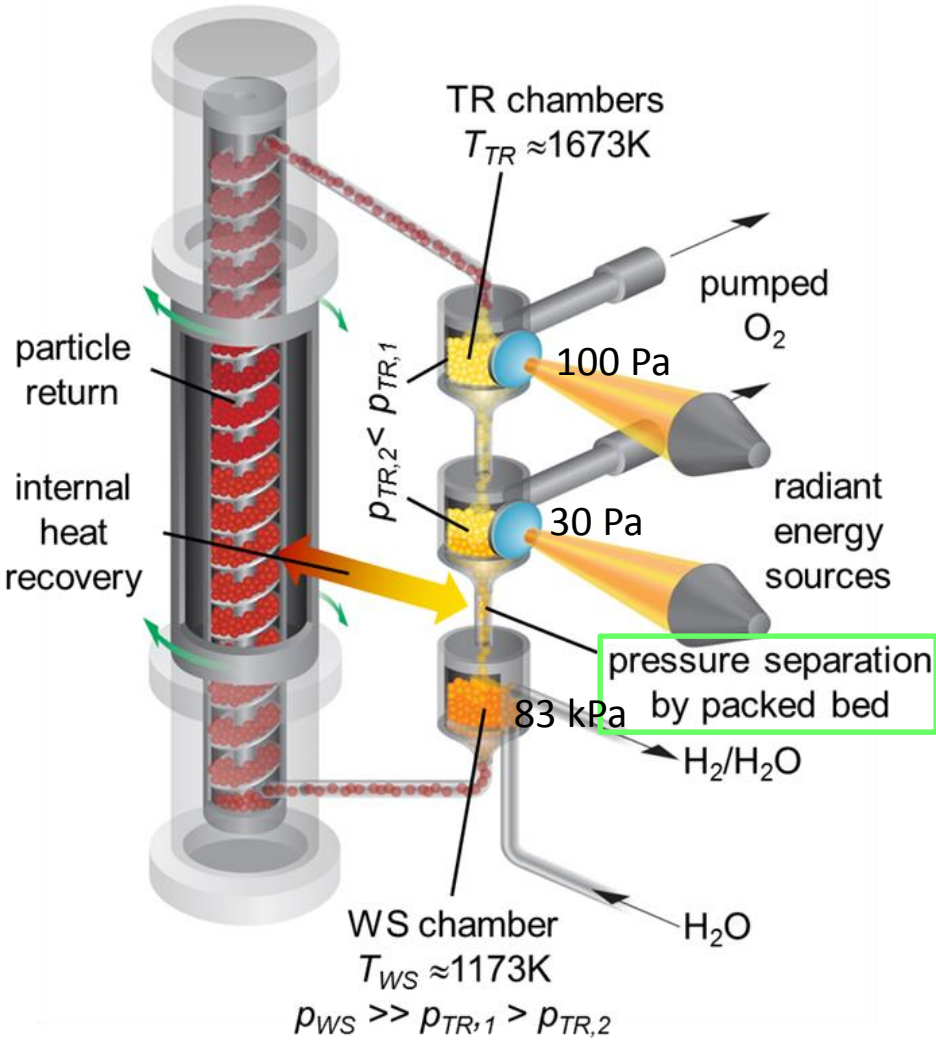
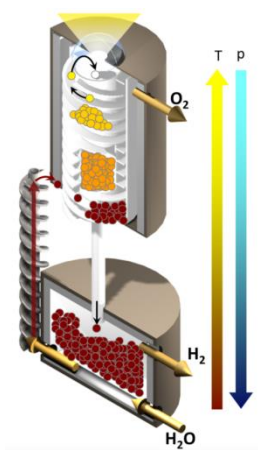
Cascading Pressure Reactor

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





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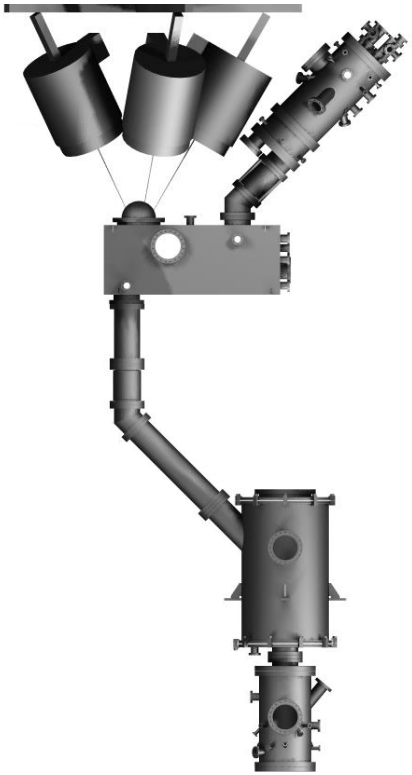
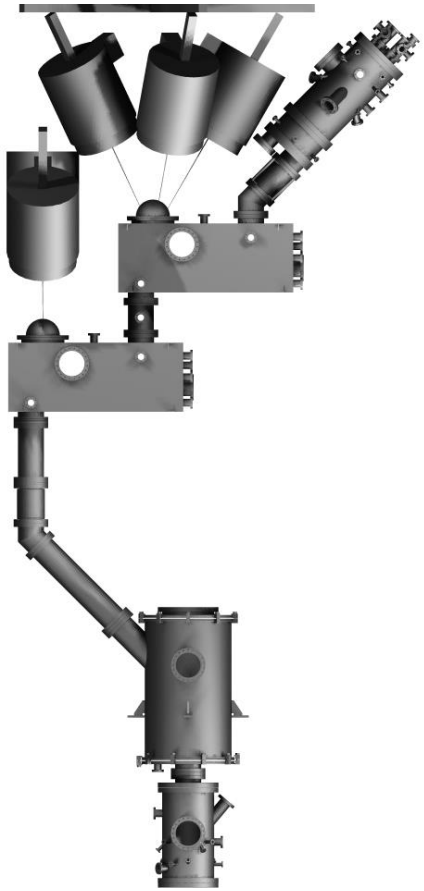
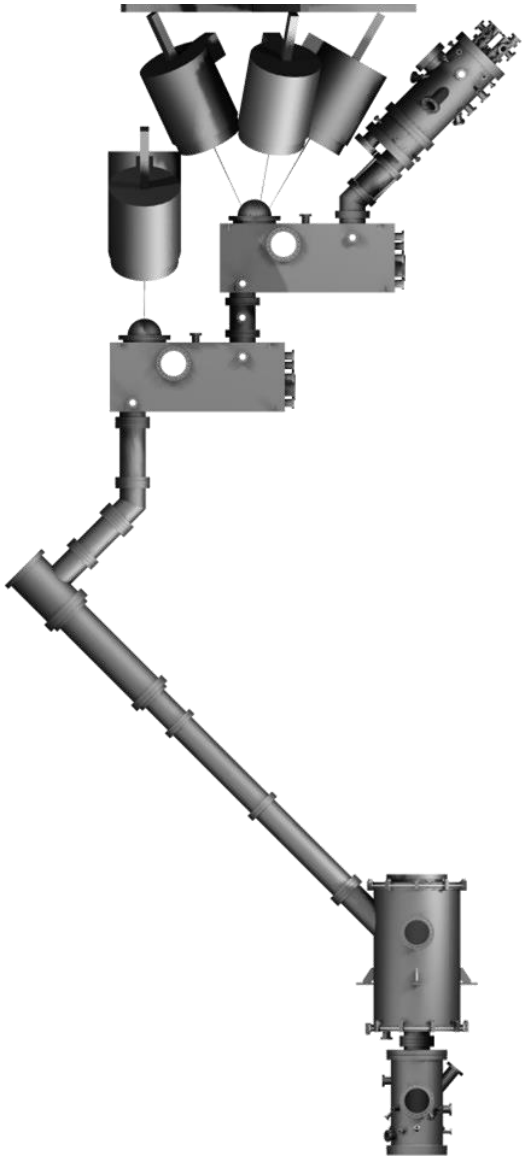
Staged Testing



Single TR Chamber
~10 kPa Oxidation



Cascading TR Chambers
~10 kPa Oxidation



Cascading TR Chambers
Ambient Pressure Oxidation

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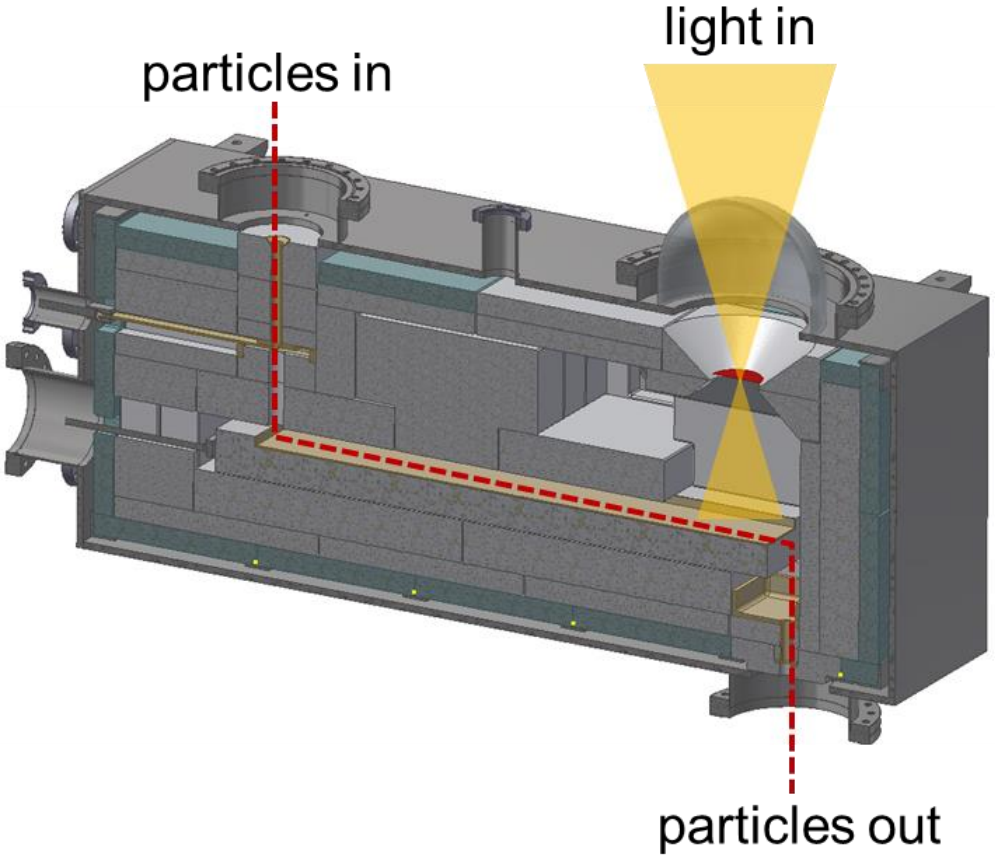
Slip-Stick Receiver



