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Rock bed thermal storage for CSP: Design considerations

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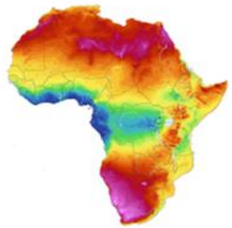

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Presentation outline

- Context and motivation for rock beds
- Design considerations
  1. Rock and containment: 'ratcheting'
  2. Air: high volumetric flow
  3. Rock bed pressure drop prediction
  4. Thermal characteristics, sizing and cost estimate
- Conclusion

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Need for thermal energy storage

Current "state of the art":

Two-tank molten salt

(Medrano *et al.*, 2010. *Renew. & Sust. Energy Rev.* 14:56-72)

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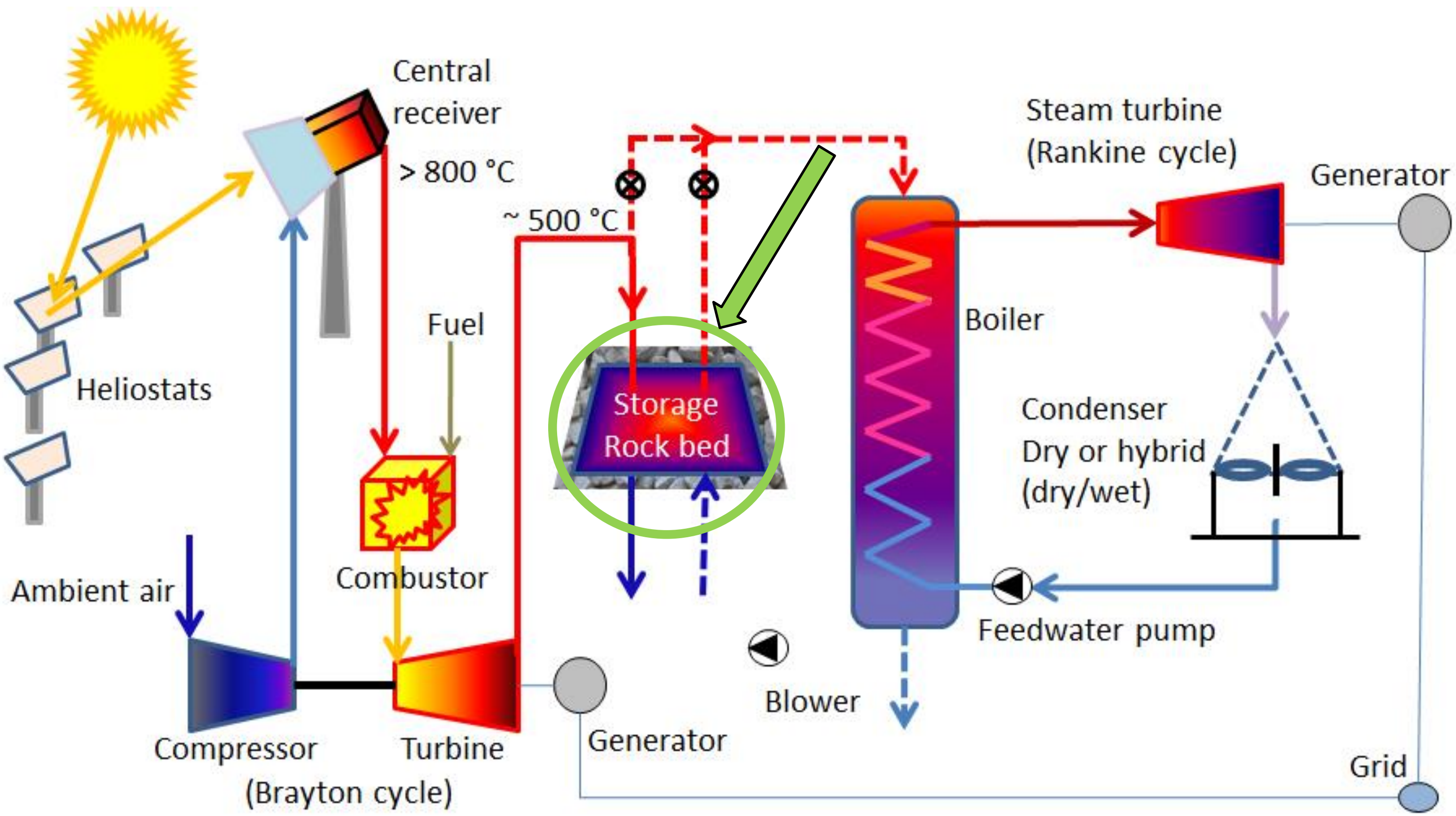
CSP & rock bed storage



