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DMAVT
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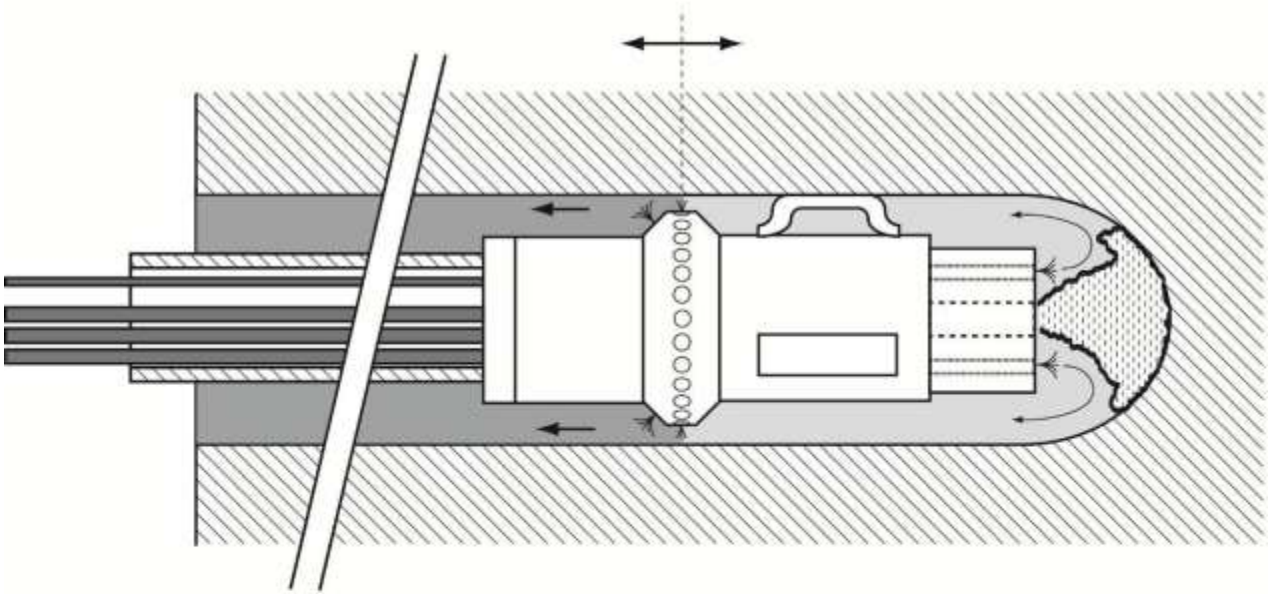
Department of Mechanical and Process Engineering

"Challenges in Hydrothermal Spallation Drilling for Deep Heat Mining Projects"

SLN-workshop "Photonics for Deep Geothermal Energy Harvesting" Neuchâtel, Switzerland, 07.11.2012

M. Schuler, T. Rothenfluh, P. Stathopoulos, D. Brkic, T. Meier, Ph. Rudolf von Rohr

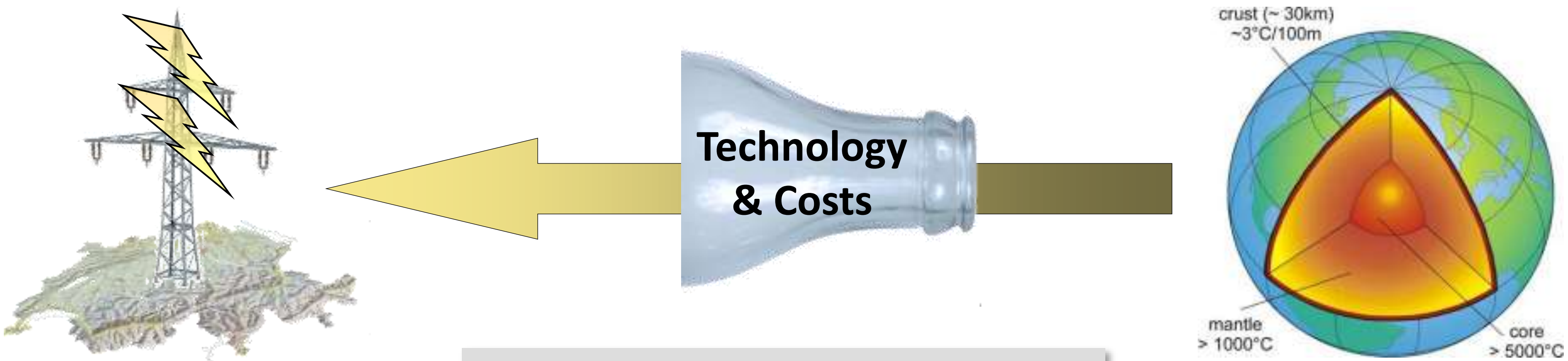


Overview

- Introduction
- Spallation Rock Drilling
- Background and Motivation
- Challenges in Hydrothermal Spallation Drilling (HSD)
  - Entrainment and turbulent mixing
  - Heat transfer of impinging hot jets
  - Ignition of hydrothermal flames
- Main Risks for Hydrothermal Spallation Drilling
- Conclusions
- Outlook

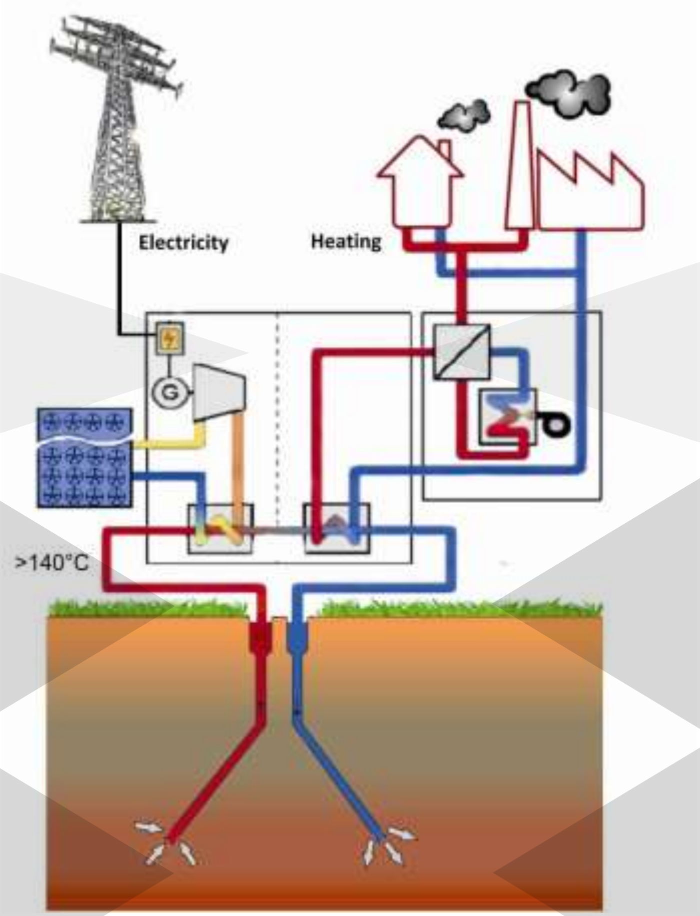
Geothermal Energy - Technology as Bottleneck

Energy Demand | **Geothermal Potential**



Overcoming Bottleneck
Developing necessary technologies and reducing costs

Geothermal Power Plant – Technical Challenges



Electricity
Rankine and Kalina cycle

Drilling
- decreasing costs
- improve convential concepts
- alternative drilling concepts

Accessing reservoir
- hydro-fracturing
- induced seismicity
- characterization

Heating
improved use of waste heat

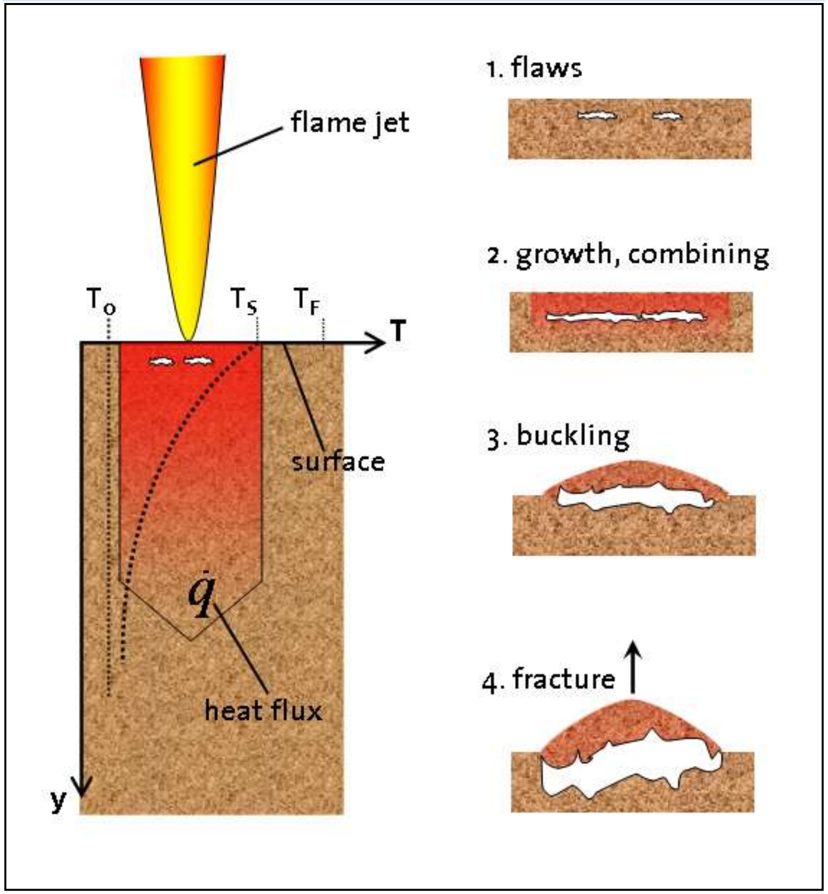
Surface prediction tools
- estimation of reservoir potential
- decreasing costs

Operation
- corrosion problems
- mineral deposits

Sources: Heuze et al. (2003)

Spallation Rock Drilling

Rock fracturing mechanism



(Preston et al. 1934, Rauenzahn et al. 1986)

Crucial parameters

Granite (Barre, USA**)**

<u>Heat flux</u>: $\dot{q} > 1.0\ MW/m^2$

<u>Surface temperature</u>: $T_s - T_o = \Delta T_s \sim 500\,°C$

R. M. Rauenzahn et al. 1989 and J. W. Tester et al. 1990

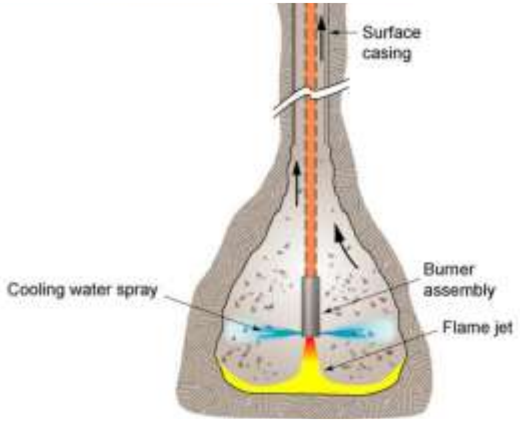
Main advantages

- ***Heat shocks instead of mechanical forces to break the rock***
- ***"Contact-free" drilling approach***
  - ***Less frequent replacement of drilling heads***
  - ***Less trip time in the drilling process***
  - ***Reduced drilling costs***

WO Patent, J. North, 1996
US Patent, Potter et al., 1998

Spallation Rock Drilling

Field test of spallation drilling at ambient conditions



Rock	Hole dimensions	Drilling rate
Limestone	15 cm x 15 cm	0.6 m/hr
Quartzite	13 cm x 30 cm	3.6 m/hr
Rhyolite	20 cm x 60 cm	2.5 m/hr

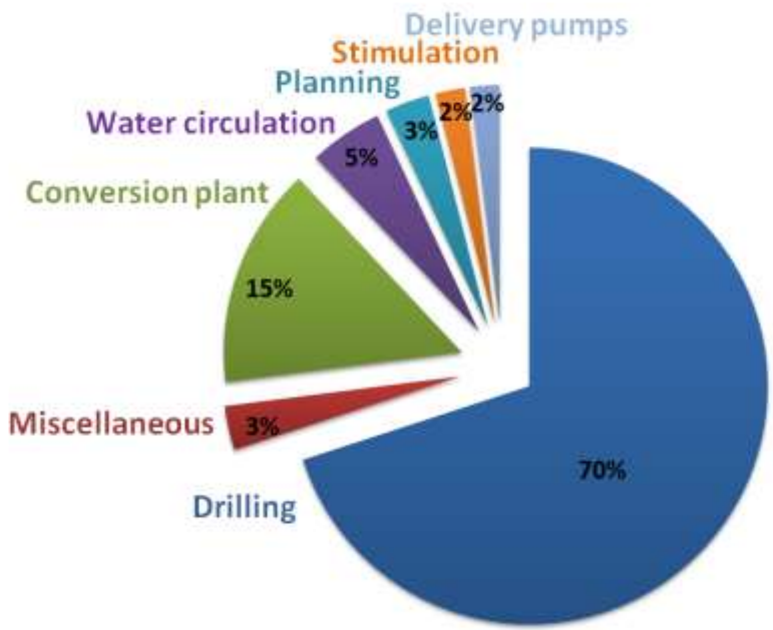
R. E. Williams, R. M. Potter and S. Miska, 1996

Researcher	Year	Rock	Depth	Diameter	Drilling rate	Fuel - oxidizer	Chamber pressure	Air flow
Browning et al.	1981	Granite, Conway, USA	335 m	0.2 - 0.25 m	15.8 m/hr	Fuel oil & air	34 bars	34.4 m^3/min
Browning et al.	1981	Granite, Barre, USA	130 m	0.35 - 0.4 m	7.6 m/hr	Fuel oil & air	8.6 bars	34.4 m^3/min
Los Alamos Laboratory	1985	Granite, Pedernal, USA	30 m	0.35 - 0.45 m	6–7 m/hr	Fuel oil & air	7.6 bars	31.5 m^3/min

Sorce figure: Donald Dreesen, Los Alamos National Laboratory, Robert Bretz, New Mexico Institute of Mining and Technology, 2004