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

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Slip-Stick Receiver Operation

Ambient particle conveying test—side view of stick-slip plate action

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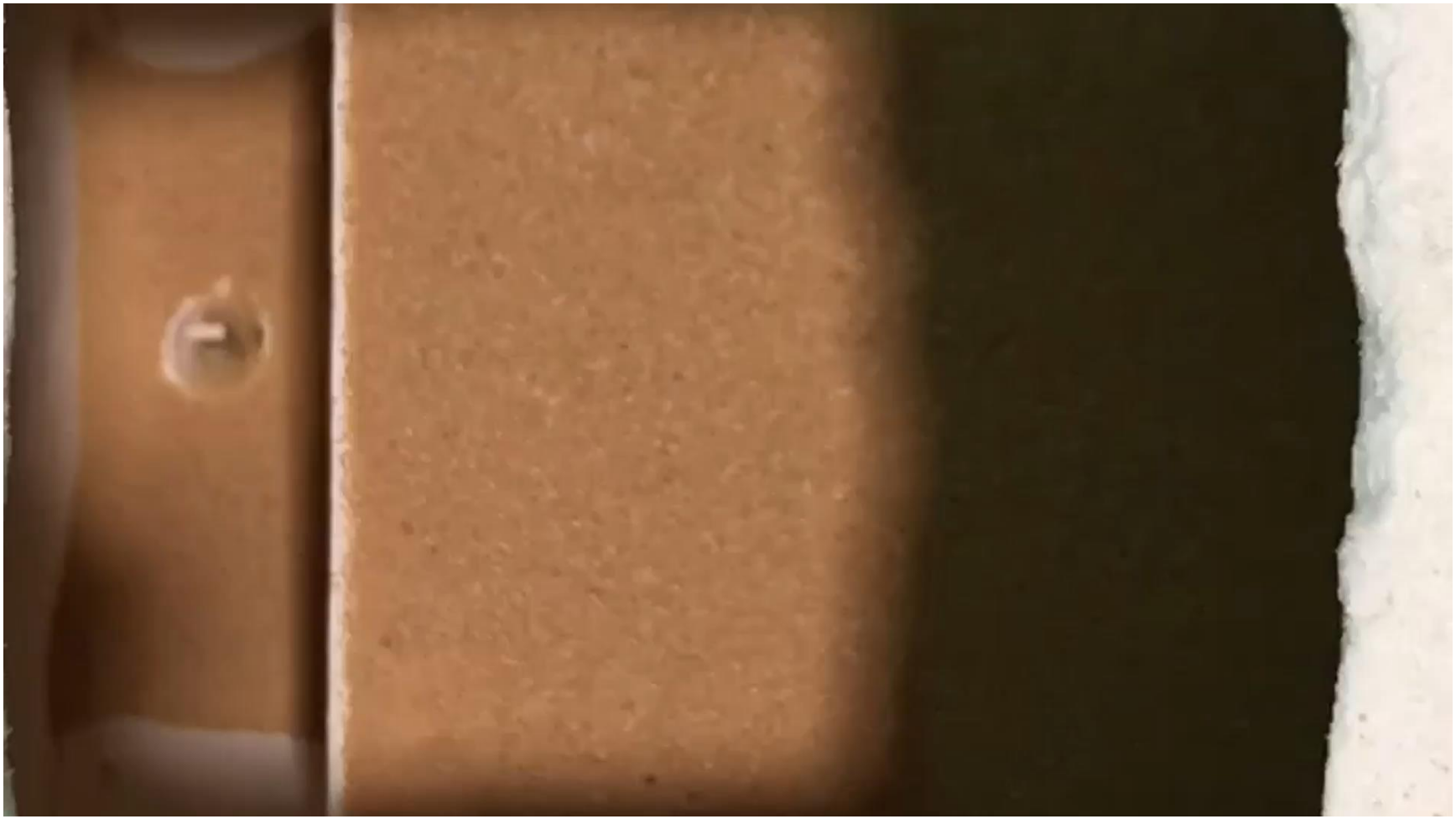
Slip-Stick Receiver Operation



Ambient particle conveying test—view of particles moving on plate

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Slip-Stick Receiver Operation

Ambient particle conveying test—particles exiting the discharge port

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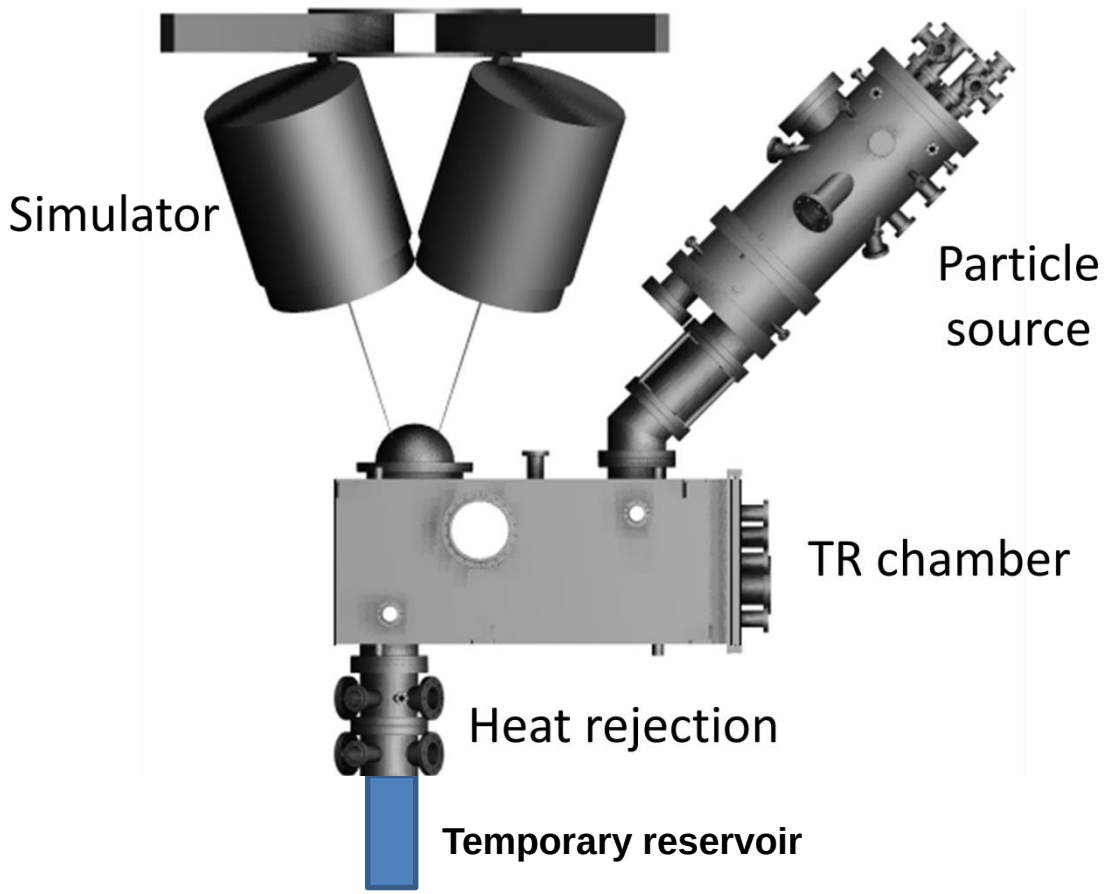
Partial System Test—Vacuum Reduction



p~100 Pa

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Slip-Stick Receiver Operation

Particle heating test—incandescent particles falling into temporary reservoir

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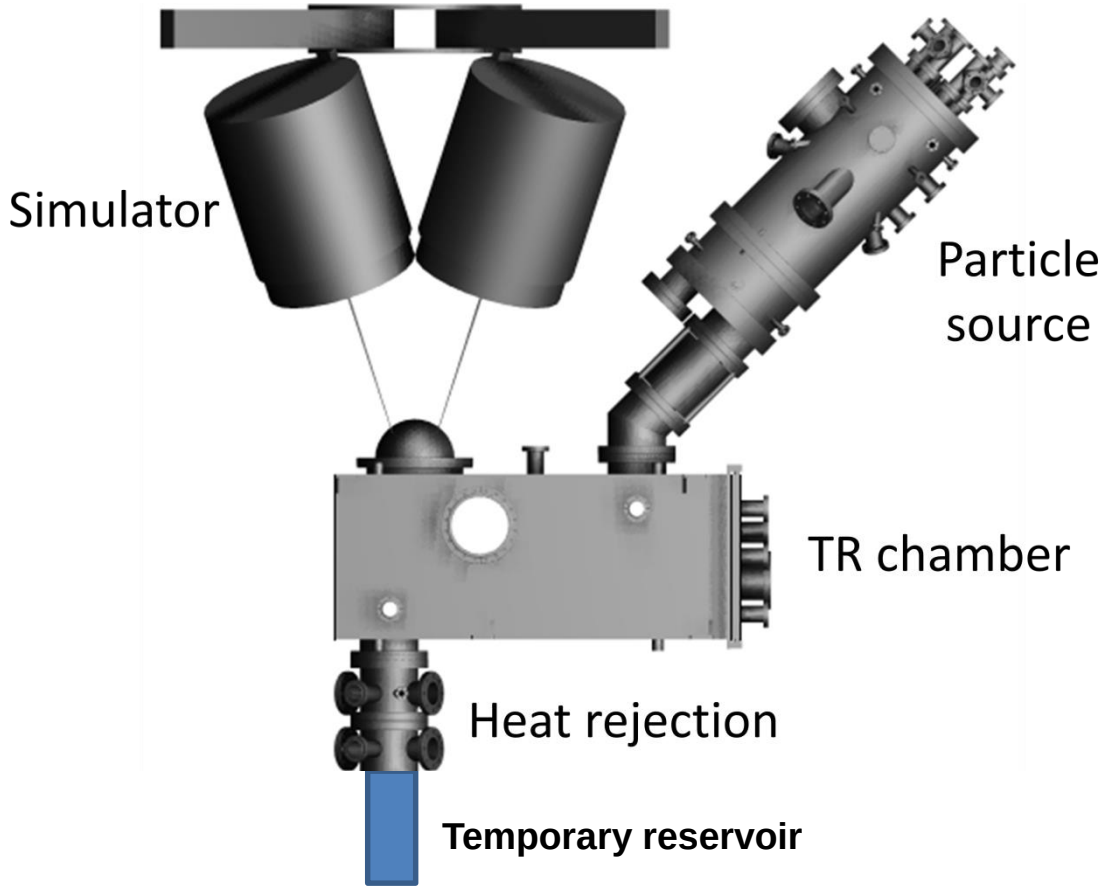
Partial System Test—Vacuum Reduction