SUNSPOT combined cycle (Kröger)

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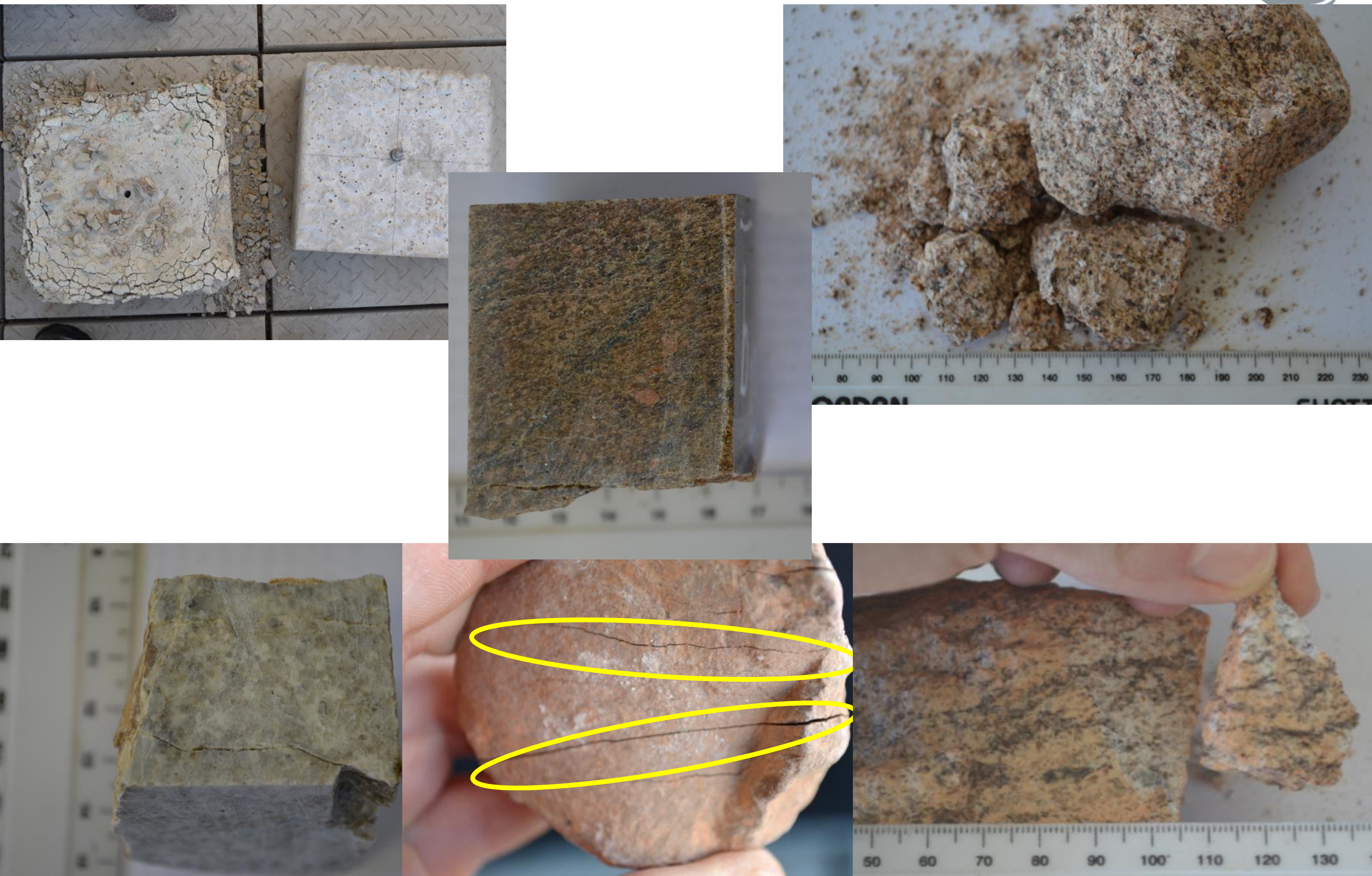