Background and Motivation

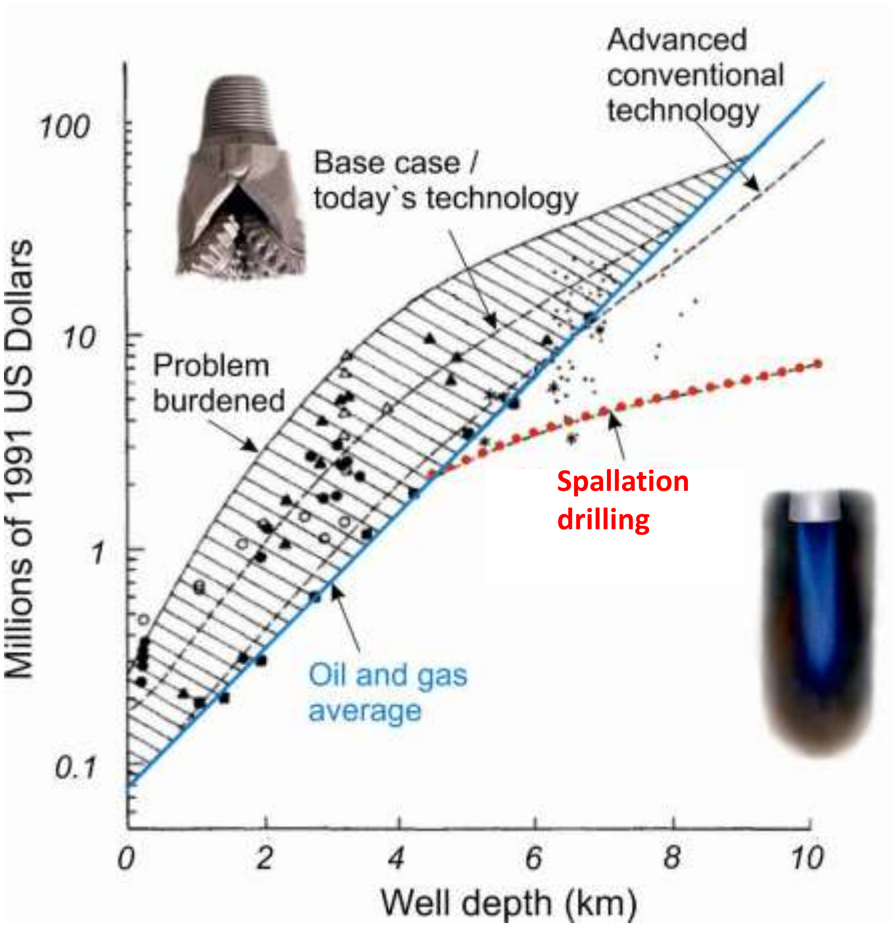
Costs for a geothermal power plant (Germany)



(Tiefe Geothermie in Deutschland, BMU, 09/2007)

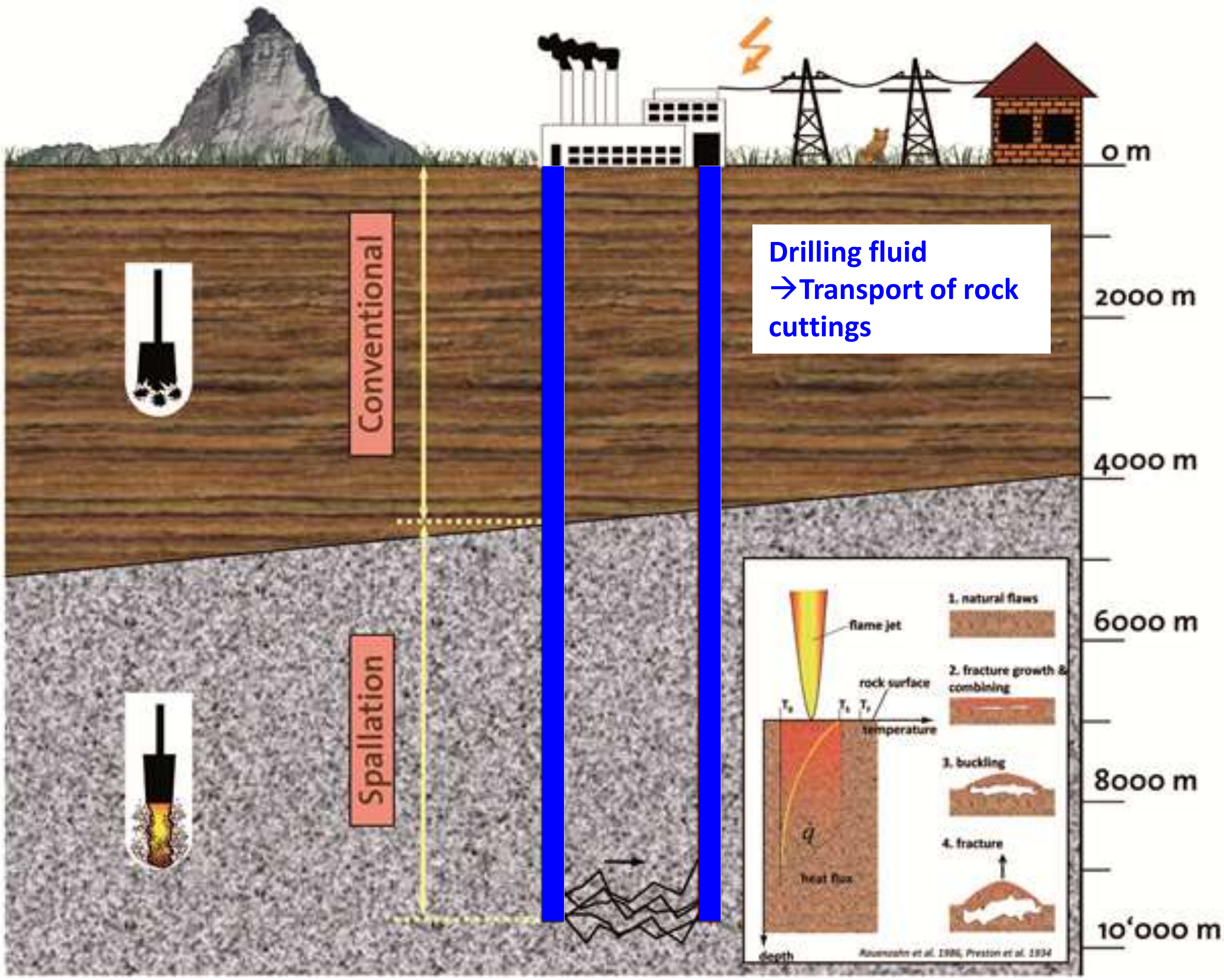
⇨ **The drilling costs account for about 70% of the total costs**

Drilling cost development with depth



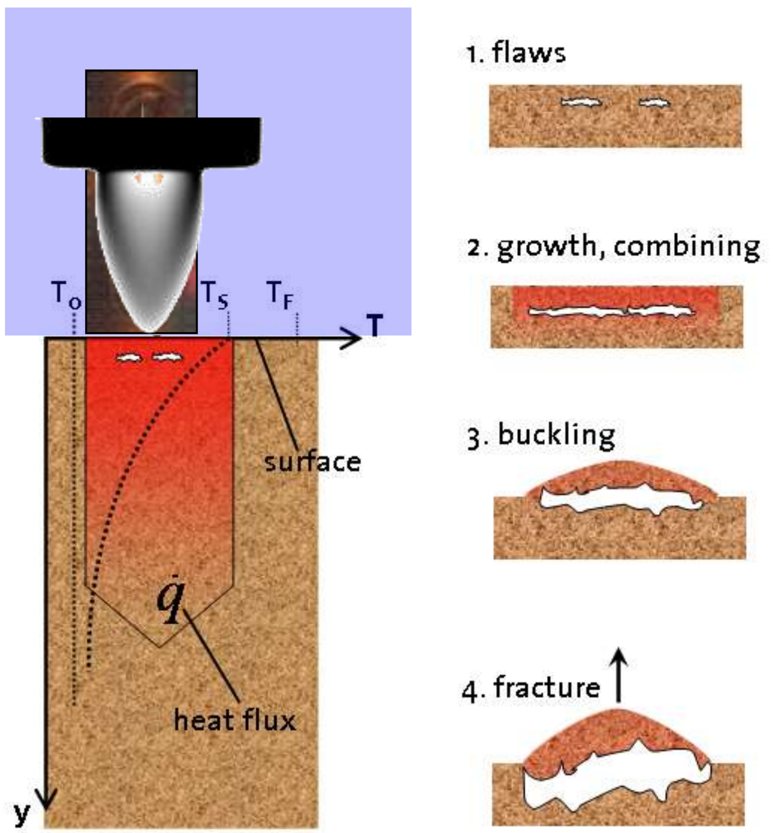
WO Patent, J. North, 1996
US Patent, Potter et al., 1998

Background and Motivation



Background and Motivation

Spallation drilling in great depth → Hydrothermal spallation drilling (HSD)



(Preston et al. 1934, Rauenzahn et al. 1986)

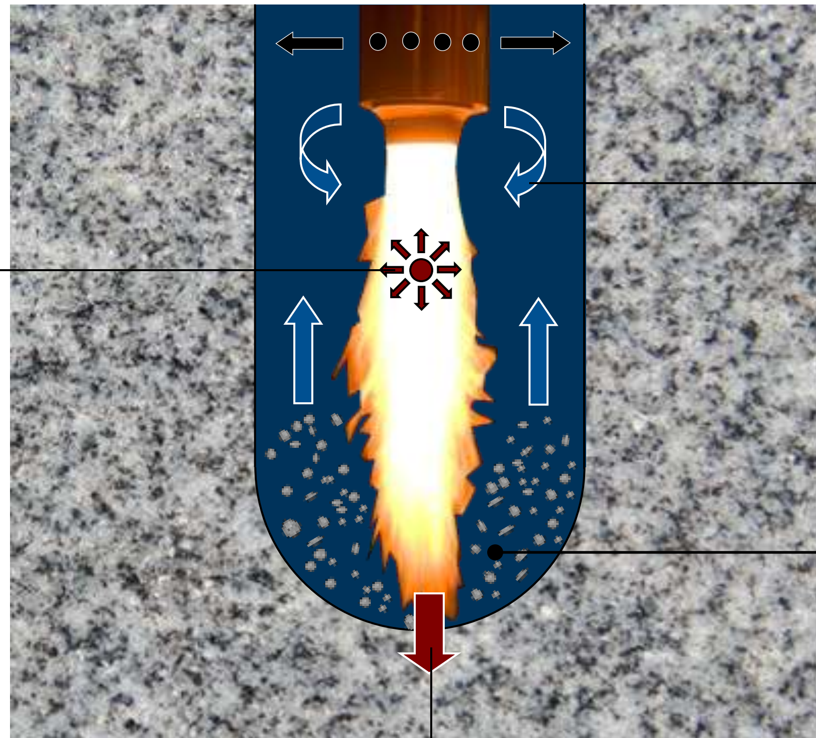
- Drilling fluid required for deep wells
- Spallation drilling in a e.g. water-based drilling fluid

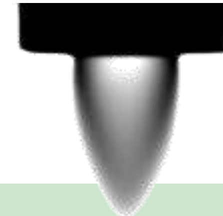
  → ***"Hydrothermal Spallation Drilling"* (HSD)**

  C. R. Augustine, PhD Thesis, MIT, 2009

- **Possible heat sources for HSD**
  - Hot supercritical water (SCW) jets

Challenges in Hydrothermal Spallation Drilling (HSD)





Combustion in aqueous environment

- Hydrothermal flame
- Ignition
- Location of reaction
- Decay of additives

Entrainment

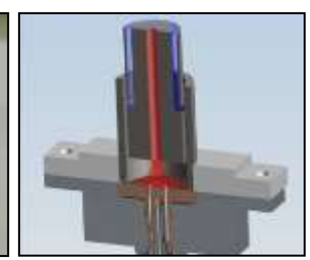
- High velocity differences
- High ρ and h differences
- Strong change in properties

Particle transport

- In treatment zone
- In annular zone
- Different injection systems

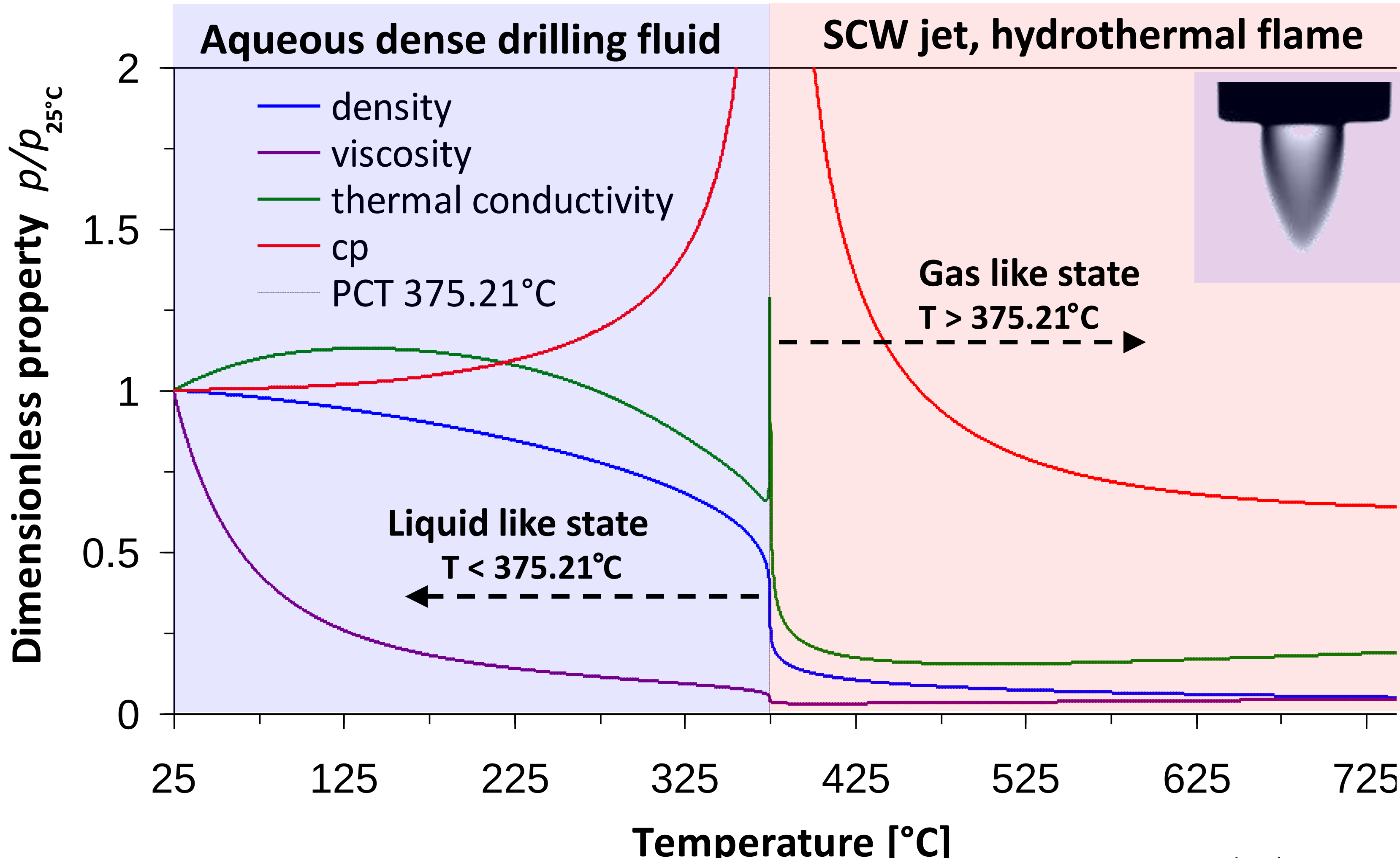
Heat transfer

- Crucial for spallation performance
- Dependency on operating conditions
- Different nozzle and burner systems
- Different sensor types