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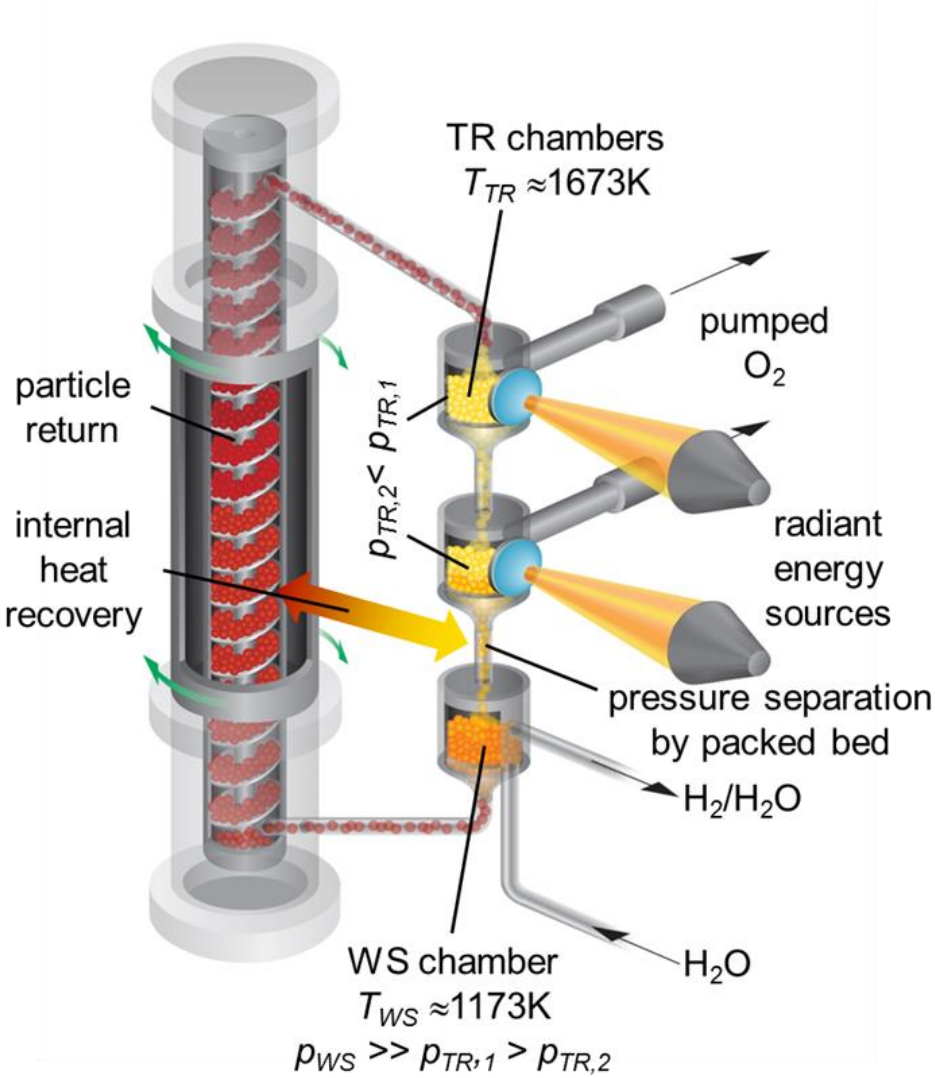
Summary and Next Steps



Thank you

Ivan Ermanoski iermano@sandia.gov

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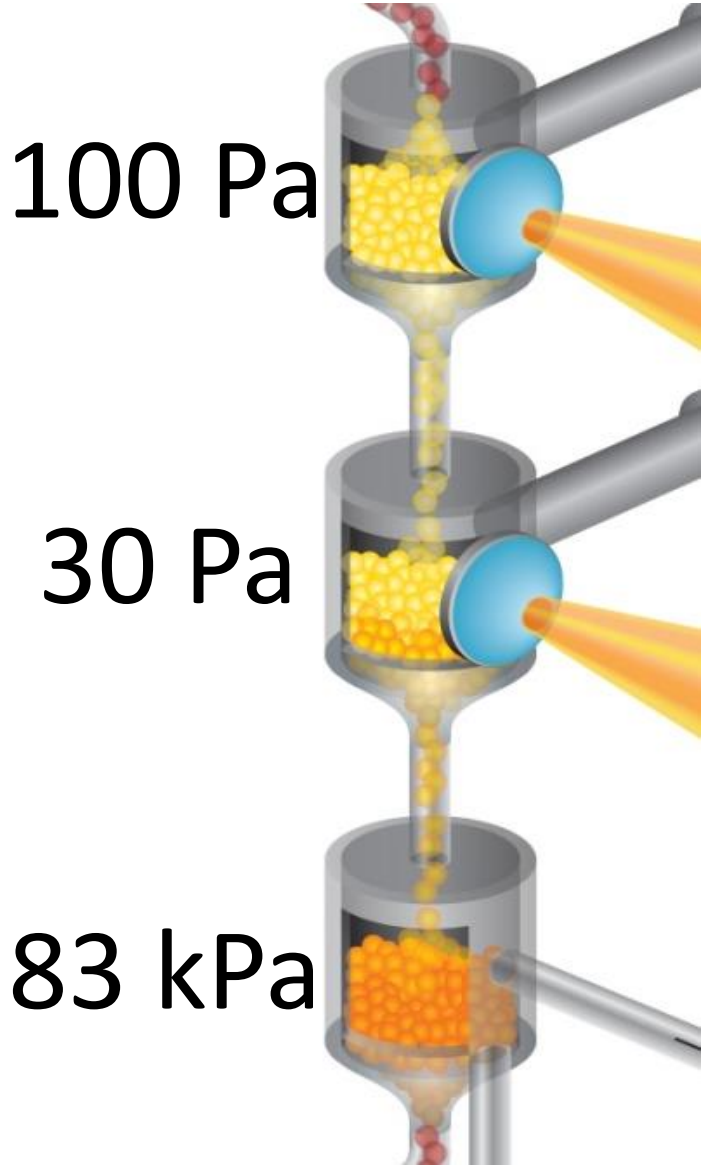
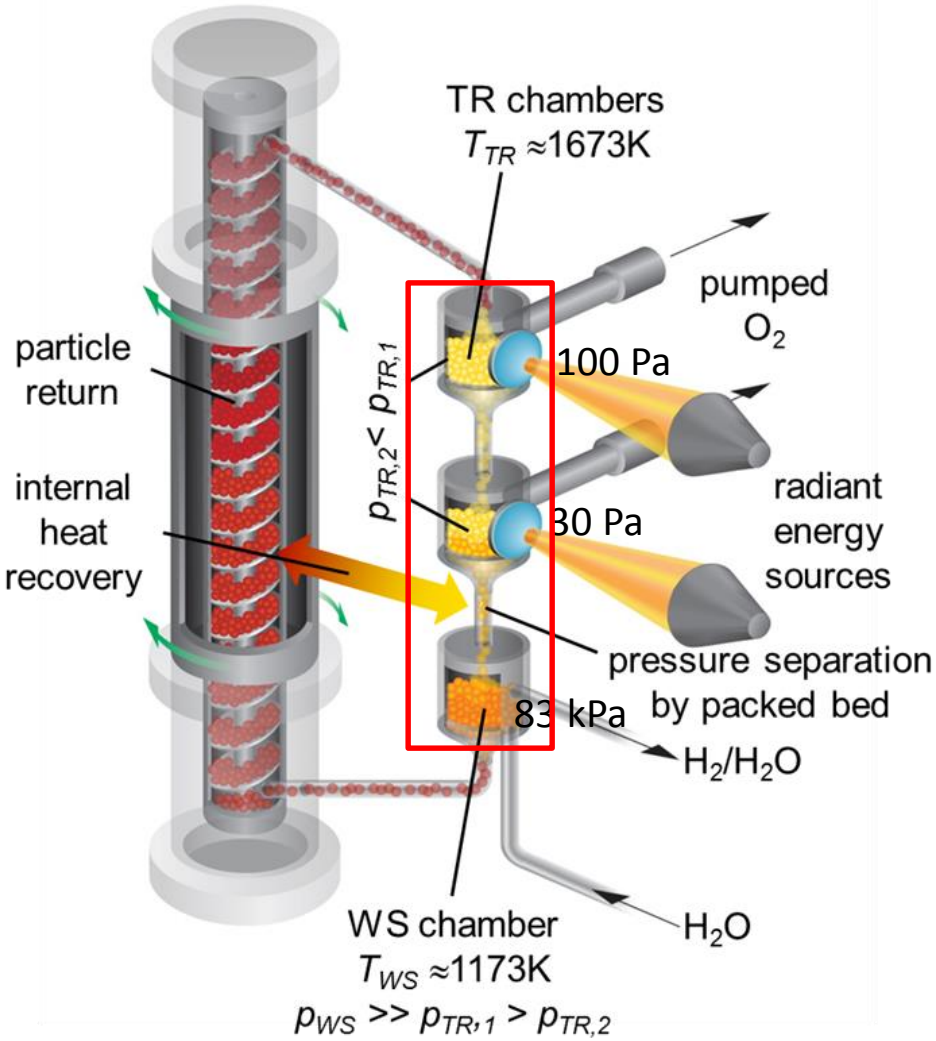
Pressure Separation by Particle Bed





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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