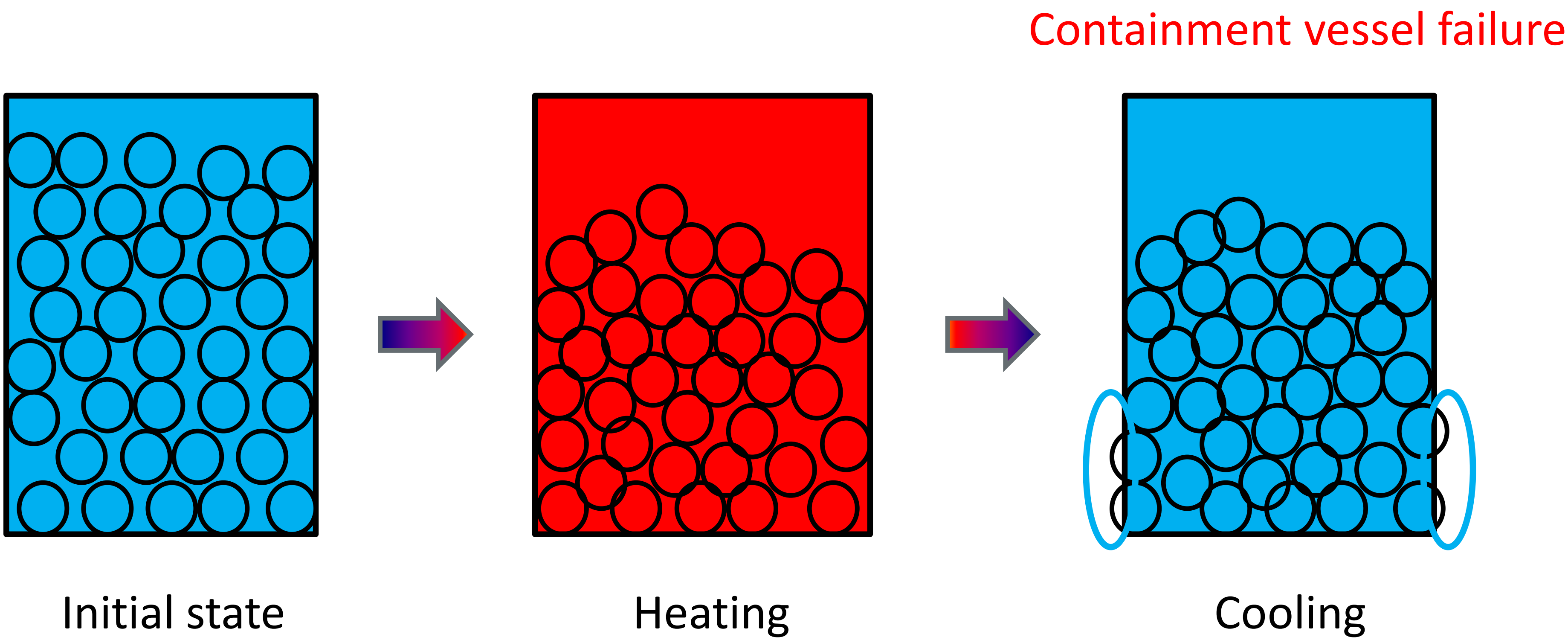
Material suitability: thermal cycling and decomposition