Entrainment

Thermo-physical properties of water at 224bar (below 2km depth)

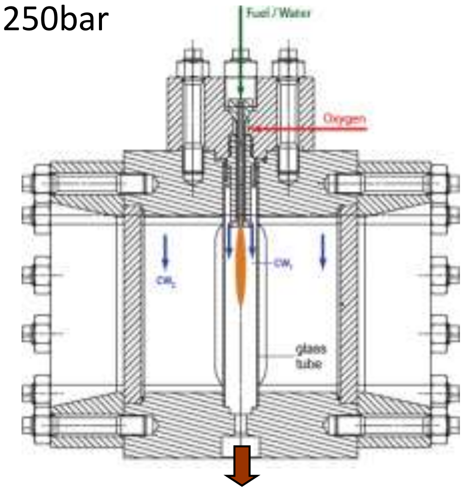


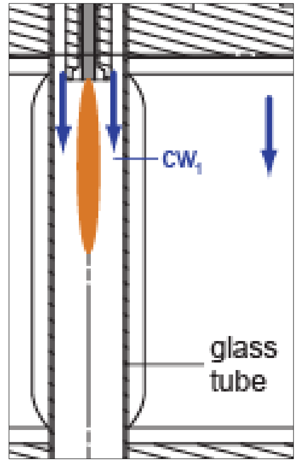
NIST database, USA, 2011

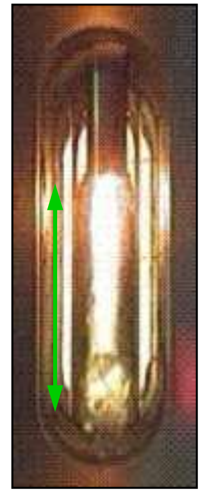
Entrainment - Hydrothermal Flame

Hydrothermal flame in a confined setup

250bar





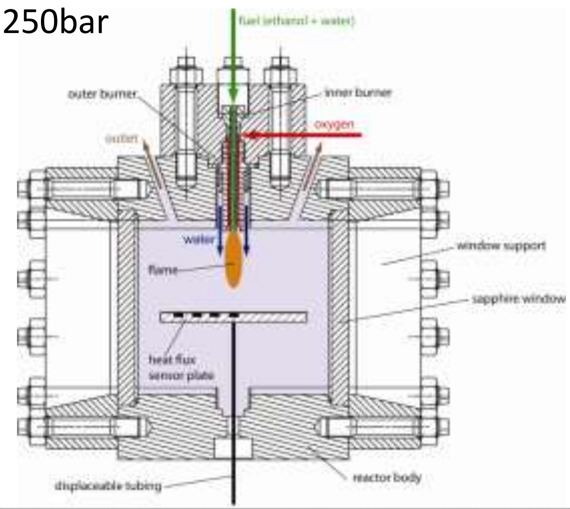


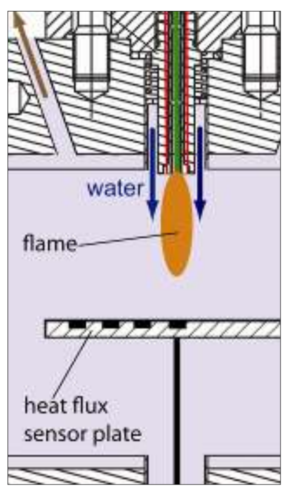
Hydrothermal flame

- 1.9 g/s fuel
- 1.5 g/s oxygen
- 15 g/s inner cooling water (CW_1)
- Nozzle diamter 6 mm
- **Long reaction zone (10 cm)**
- **Intensive combustion process**

Hydrothermal flame as a free jet

250bar





Hydrothermal flame

- Ball-shaped flame jet (1 cm)
- Massive entrainment rates
- Fast quenching of reaction

→ ***Significant heat losses***

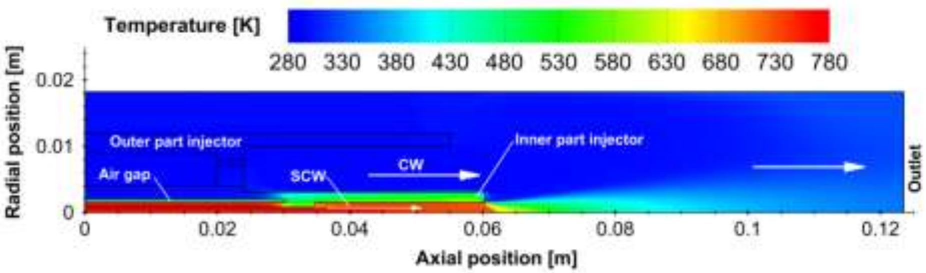
→ ***Fast cool down***

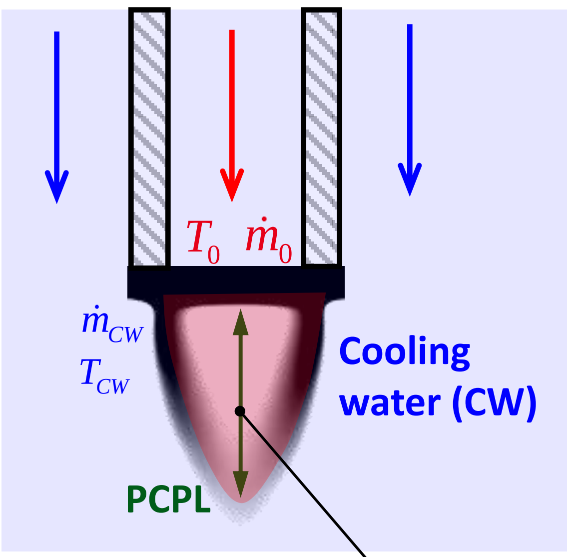
→ ***Less efficient combustion***

Entrainment Supercritical Water Jet

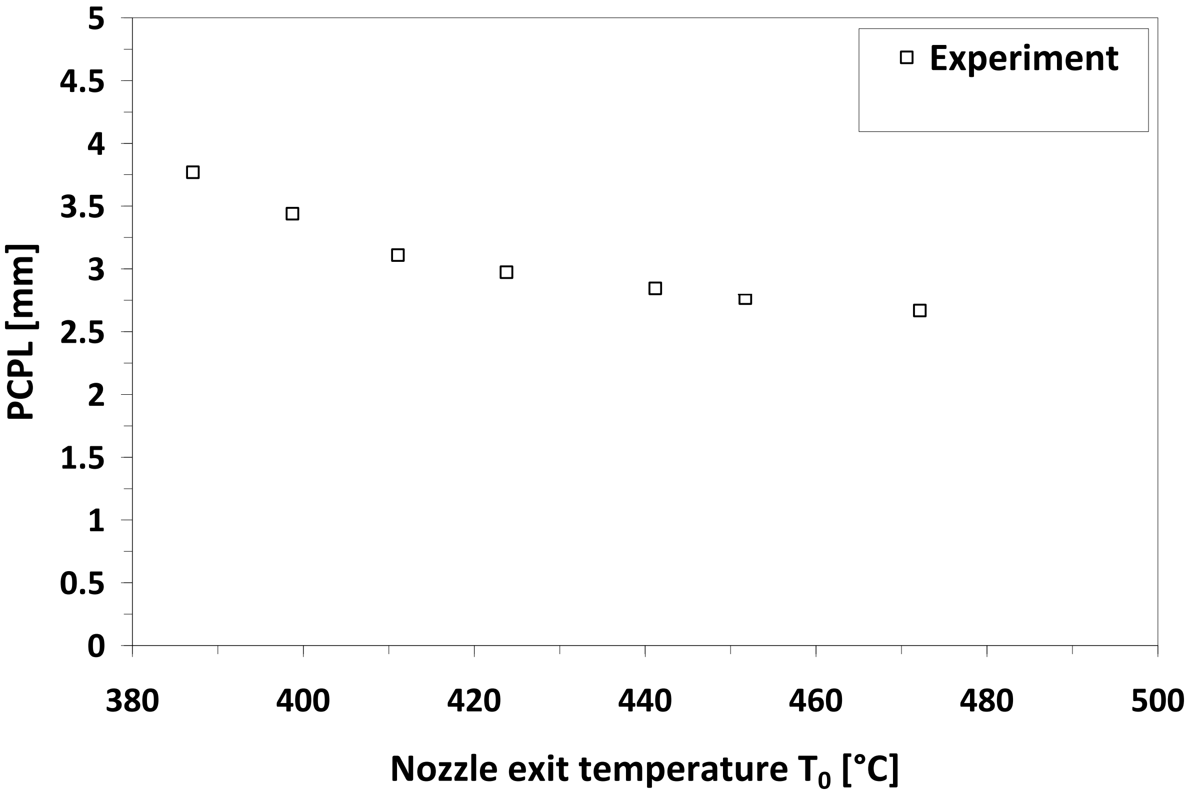
Comparison Experiment - Simulation

- T_0 varying, $\dot{m}_0$ = 4 g/s
- T_{CW} = 20 ° C, $\dot{m}_{CW}$ = 65 g/s





Pseudo critical penetration length (PCPL)

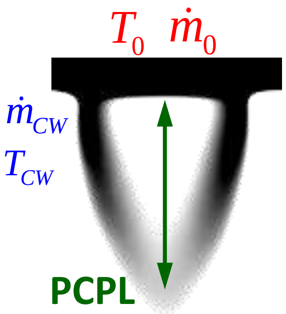


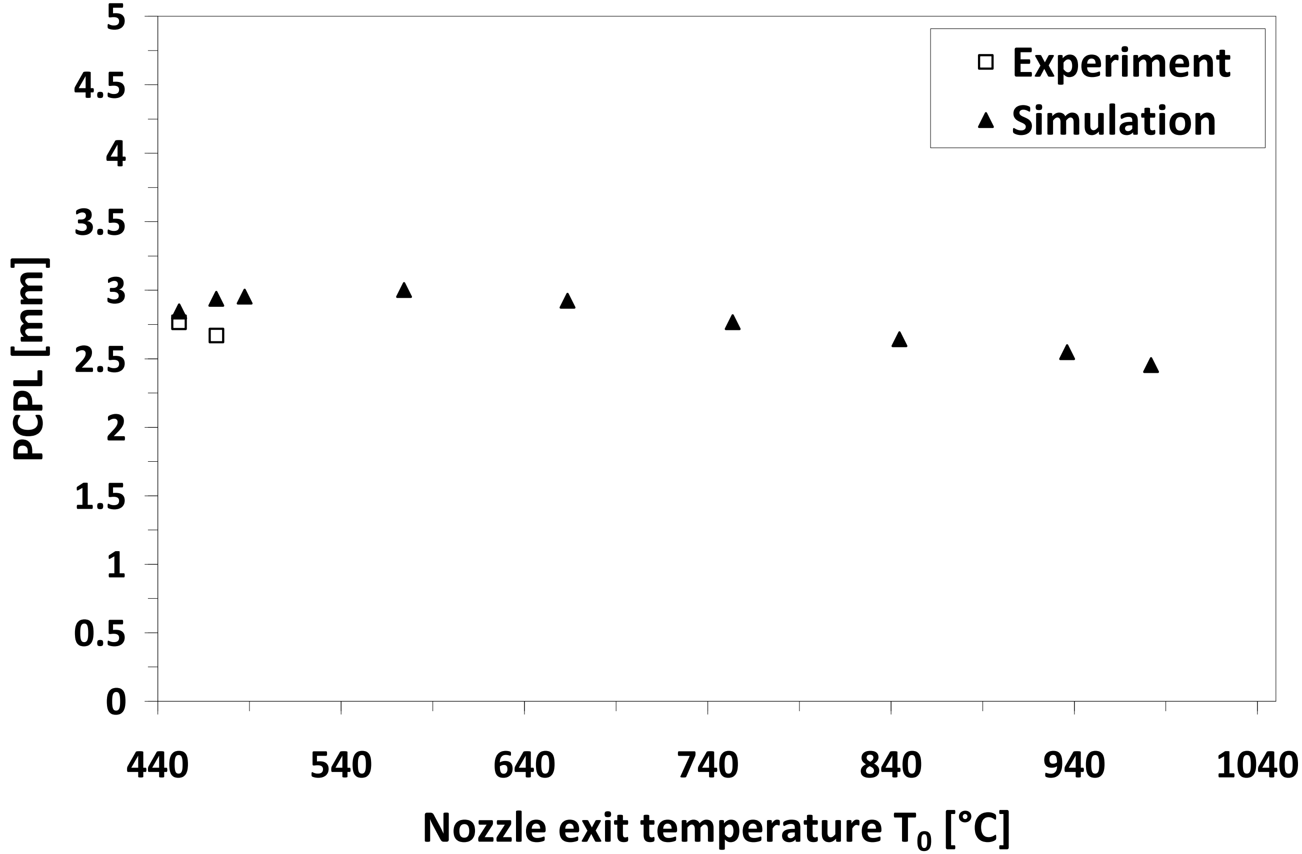
Rothenfluh et al. 2011

Entrainment Supercritical Water Jet

Comparison Experiment - Simulation

- T_0 varying, $\dot{m}_0$ = 4 g/s
- T_{CW} = 20 ° C, $\dot{m}_{CW}$ = 65 g/s
- Pressure: 224 bar
- Exit nozzle diameter d_0 = 3 mm