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

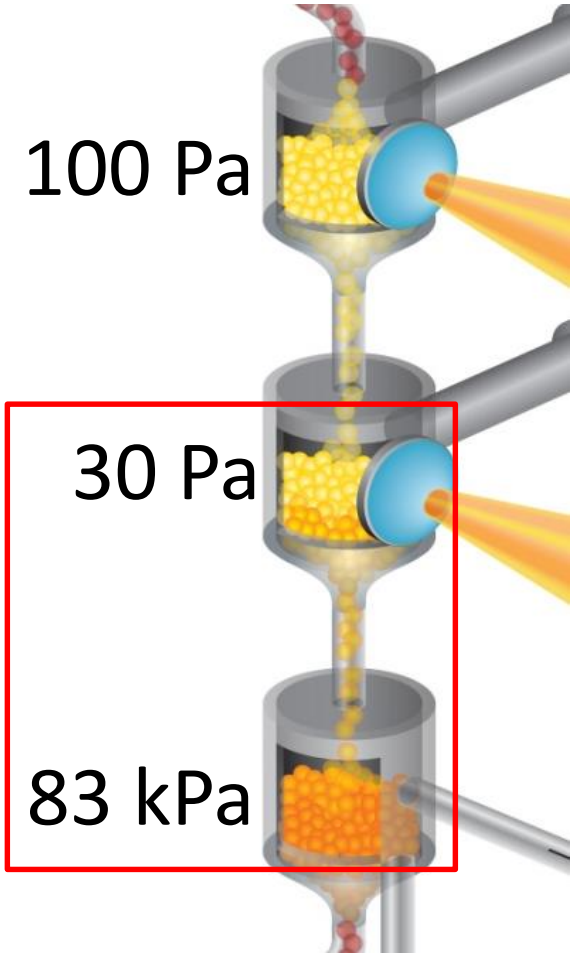
Knudsen correction factor

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

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

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

Must use full equations because of substantial pressure drops



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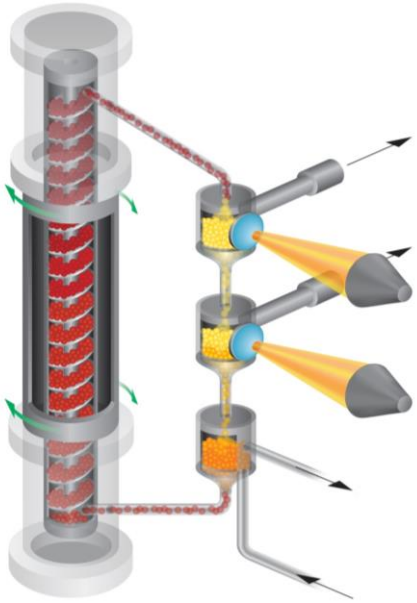
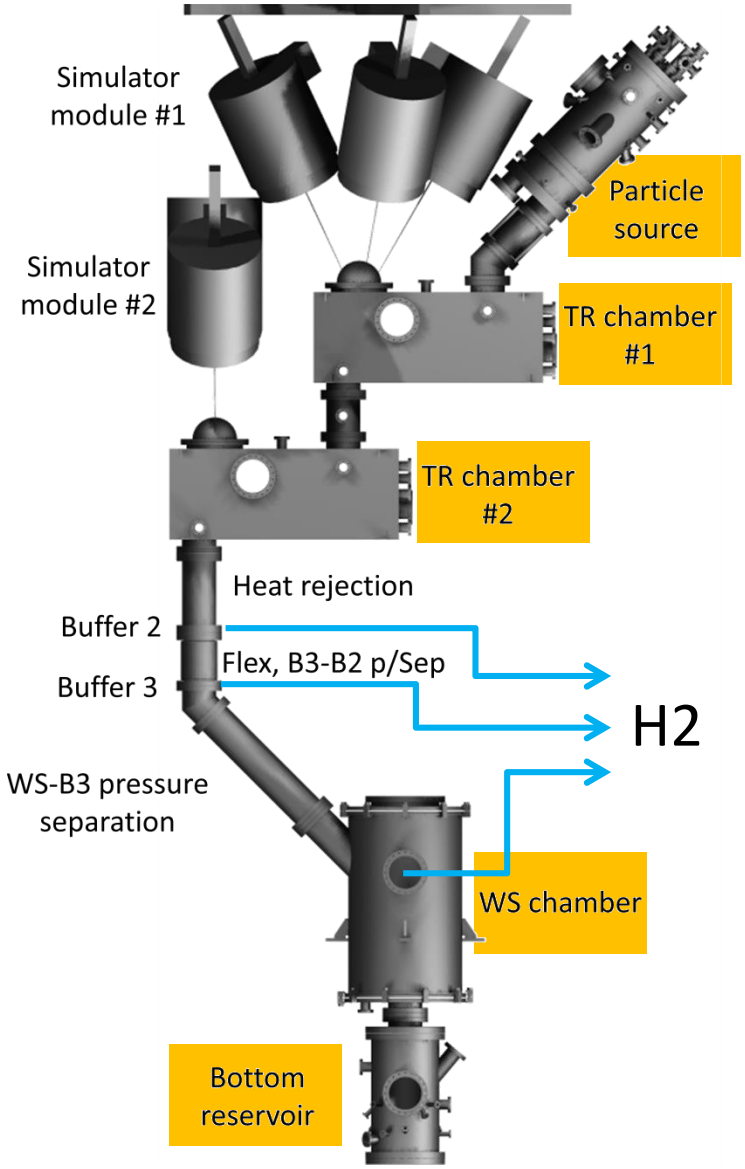
Staging Pressure Separation



Concept



Prototype

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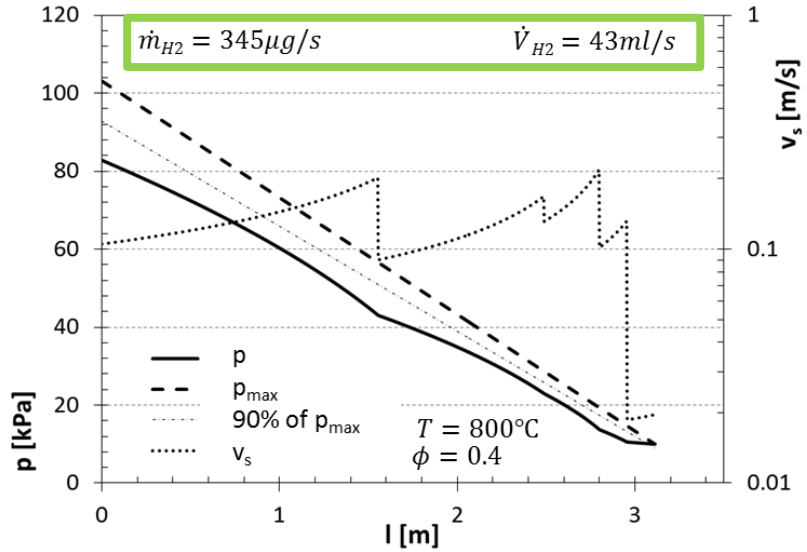
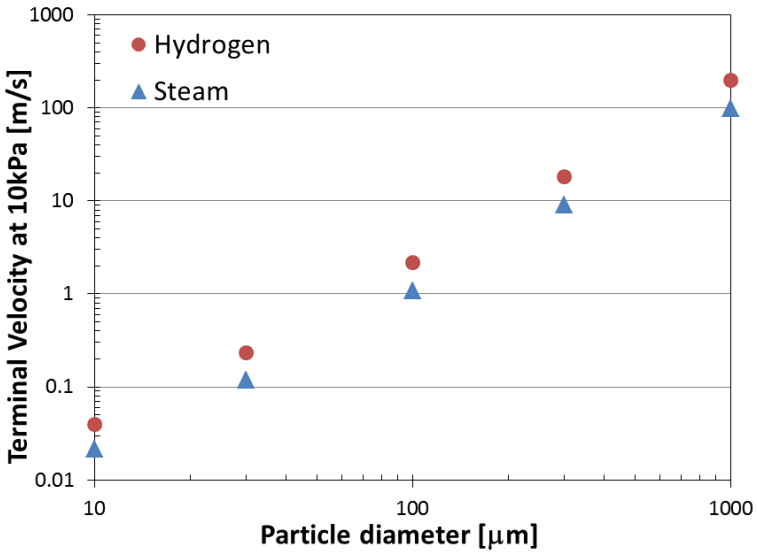
H_2 Permeation: WS to Buffer 3





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

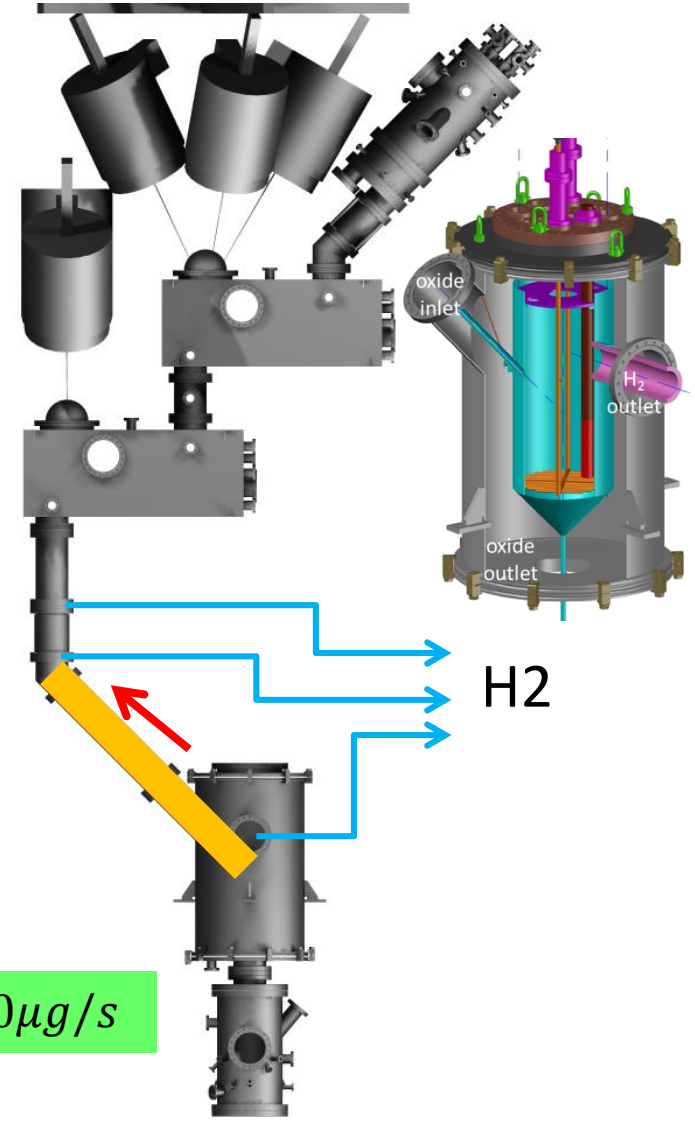
ID_i=15 mm
ID_f=50 mm
incline=45°

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

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

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

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



H_2 permeation vastly decreased by including buffer stage.