1. Thermal cycling and 'ratcheting'

- Stress-induced failure of containment/particles
- Expansion and contraction of particles and container



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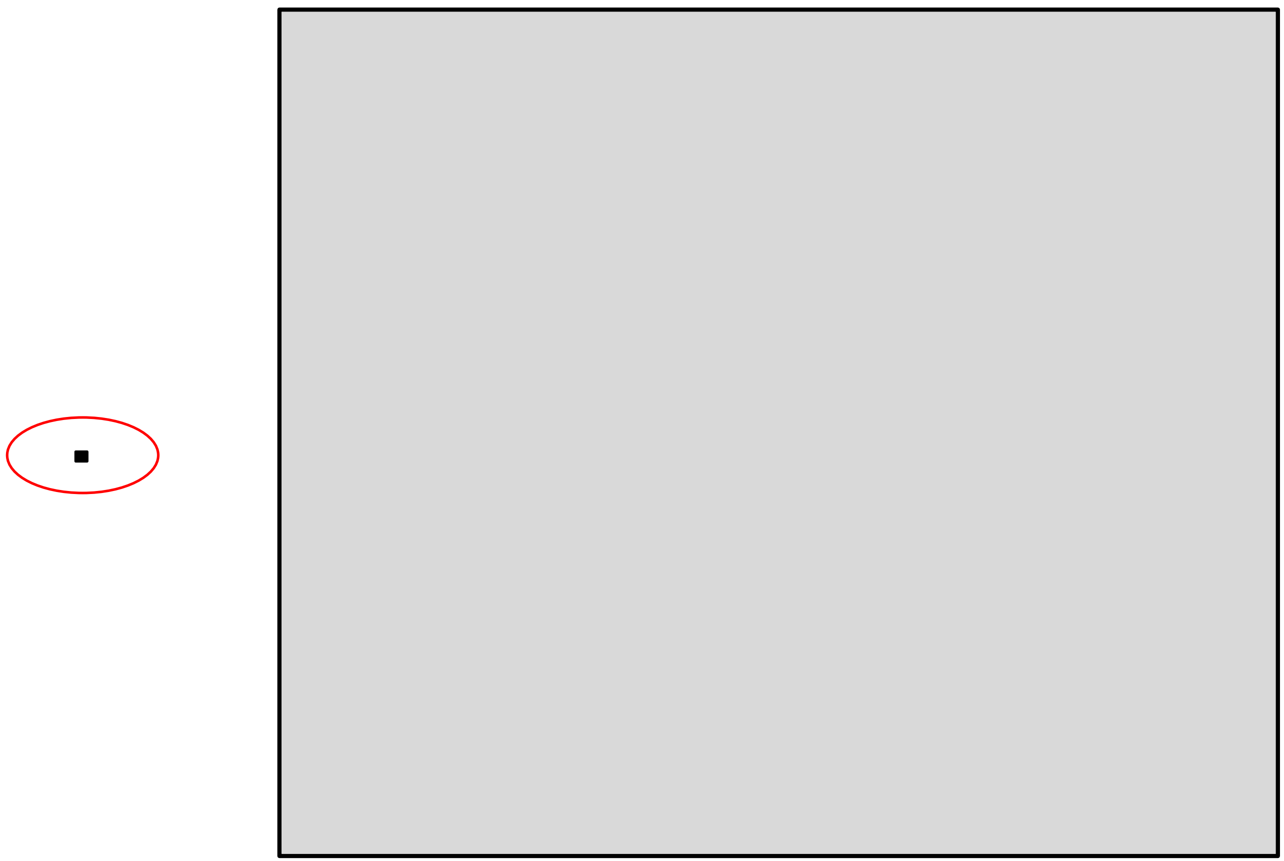
2. Air volumetric flow rate