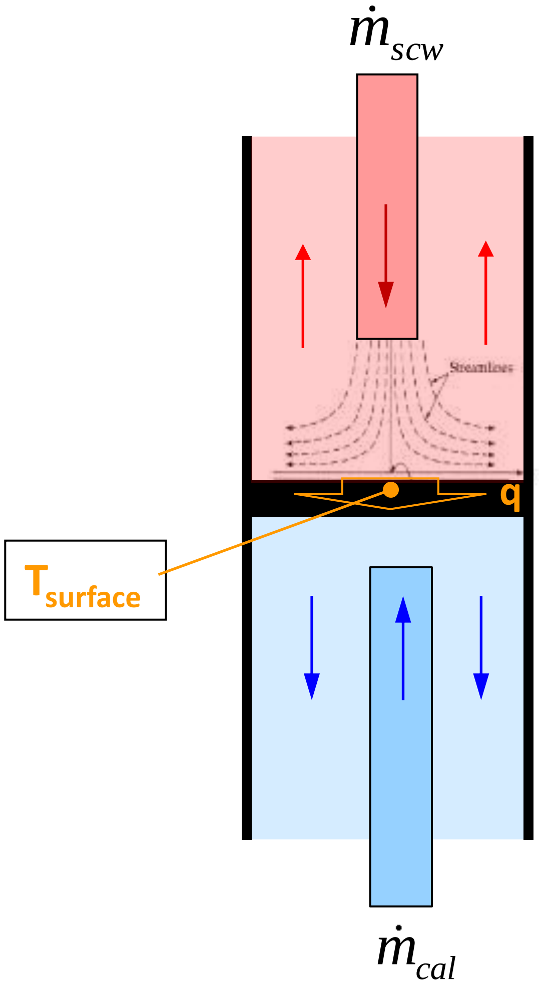


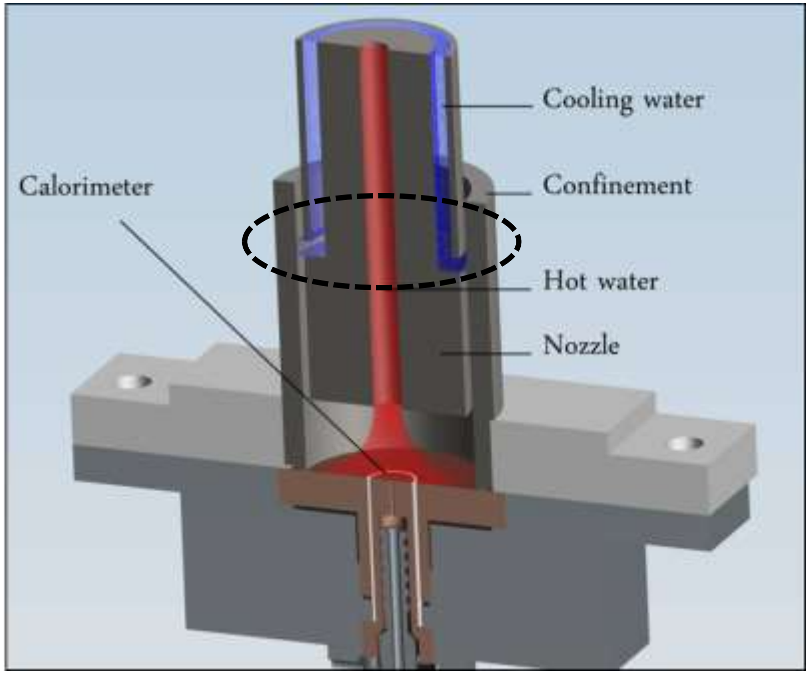


Rothenfluh et al. 2011

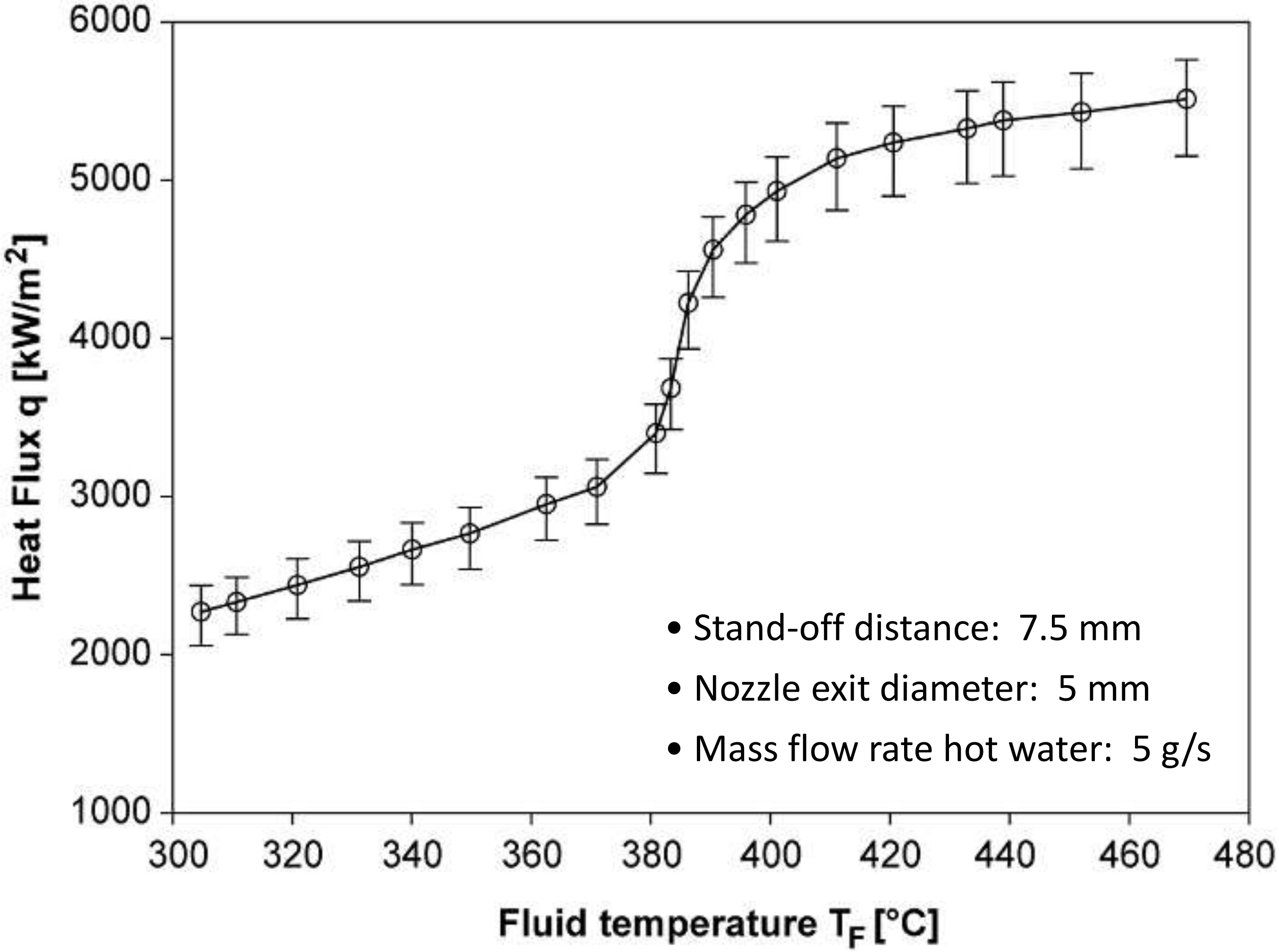
Heat Transfer Supercritical Water Jet

Heat transfer of confined impinging supercritical water jets



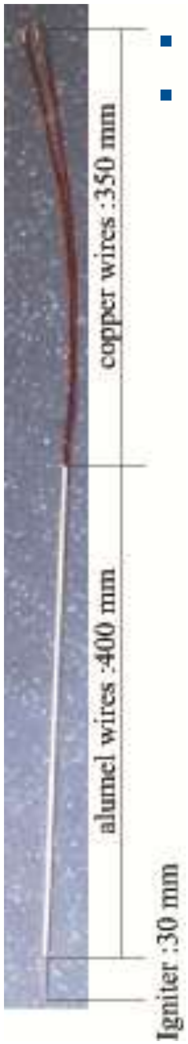


Heat Transfer Supercritical Water Jet



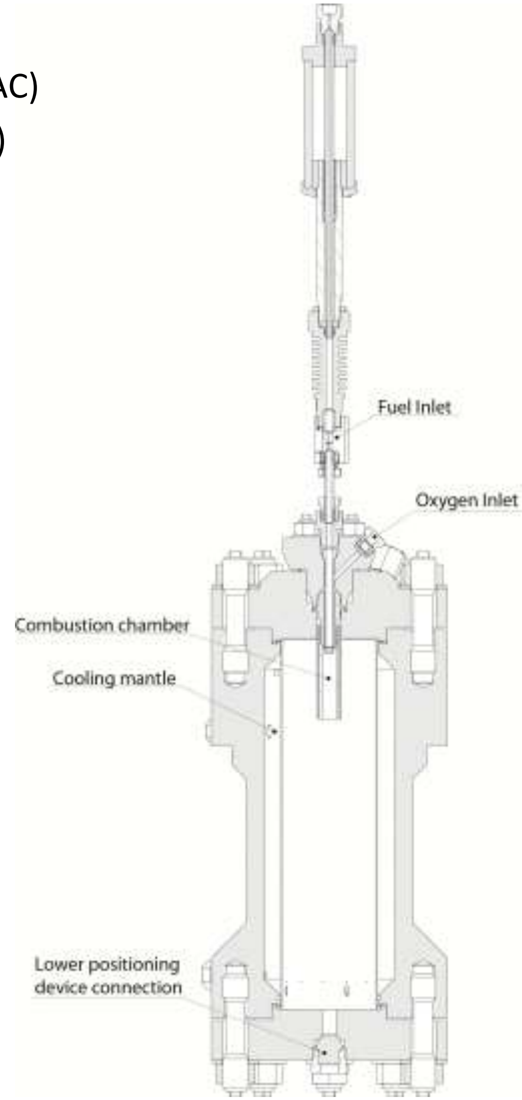
Ignition of Hydrothermal Flames

Igniter

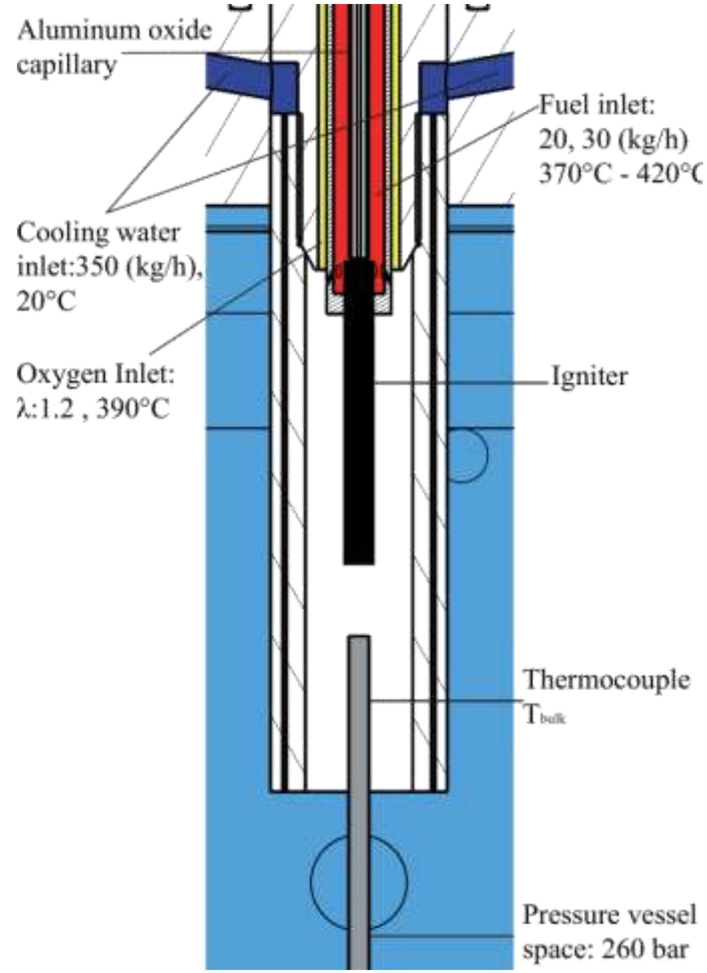


- V_{max}:230V (AC)
- I_{max}: 9 A (AC)

Experimental Setup



Flame Ignition



Main Risks for Hydrothermal Spallation Drilling

- **Entrainment and turbulent mixing**
  - Fast cool down of the jet before impingement
  - Lower the overall efficiency of hydrothermal spallation drilling

- **Rock behavior in the field under stress conditions**
  - Rock under stress conditions behaves different compared to laboratory experiments during hydrothermal spallation drilling

- **Significantly lowered drilling performance in sedimentary rock formations** (Limestone, Sandstone, …)

- **Development of a sensor system applicable at the harsh conditions found down hole**
  - Record drilling performance, hole diameter, drilling direction
  - Distance between nozzle exit and rock surface (SOD)

Conclusions for Hydrothermal Spallation Drilling

→ ***A long way to go for developing hydrothermal spallation drilling***

Entrainment and turbulent mixing

- ***Entrainment effects have to be considered in hydrothermal spallation drilling***
- ***High heat transfer to drilling fluid reduces heat transfer to rock surface***
- ***Efficiency of hydrothermal spallation drilling reduced by entrainment***