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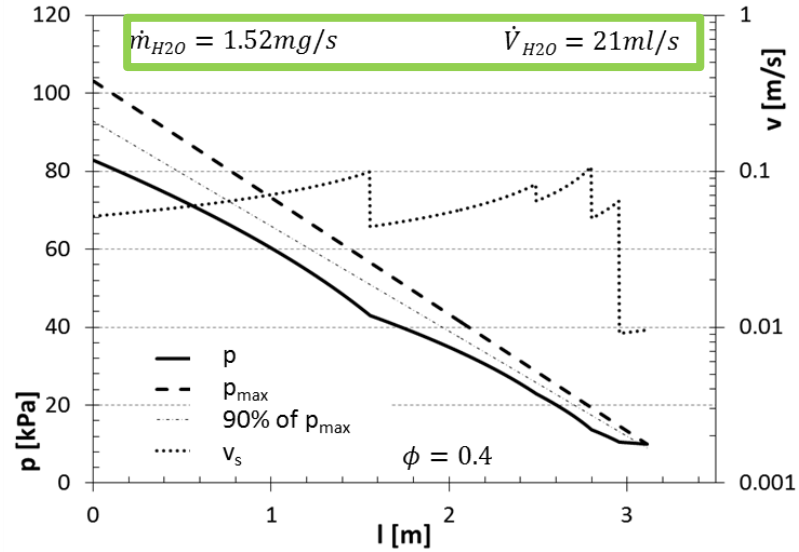
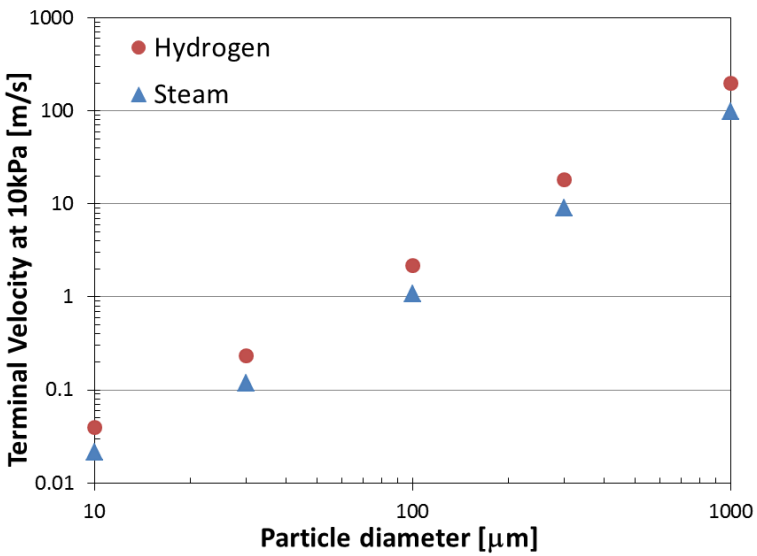
H_2O Permeation: WS to Buffer 3





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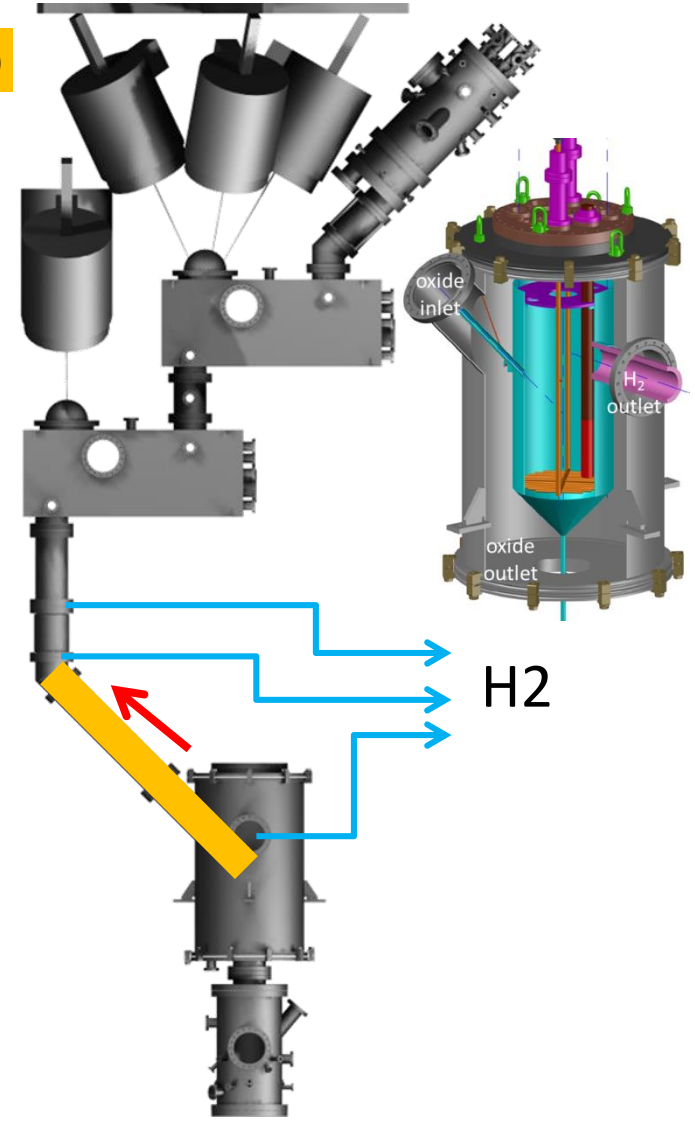

H_2 and H_2O pressure profiles are virtually identical.

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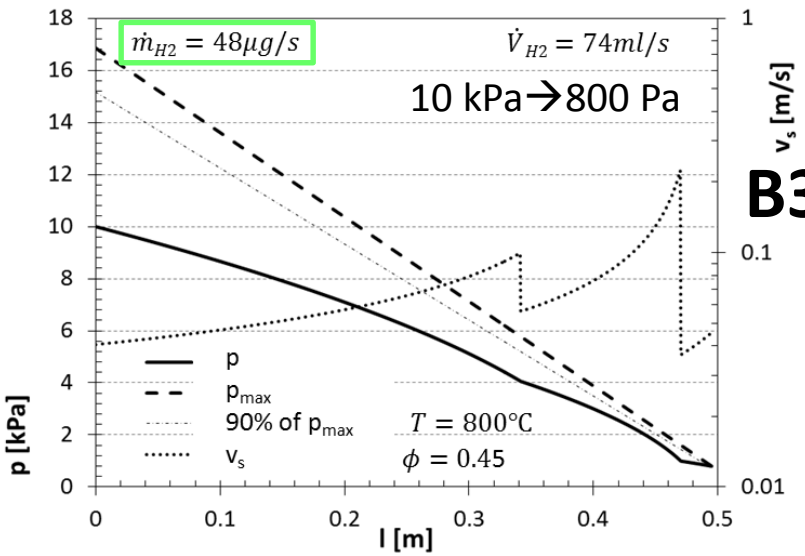
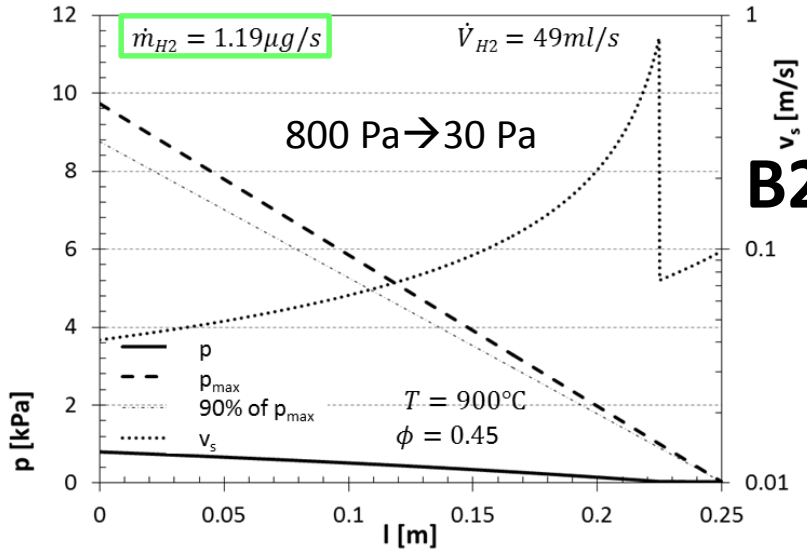
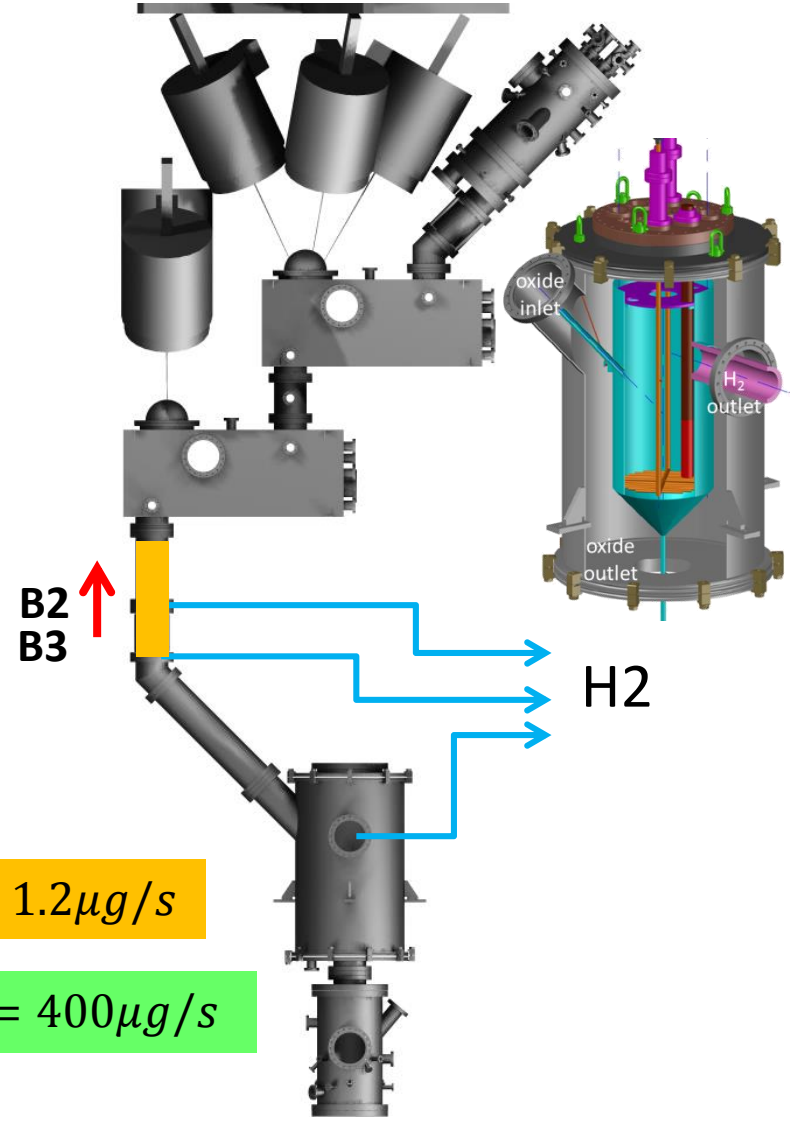
Buffer 3 to TR Chamber Permeation