- Heat transfer capacity of 1 MW with ΔT = 300 °C:
- Q = ρVcΔT; air c = 1040 J/kgK, ρ = 0.67 kg/m^3; molten salt c = 1200 J/kgK, ρ = 1700 kg/m^3
- V air: 4.8 m^3/s; V salt: 1.6 × 10^{-3} m^3/s – a factor of 3000 …



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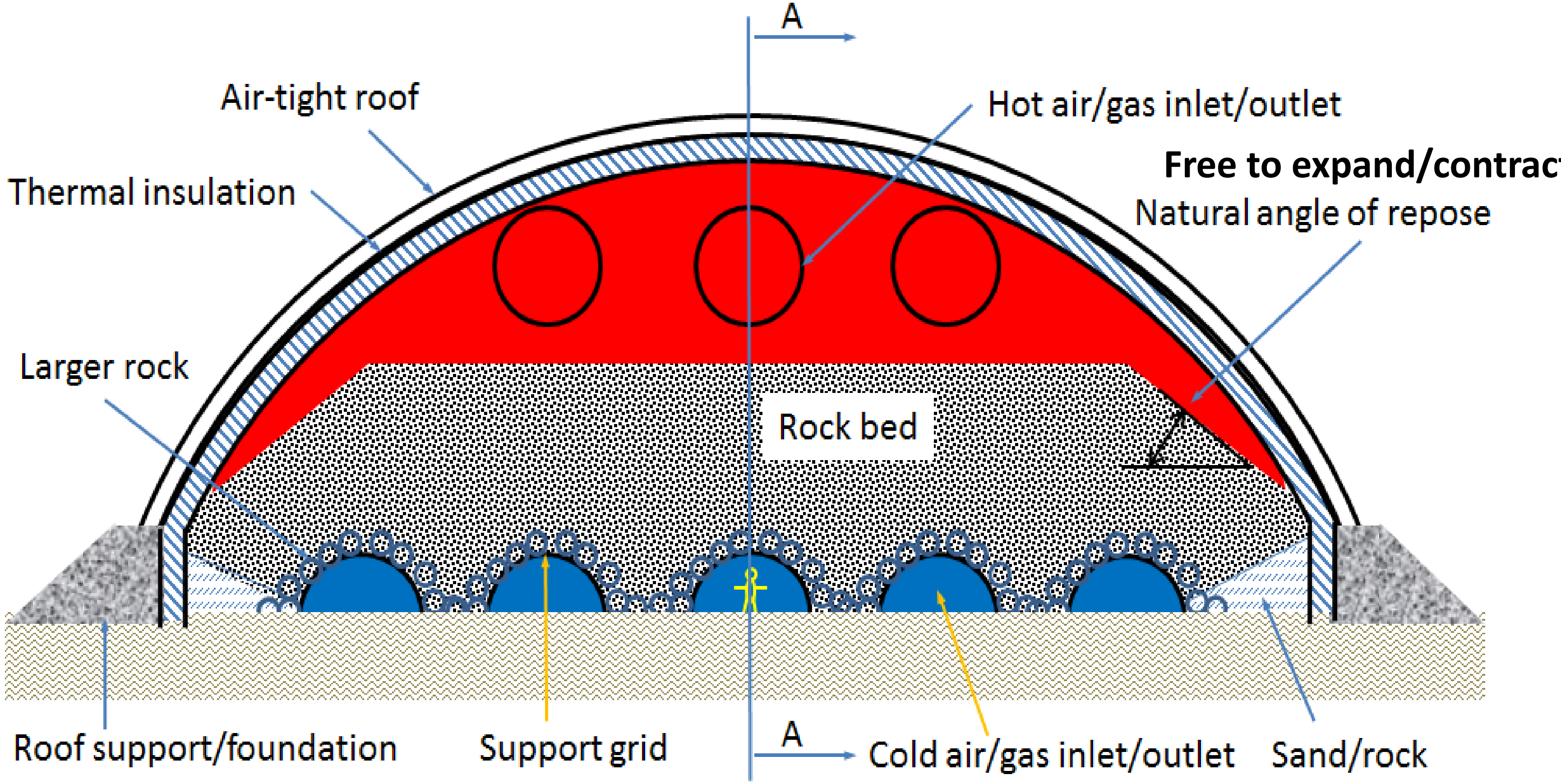
Bed containment: the concept of Kröger (2013)