Ignition of hydrothermal flames

- ***Electrical ignition of hydrothermal flames under the harsh conditions found downhole possible***

Heat transfer of impinging jets to the rock surface

- ***High heat transfer rates under supercritical aqueous conditions***
- ***Quite promising for hydrothermal spallation drilling***

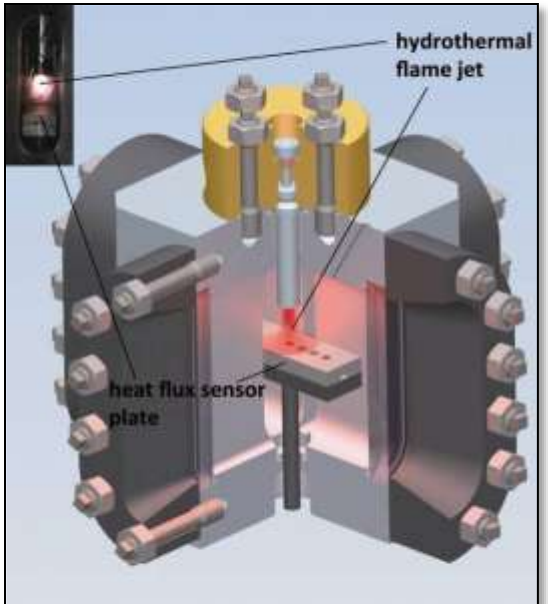
Engineering tool

- ***CFD model able to predict entrainment and heat transfer reasonable well***
- ***Tool for the design of a possible "HSD spallation drilling head"***

Outlook: Spallation @ ETH Zurich

Former SCWO Plant

up to 300bar and 300° C



- Basic investigations of SCW-jets
  - Entrainment effects
  - Heat transfer
- Heat flux sensor development
- Development of a engineering tool
- HSD experiments with SCW-jets
  - Squared rock samples (5cm x 4cm x 1.5cm)

HSD Pilot Plant

up to 500bar and 600 ° C

- Heat flux sensor development
- Burner developments
- Hydrothermal flames
  - Ignition, Characterization
  - Heat transfer, Optimization towards HSD
- HSD experiments
  - Rock samples (10cm x 20cm)

Ambient Spallation Plant

melting)

- Parametric studies for optimization
- Alternating heating and cooling
- Penetration rates

Financial Support

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Swiss Federal Office of Energy SFOE