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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Obstacles: Pressure Drop and Gas Expansion

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

83 kPa→100 Pa H_2
T=800°C
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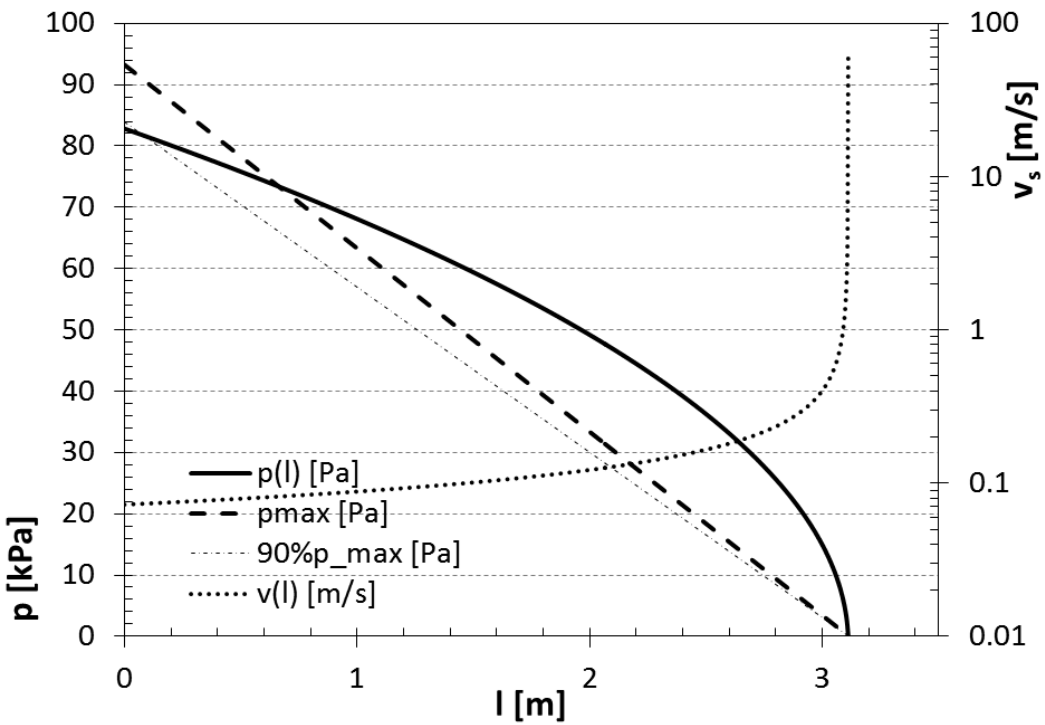
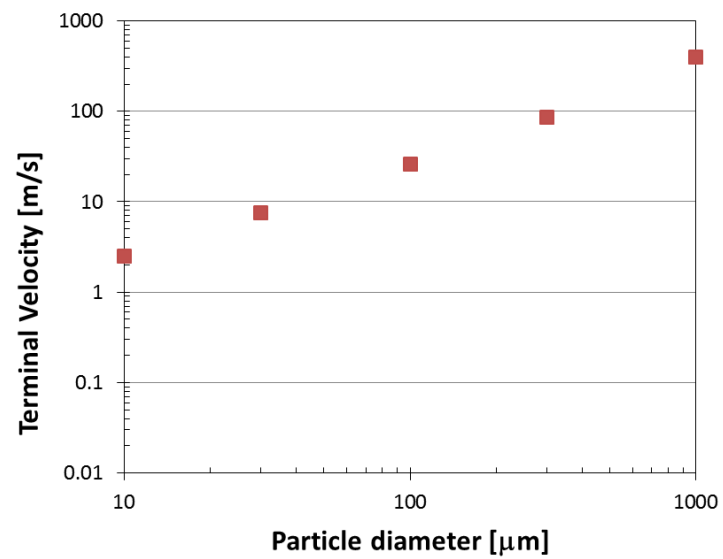
ID=15 mm
incline=45°





No solution under constant ID assumption: Fluidization occurs

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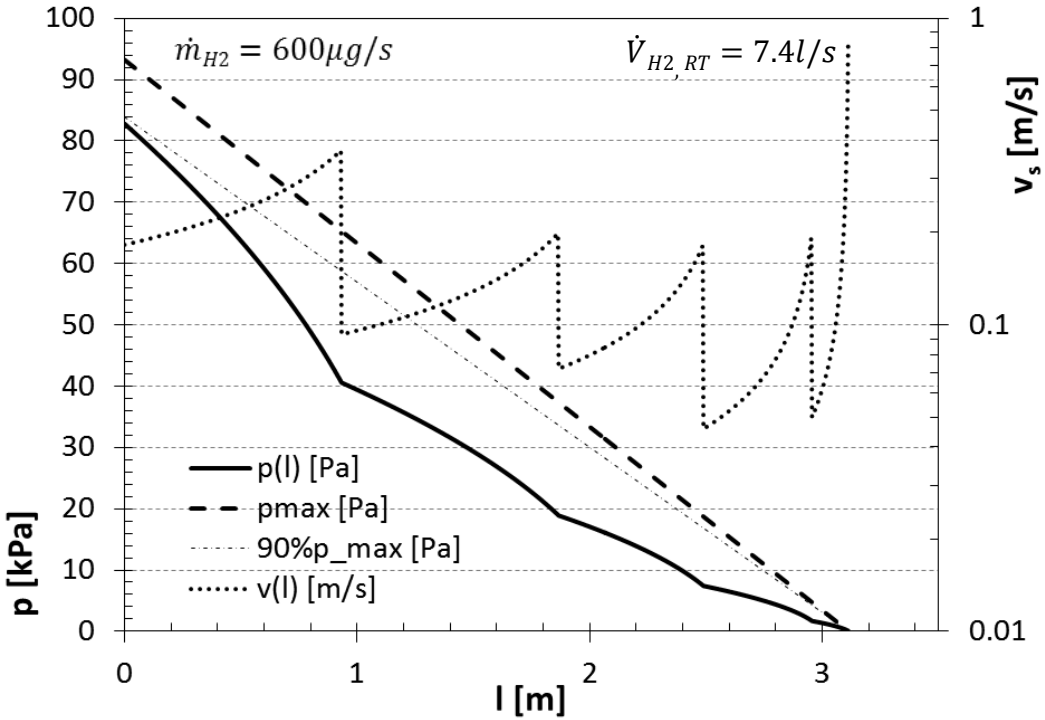
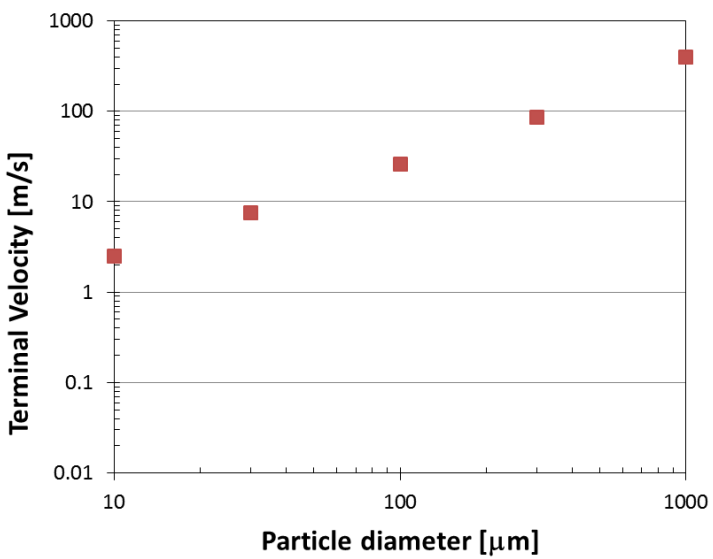
ID/Flow Expansion: Problem Solved?

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

83 kPa→100 Pa H_2
T=800°C
ϕ=0.4
D_p=300 μm

ID_i=15 mm
ID_f=200 mm
incline=45°





Staged flow expansion ensures pressure separation without fluidization

But…

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Obstacle: H_2-O_2 Recombination Loss

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

83 kPa→100 Pa H_2
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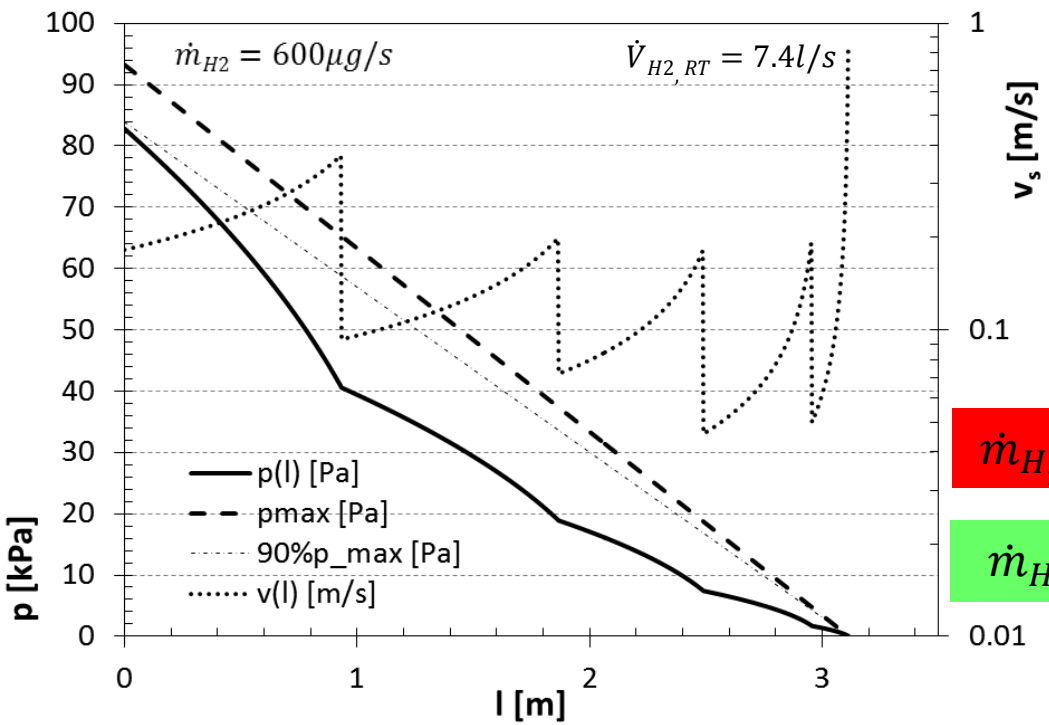

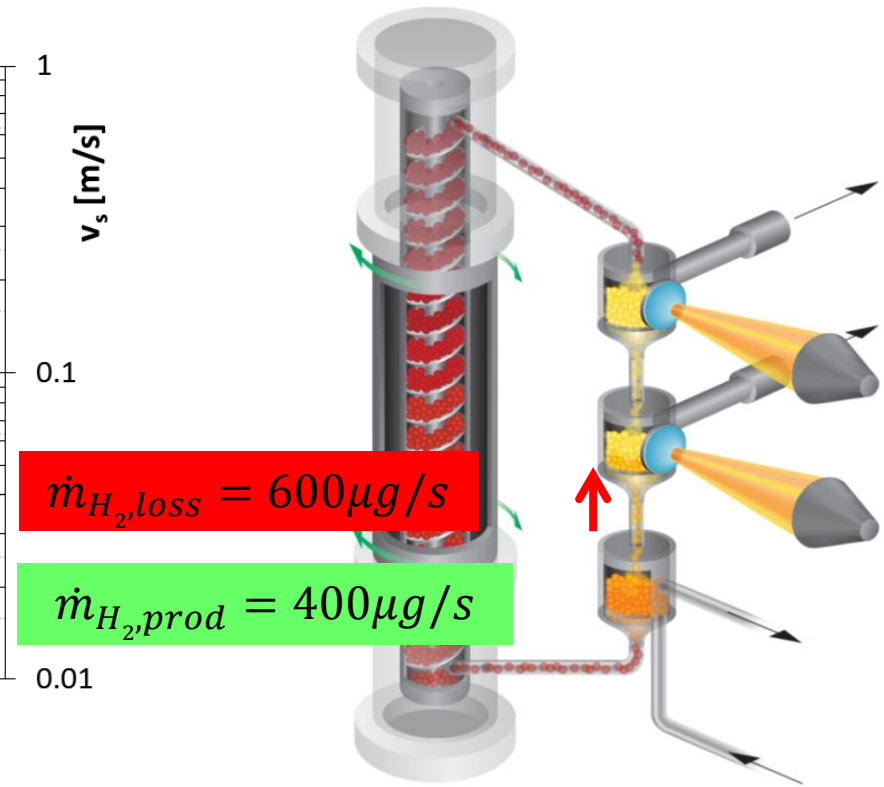

Staged flow expansion ensures pressure separation without fluidization

Gas flow to TR chamber must be significantly decreased

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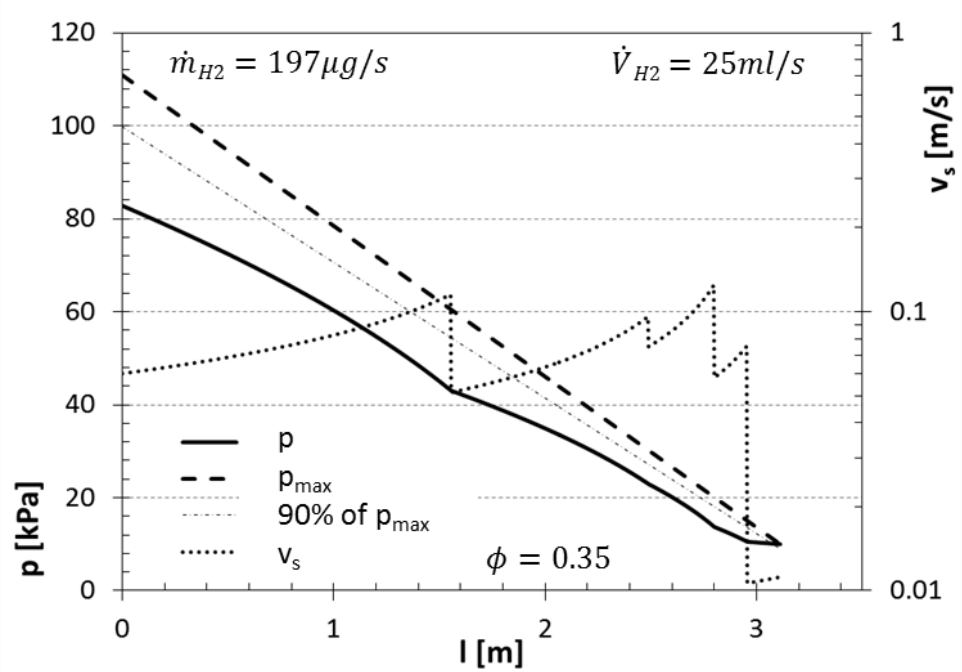
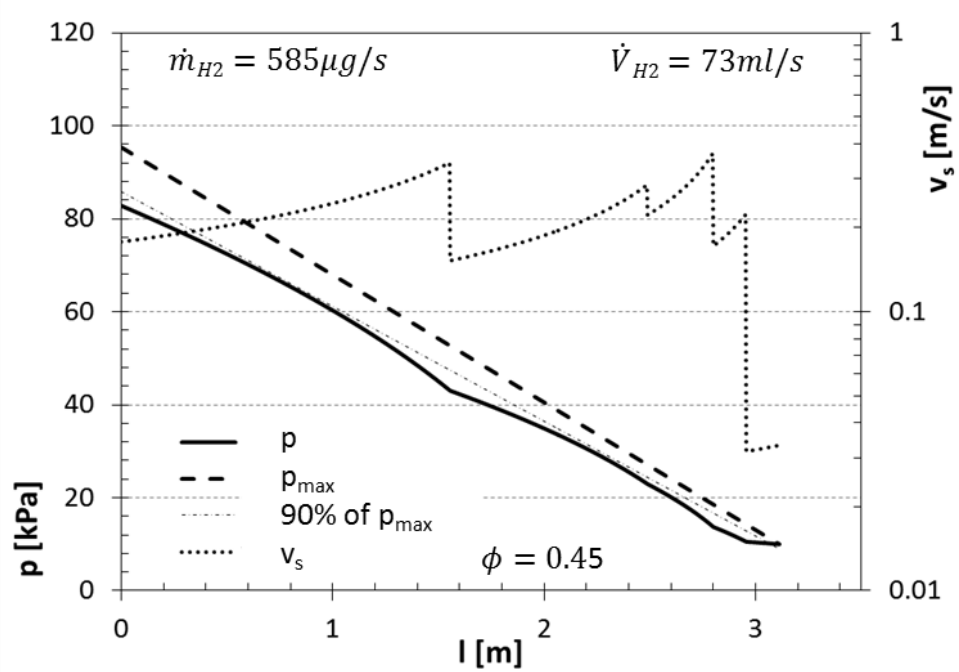
Permeation vs. Void Fraction





Nominal ϕ=0.4

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

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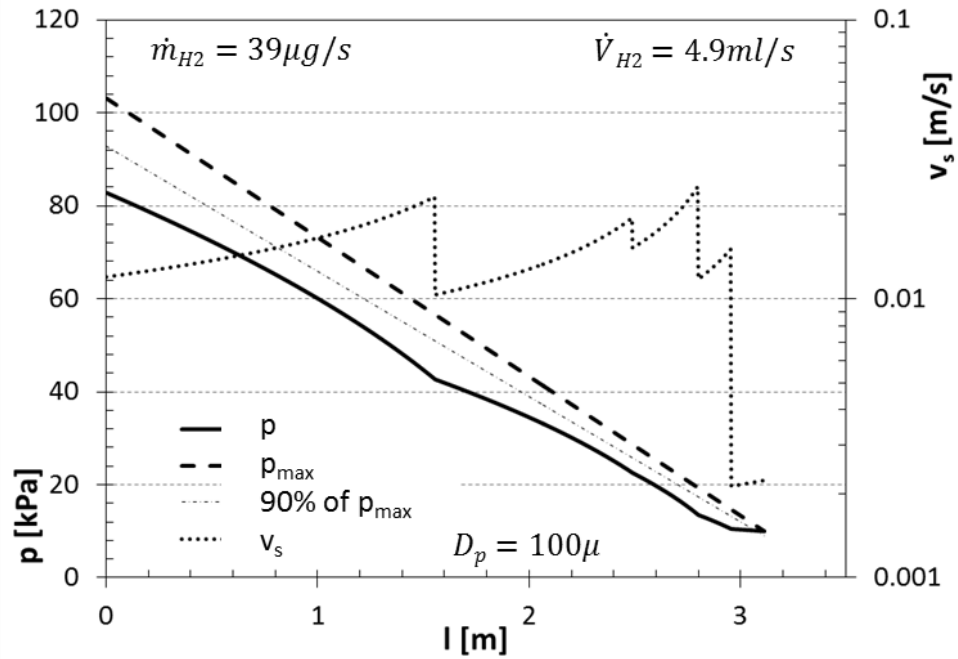
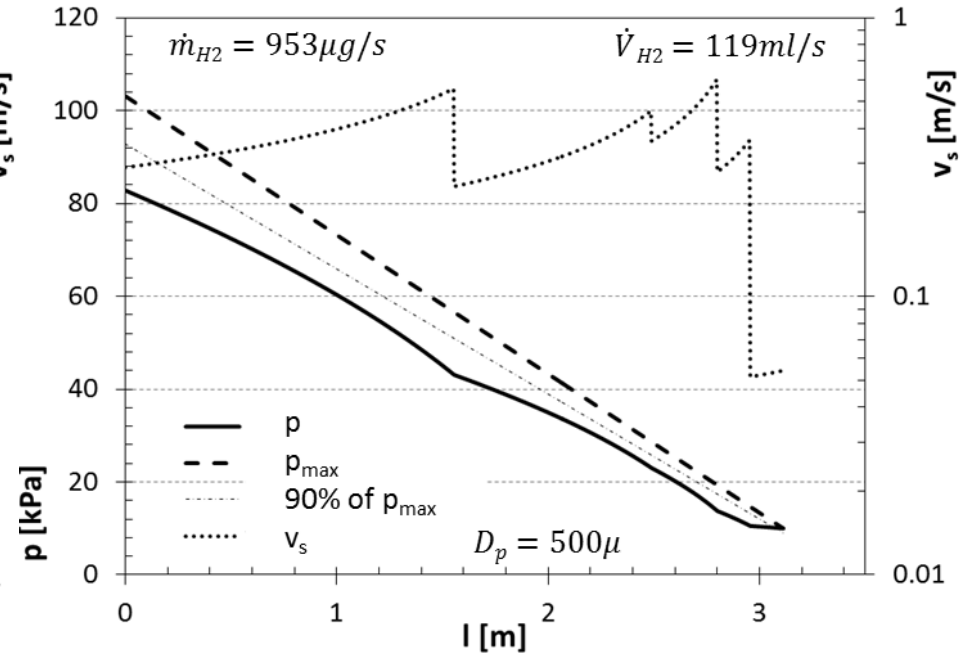
Permeation vs. Particle Size