FNSNF
SCHWEIZERISCHER NATIONALFONDS
ZUR FÖRDERUNG DER WISSENSCHAFTLICHEN FORSCHUNG

swisselectric
research

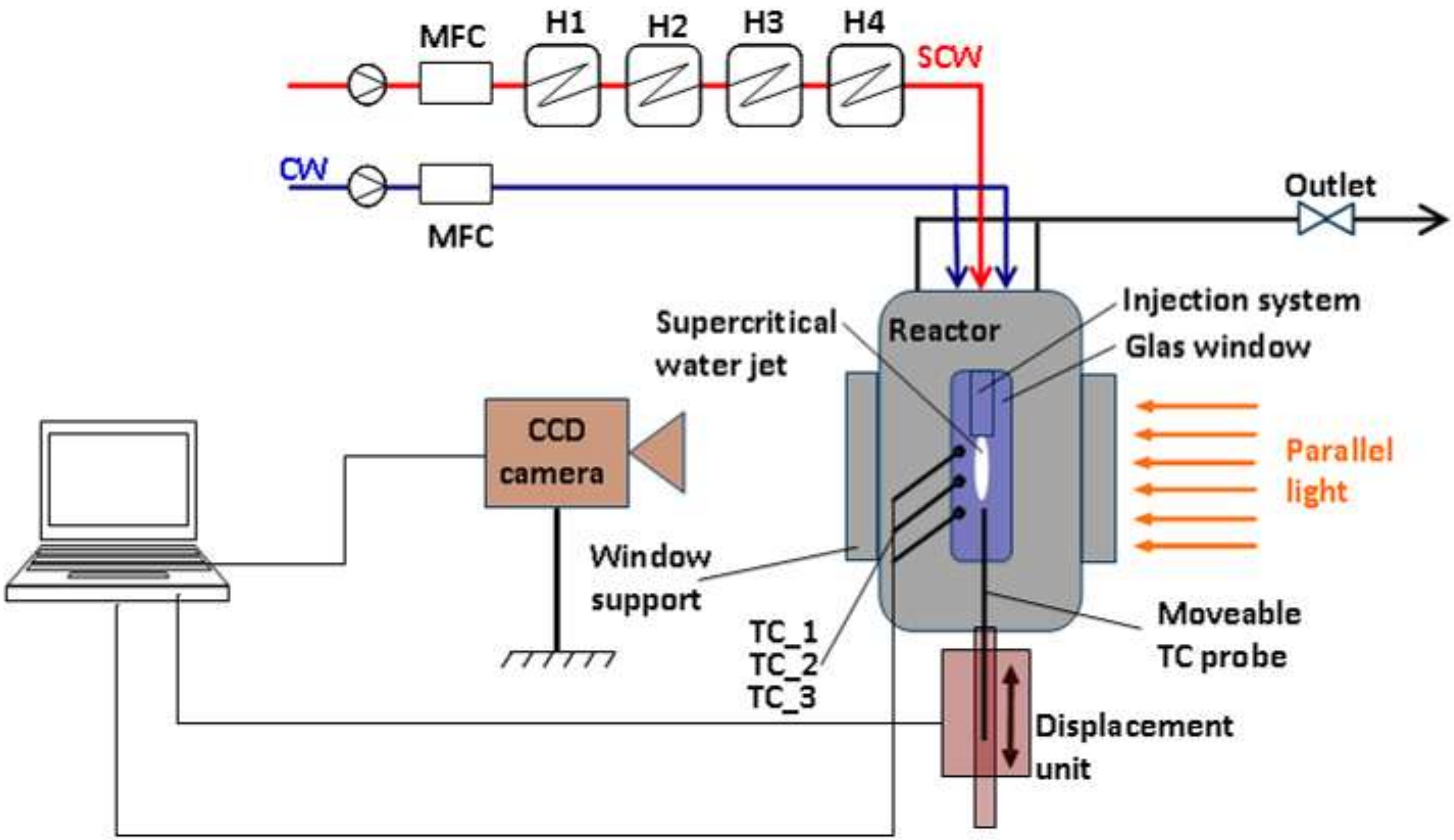
Collaborations

International
Partnership for
Geothermal
Technology

EERA
European Energy Research Alliance
JointProgrammeGeothermalEnergy

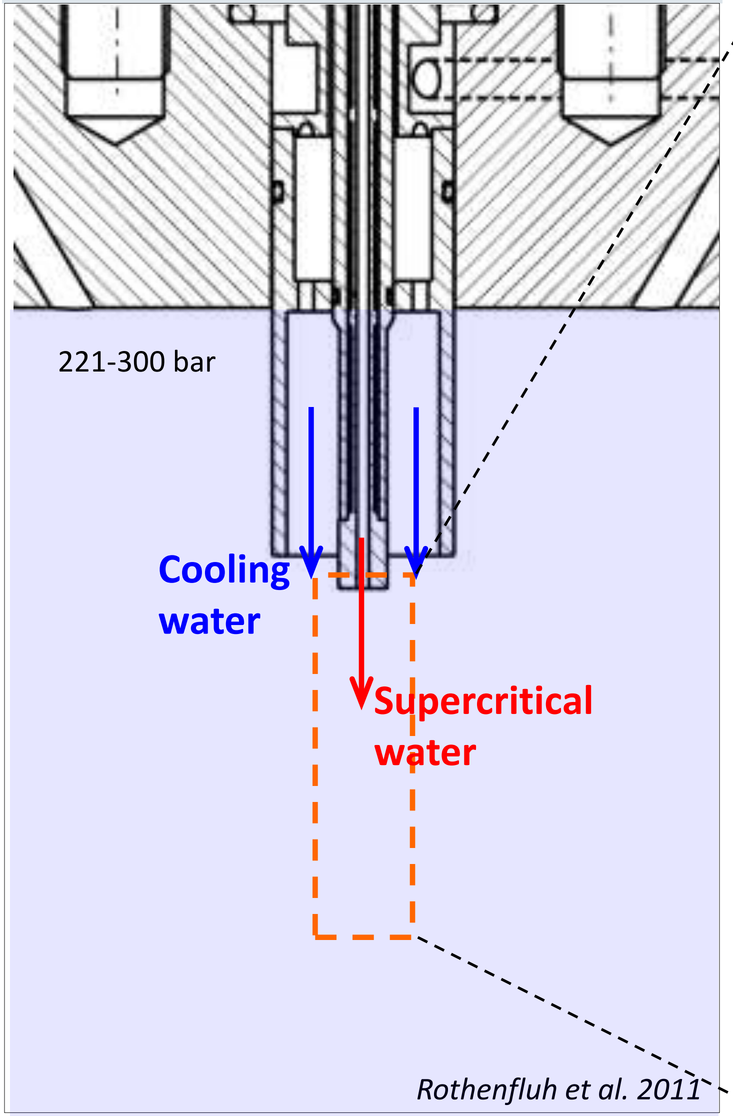
HSD: Entrainment

Experimental Setup

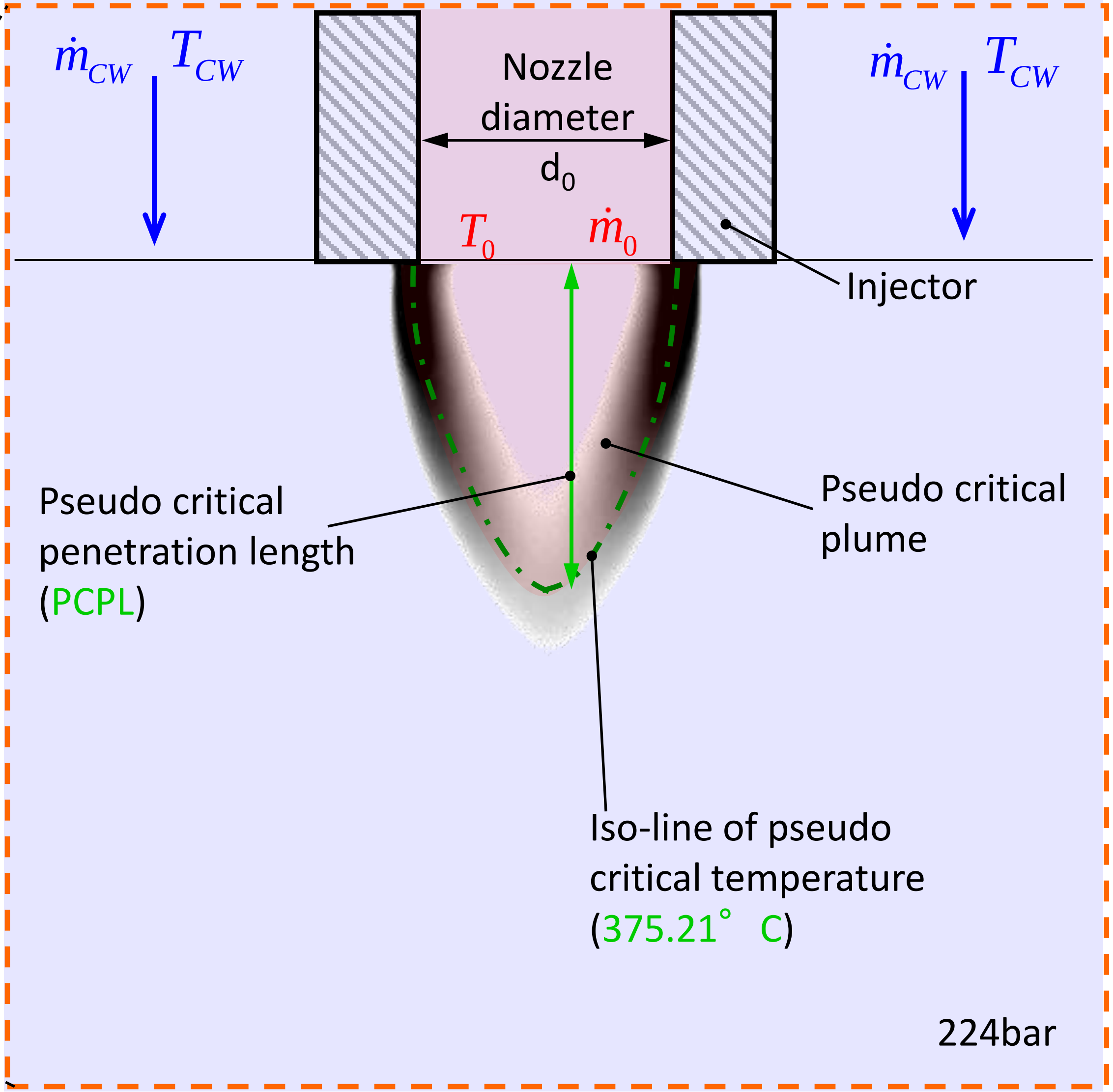


Entrainment Supercritical Water jet

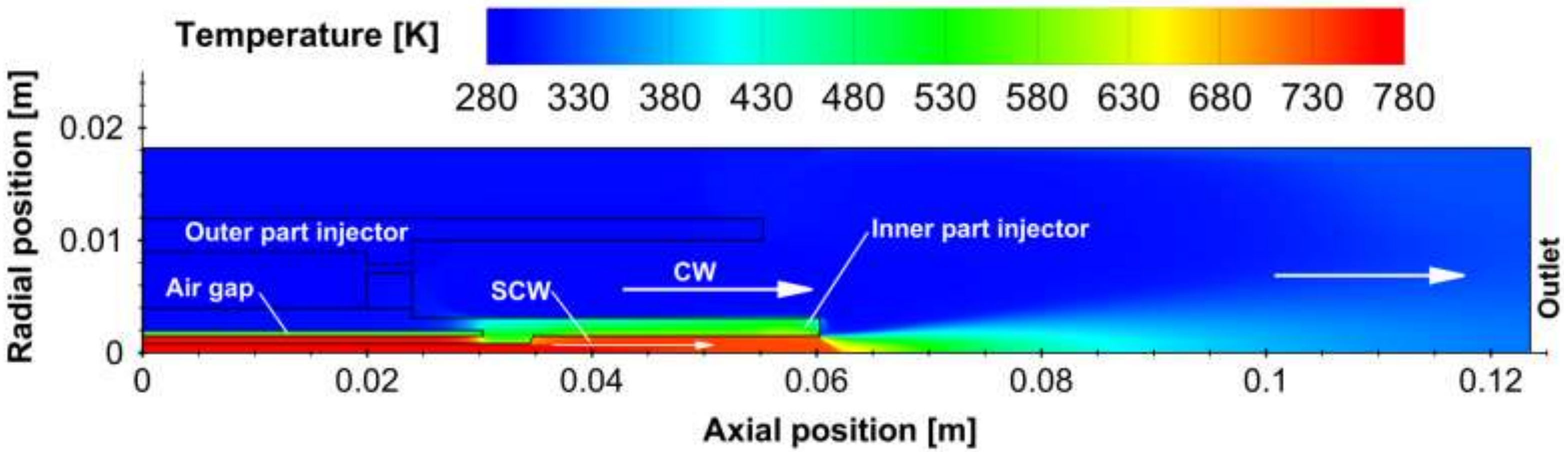
Experimental Setup

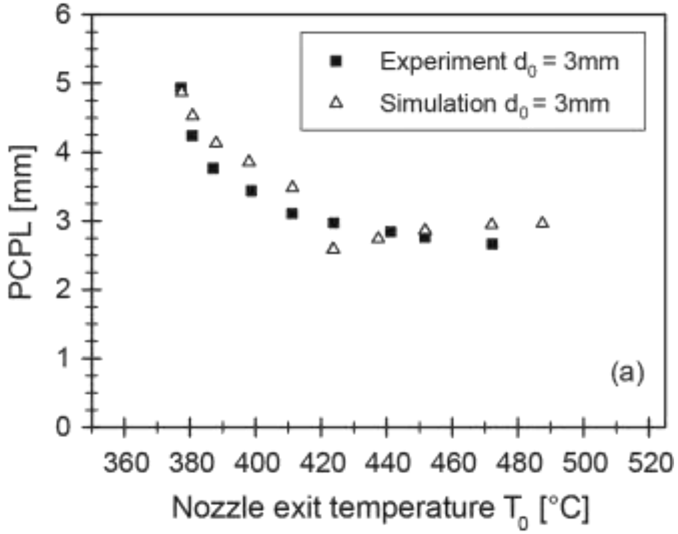


Experimental Methods



Simulations of SCW-jets



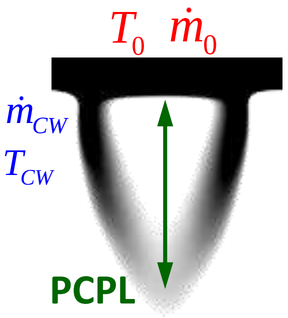


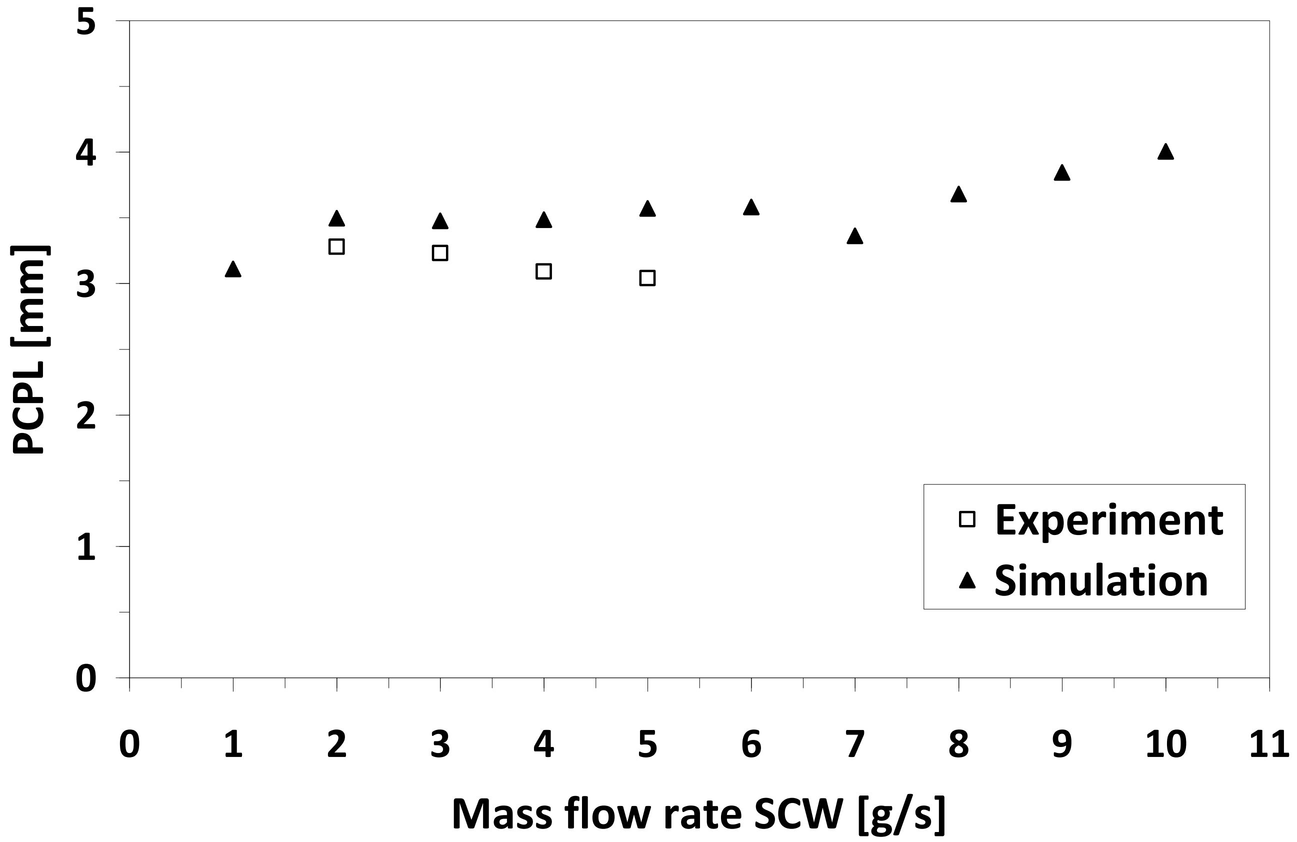
- **Thermo physical properties of water via UDFs (NIST)**
- **Structured grid (800`000 - 2'000'000 cells)**
- Realizable k-epsilon turbulence model (rke)
- 2D and 3D domain
- ...

HSD: Entrainment

Comparison Experiment - Simulation

- T_0 = 410° C, $\dot{m}_0$ varying
- T_{CW} = 20 ° C, $\dot{m}_{CW}$ = 65 g/s
- Pressure: 224 bar
- Exit nozzle diameter d_0 = 3 mm

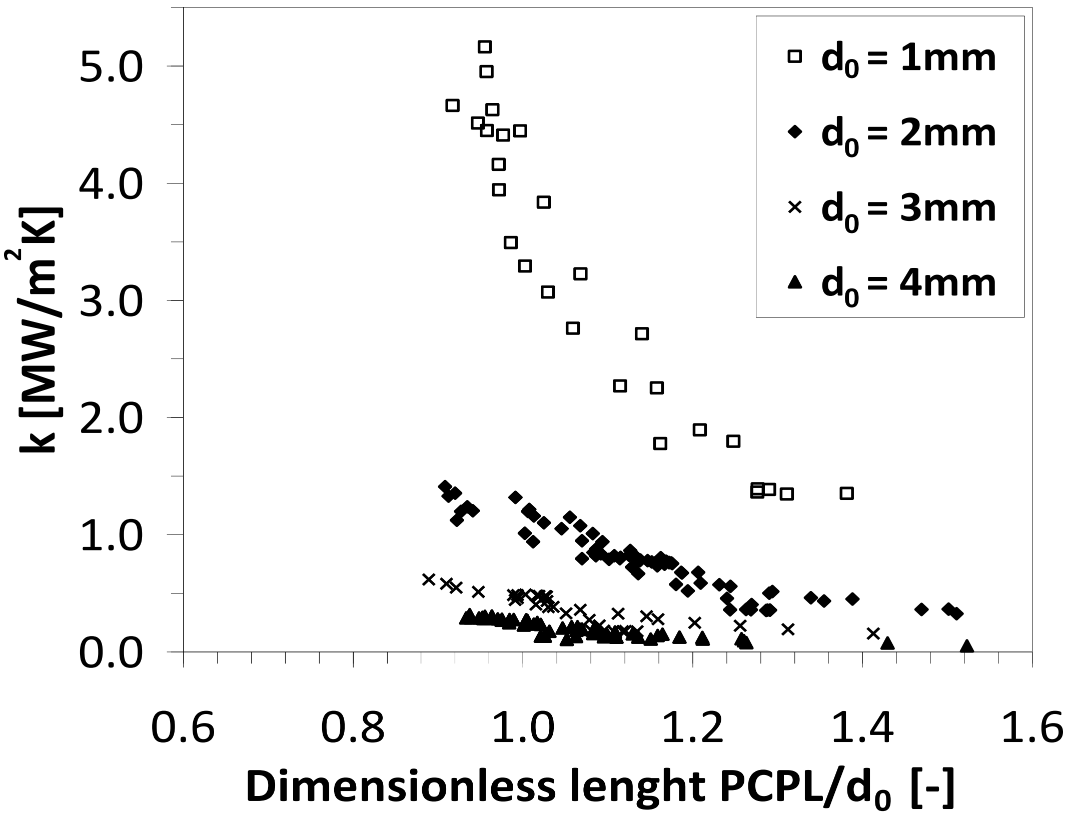


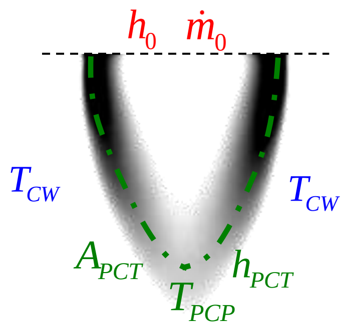


Entrainment SCW Jets – Overall Heat Transfer Coefficient

Overall heat transfer coefficient

$$k = \frac{\dot{m}_0 \cdot (h_0 - h_{PCT})}{A_{PCT} \cdot (T_{PCP} - T_{CW})}$$





- Increasing overall heat transfer coefficient k with
  - increasing T_0
  - increasing SCW mass flow rate
  - decreasing nozzle diameter d_0

- **For the highest energy inputs**

  → Highest values for the heat transfer coefficient

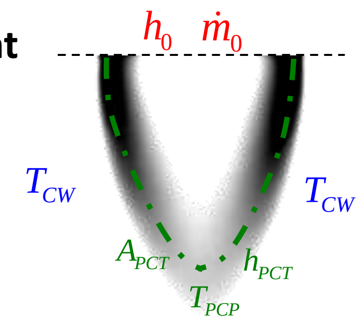
  → Shortest PCPL

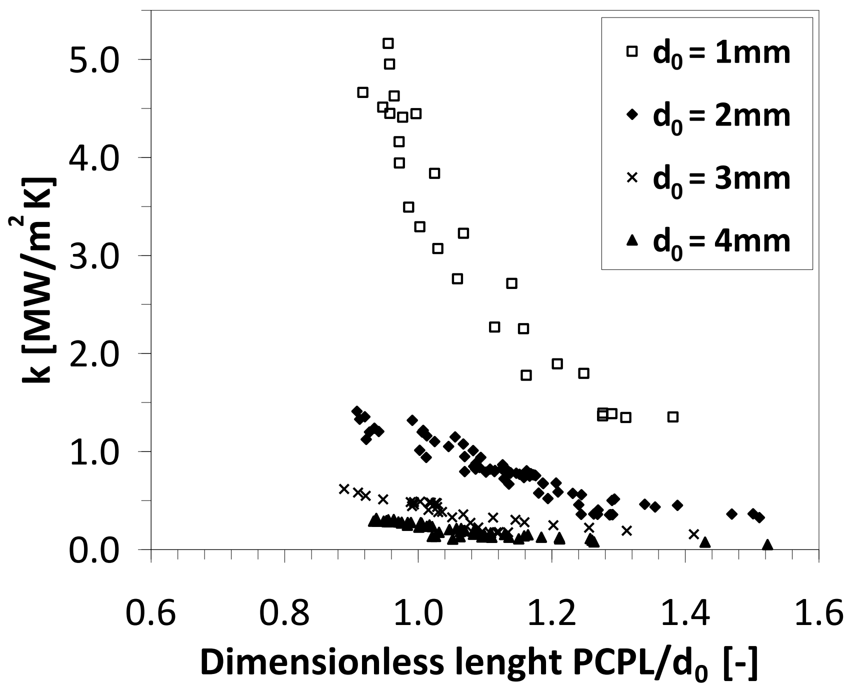
Entrainment – Overall Heat Transfer Coefficient