Nominal D_p=300 μm

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

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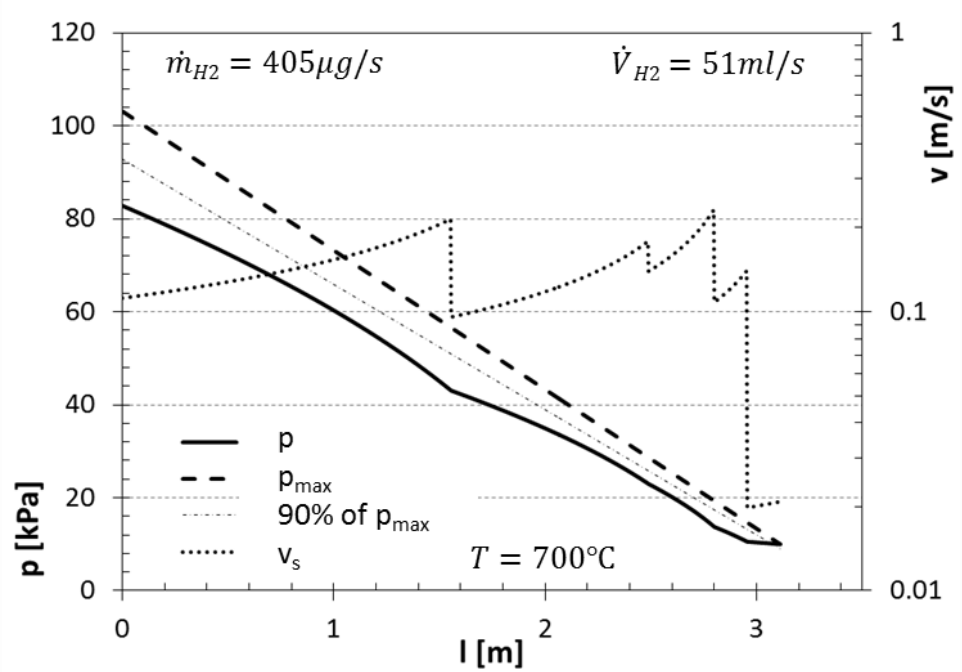
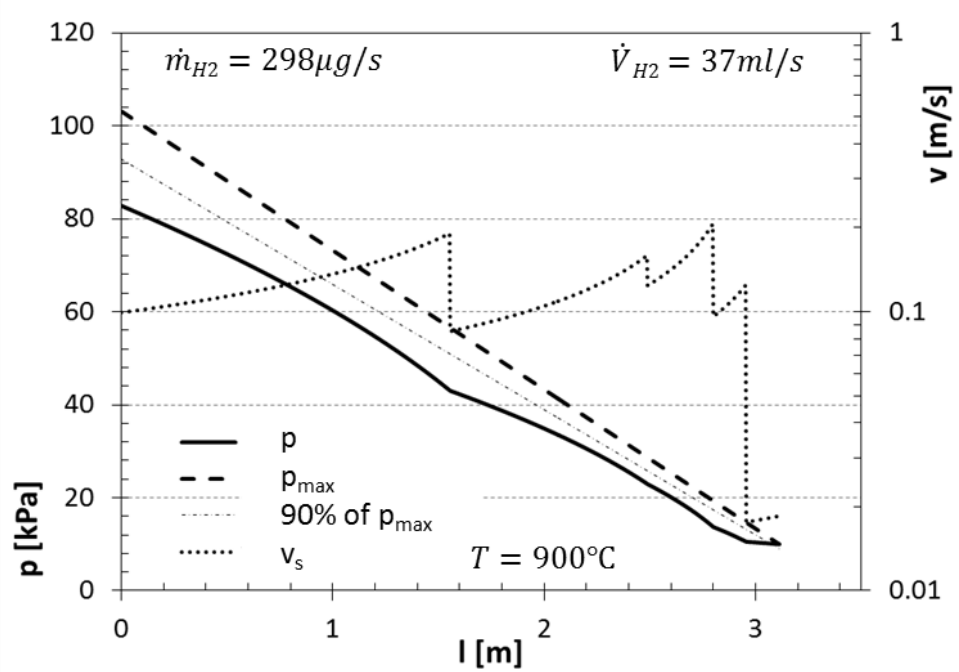
Permeation vs. Temperature





Nominal T=800°C

Temperature variations are of negligible importance.

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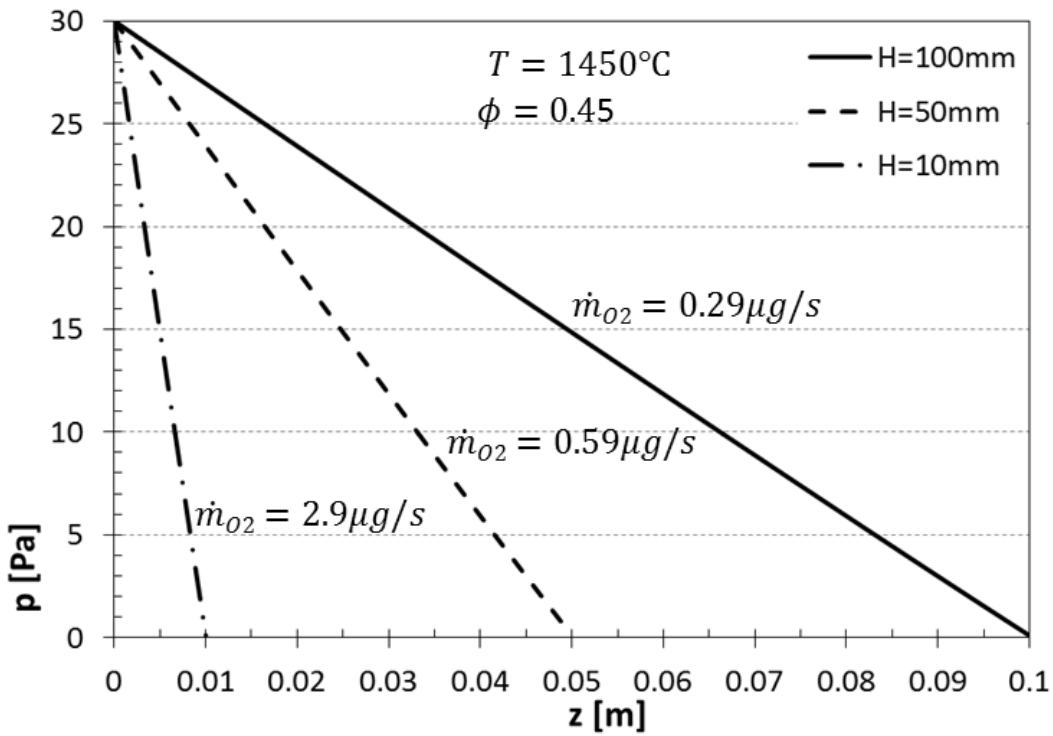
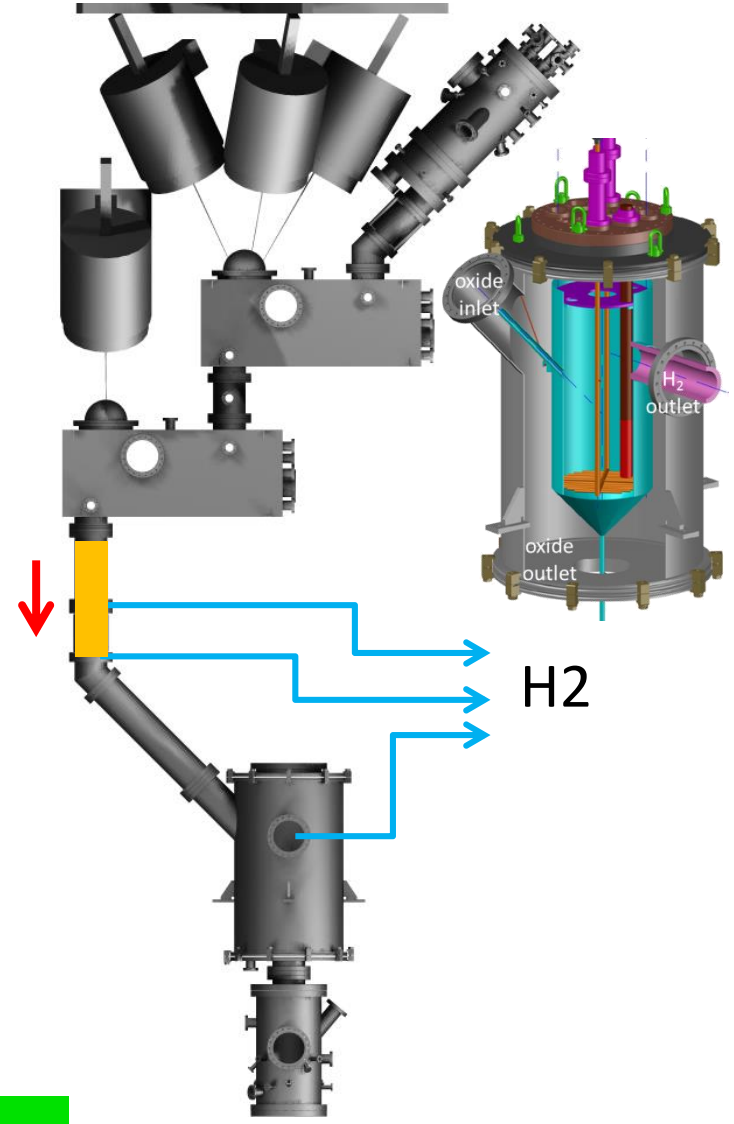
O_2 Permeation *From* TR Chamber





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

Oxide reoxidation is of negligible importance

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