Supercritical water jet

Overall heat transfer coefficient

$$k = \frac{\dot{m}_0 \cdot (h_0 - h_{PCT})}{A_{PCT} \cdot (T_{PCP} - T_{CW})}$$





Direct contact steam condensation

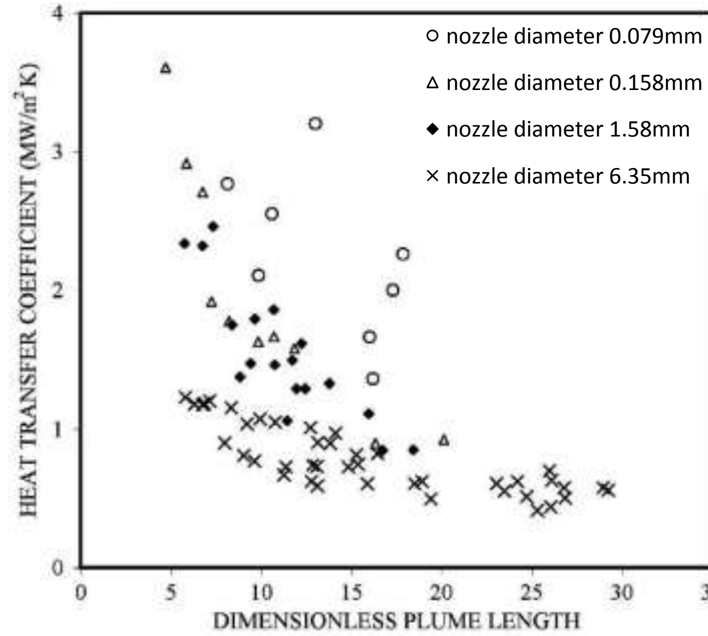


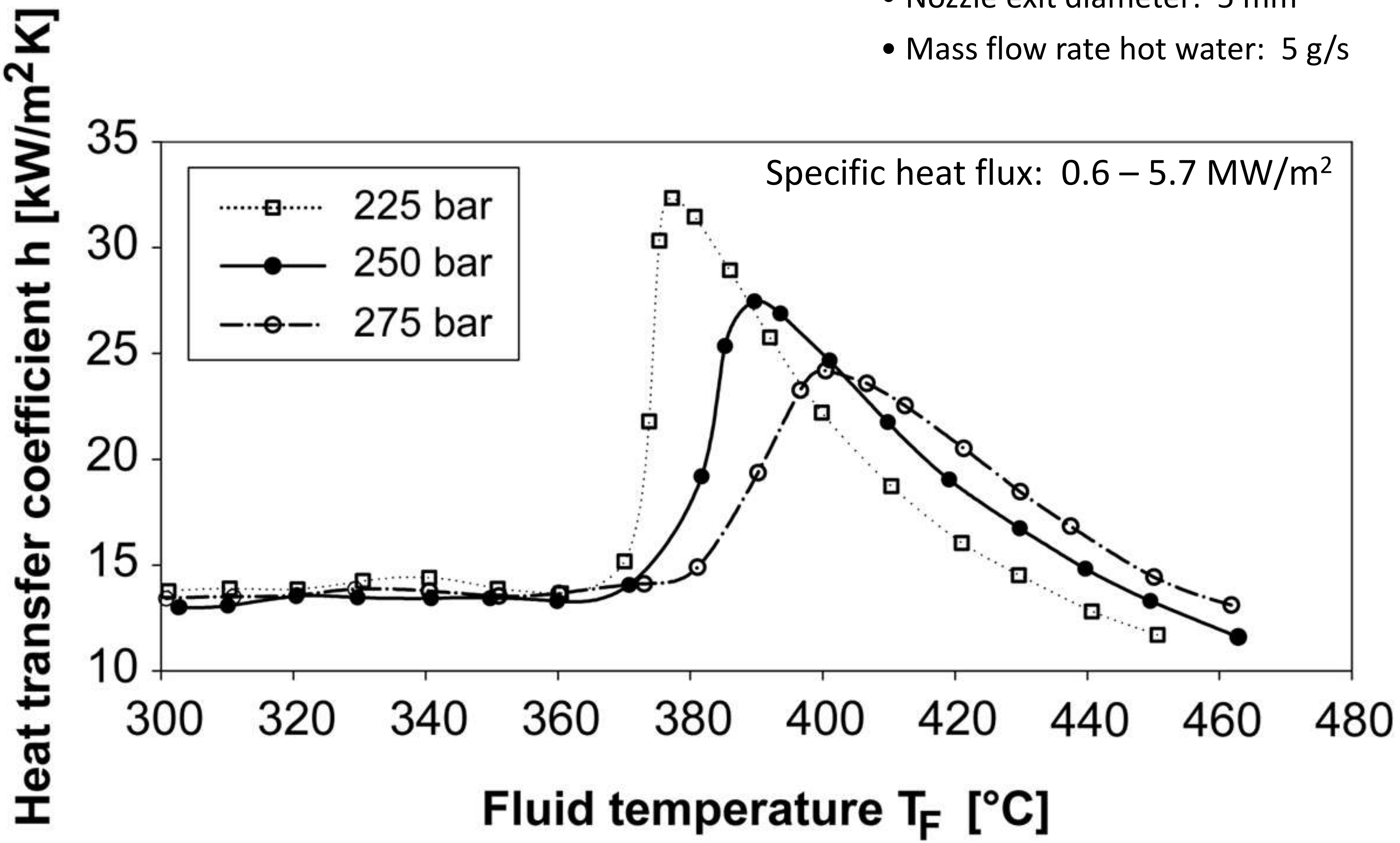
Fig. 13. Heat transfer coefficient variations with nozzle diameter (Kerney et al., 1972). Flat, $d = 0.000079$ m ●; flat, $d = 0.00158$ m ♦; flat, $d = 0.00635$ m ×; conical, $d = 0.000158$ m ▲.

- Latent heat release during condensation
- Removal of this energy is limiting step
- Elevated plume length in two phase region of water

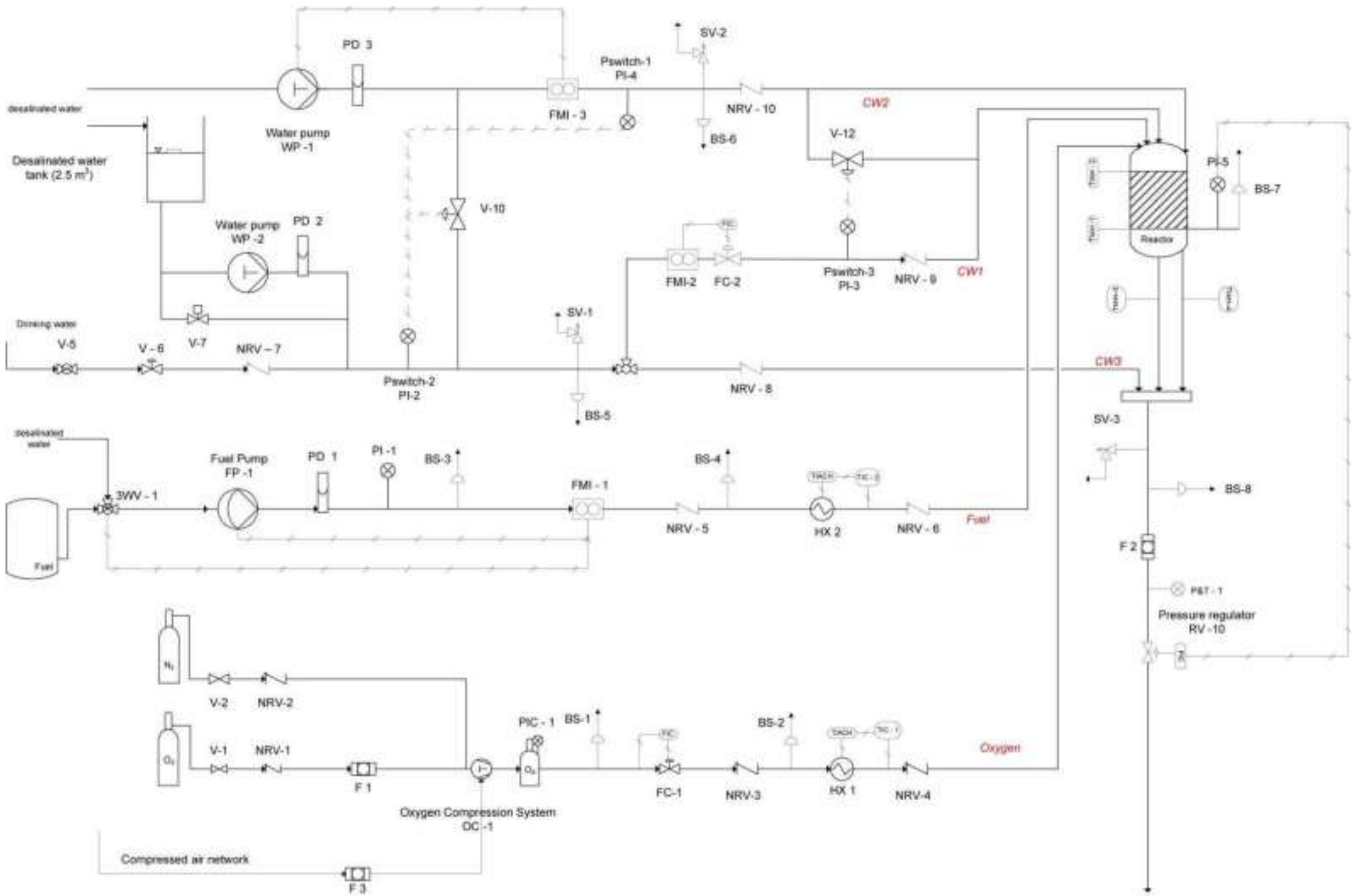
P. J. Kerney et al. 1972, S. S. Gulawani et al. 2006

Heat Transfer Supercritical Water Jet

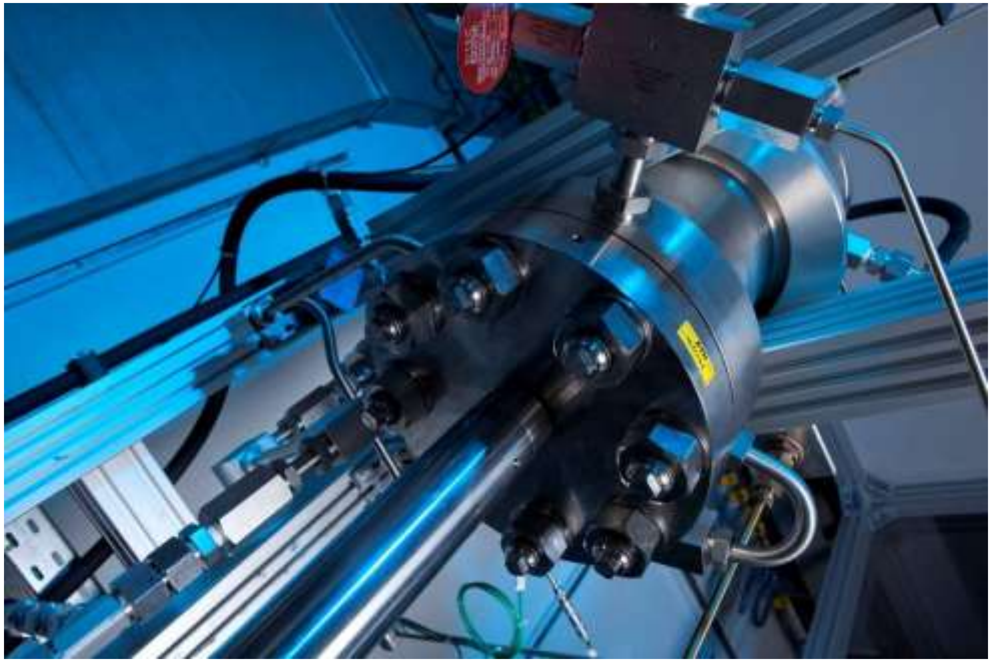
- Stand-off distance: 7.5 mm
- Nozzle exit diameter: 5 mm
- Mass flow rate hot water: 5 g/s



Hydrothermal Spallation Drilling Pilot Plant

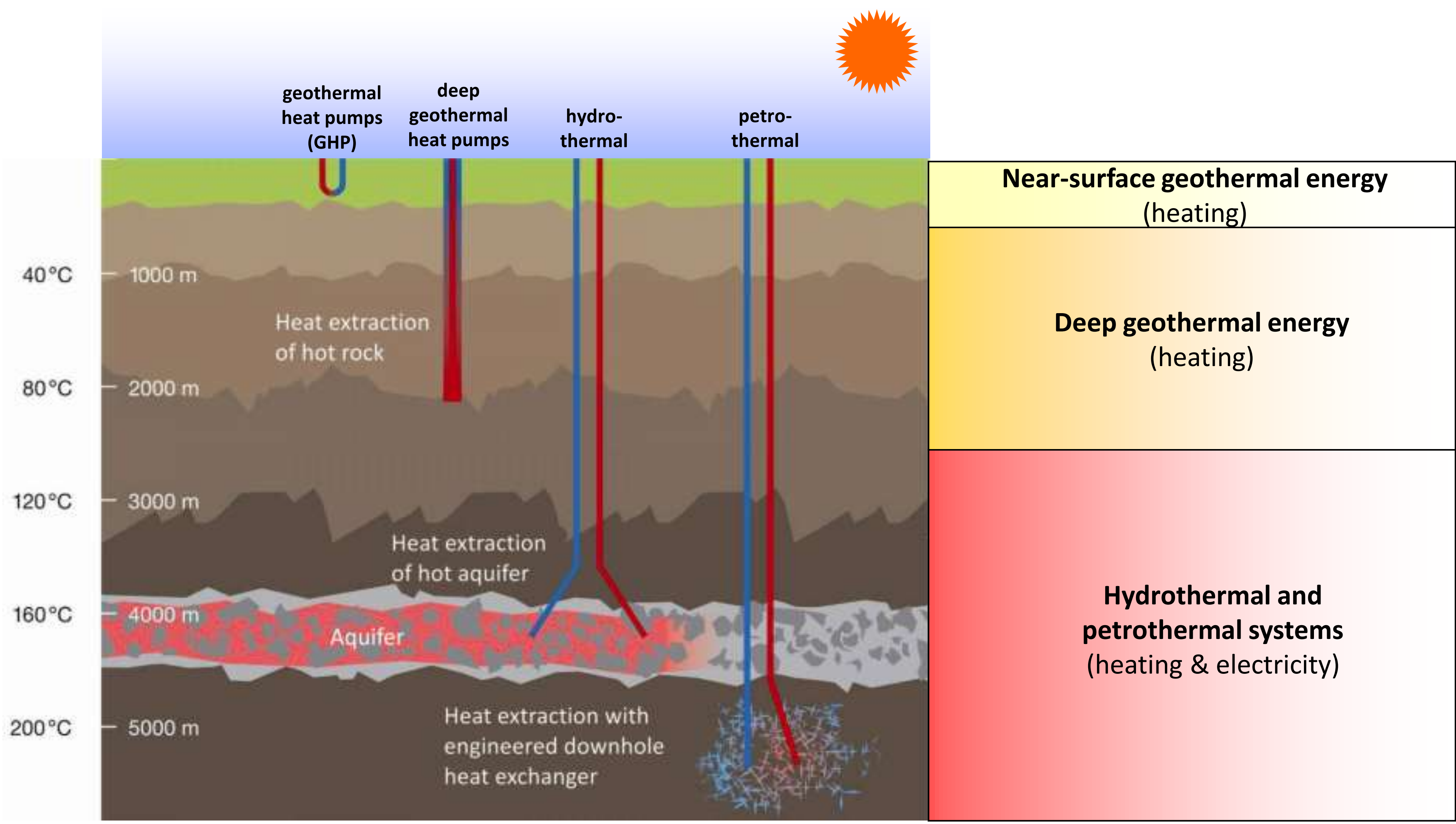


Hydrothermal Spallation Drilling Pilot Plant



Hydrothermal Spallation Drilling Pilot Plant

Geothermal Systems

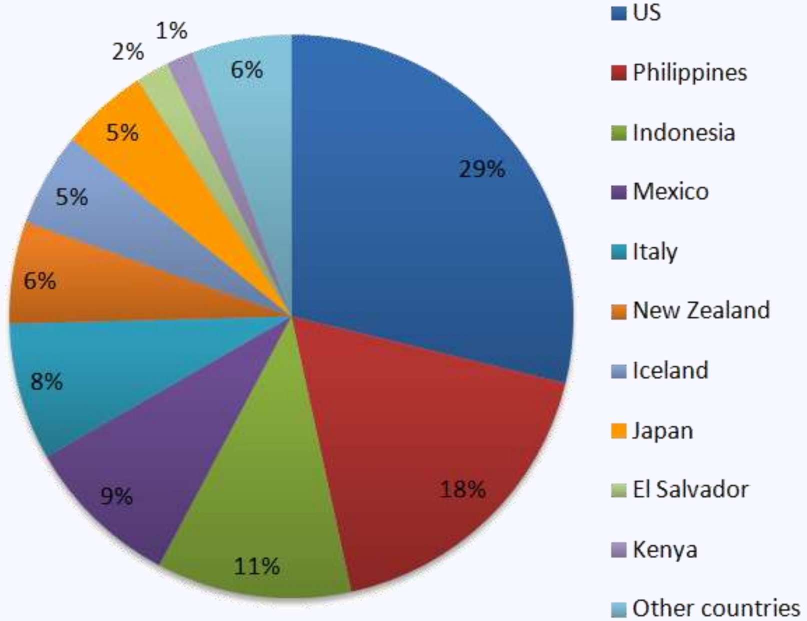


Sources: Lund, Freeston, Boyd (2010), www.geothermie.stadt.sg.ch

Geothermal Energy Production Worldwide

Electricity generation

10.7 GW_{el} (2009)

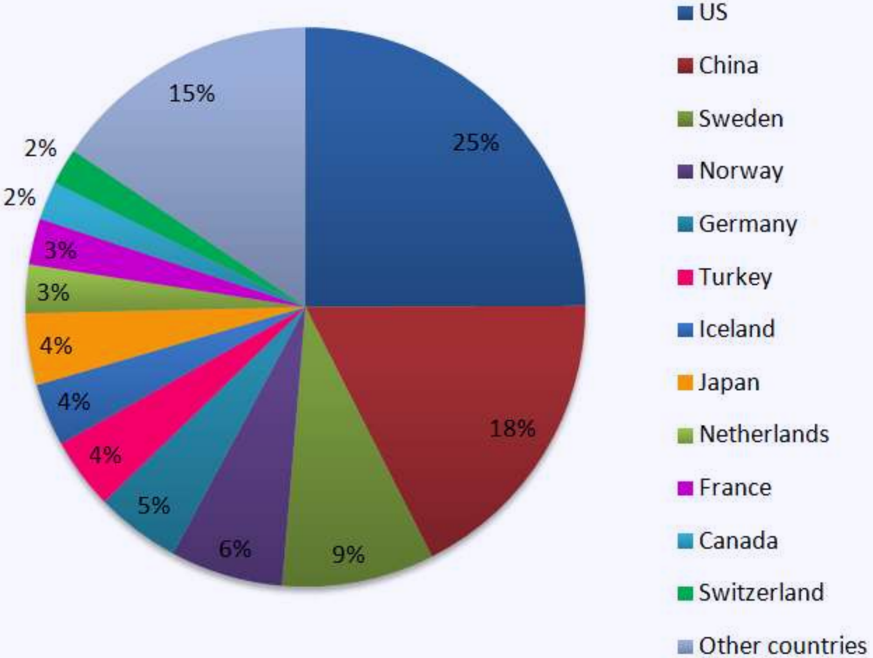


Additional facts

- 10.7 GW corresponds to 0,7% of world capacity
- Installed capacity in CH (2009): **6.56 GW_{el}**

Heat generation

50.6 GW_{th} (2010)



Addtional facts

The “top five” for installed capacity (W/population):
Iceland, Sweden, Norway, New Zealand and Switzerland

Sources: Lund, Freeston, Boyd (2010), Bundesamt für Energie

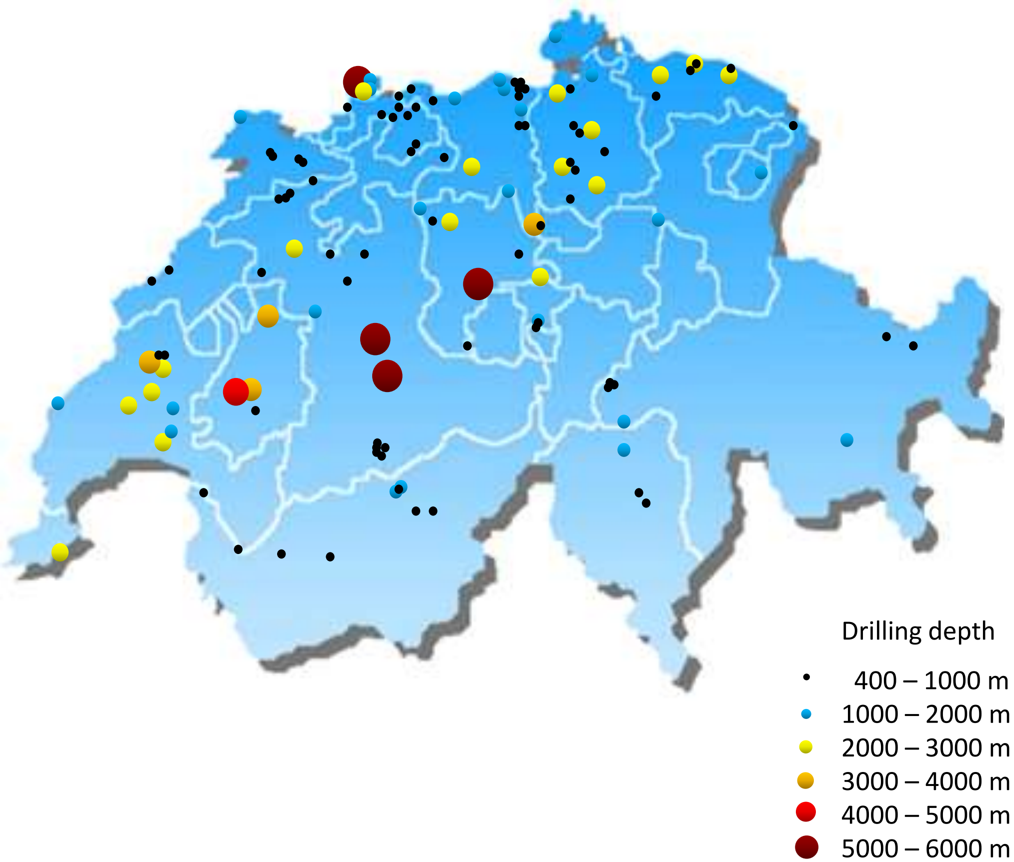
Geothermal Energy Production in Switzerland

- **Over 40** geothermal drilling companies in Switzerland (2009)

- **Installed Power**

Electricity	0.0 W_{el}
Heat	1.06 GW_{th}

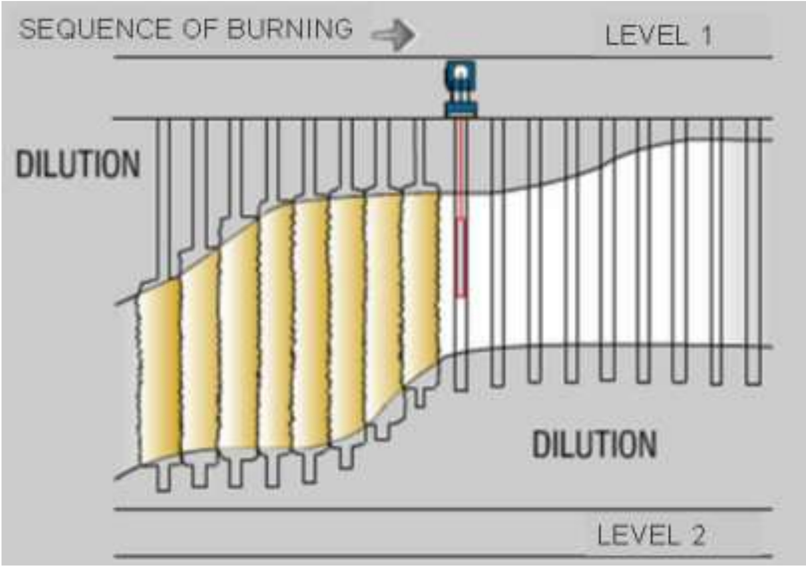
Geothermal heat pumps	1.02 GW_{th}
Bathing and swimming	34.9 MW_{th}
Tunnel water	2.4 MW_{th}
District heating	3 MW_{th}
Individual space heating	2 MW_{th}
Air conditioning	1.4 MW_{th}



Sources: Rybach, Signorelli (2010), geothermie.ch

Spallation Drilling in Application

Spallation drilling in Canada, Russia and Ukraine

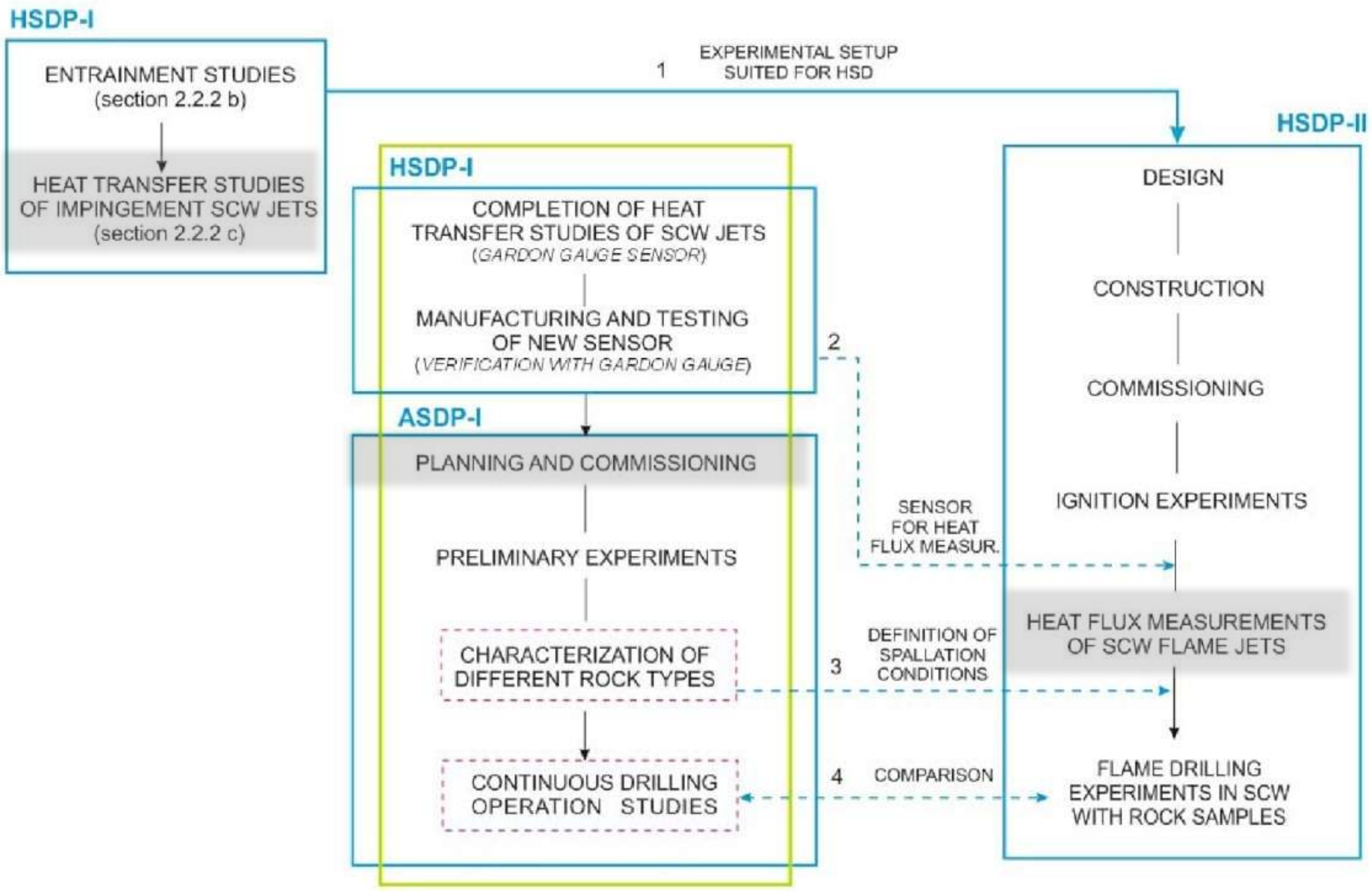


Selective ore extraction by means
of spallation drilling

spallation drilling plant in the field

(CIM Bulletin, Poirier et al. 2003)

Spallation Drilling @ ETH Zurich



Spallation Drilling @ ETH Zurich

Project milestones

- 10.2012 — First successful spallation experiments
- 10.2013 — Technology demonstration in the lab
- 10.2014 — Cooperate with a drilling industry to transfer technology
- 10.2015 — Design of the hydrothermal spalation drilling bit
- 10.2016 — Hydrothermal spallation drilling field tests
- 10.2017 — Hydrothermal spallation drilling field demonstration
- 10.2018 — First commercial borehole