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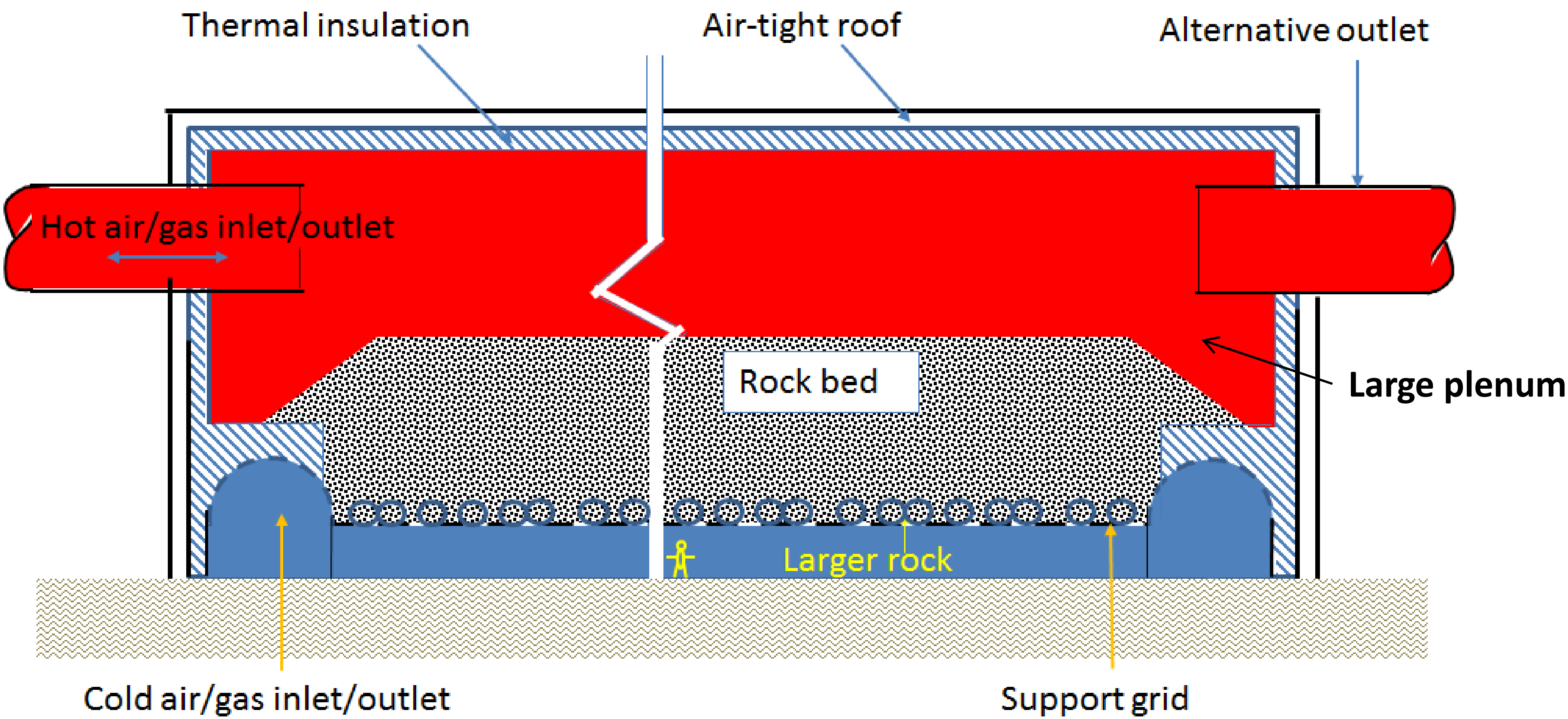
Bed containment: section on A-A



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3. Packed bed pressure drop

Influence of:

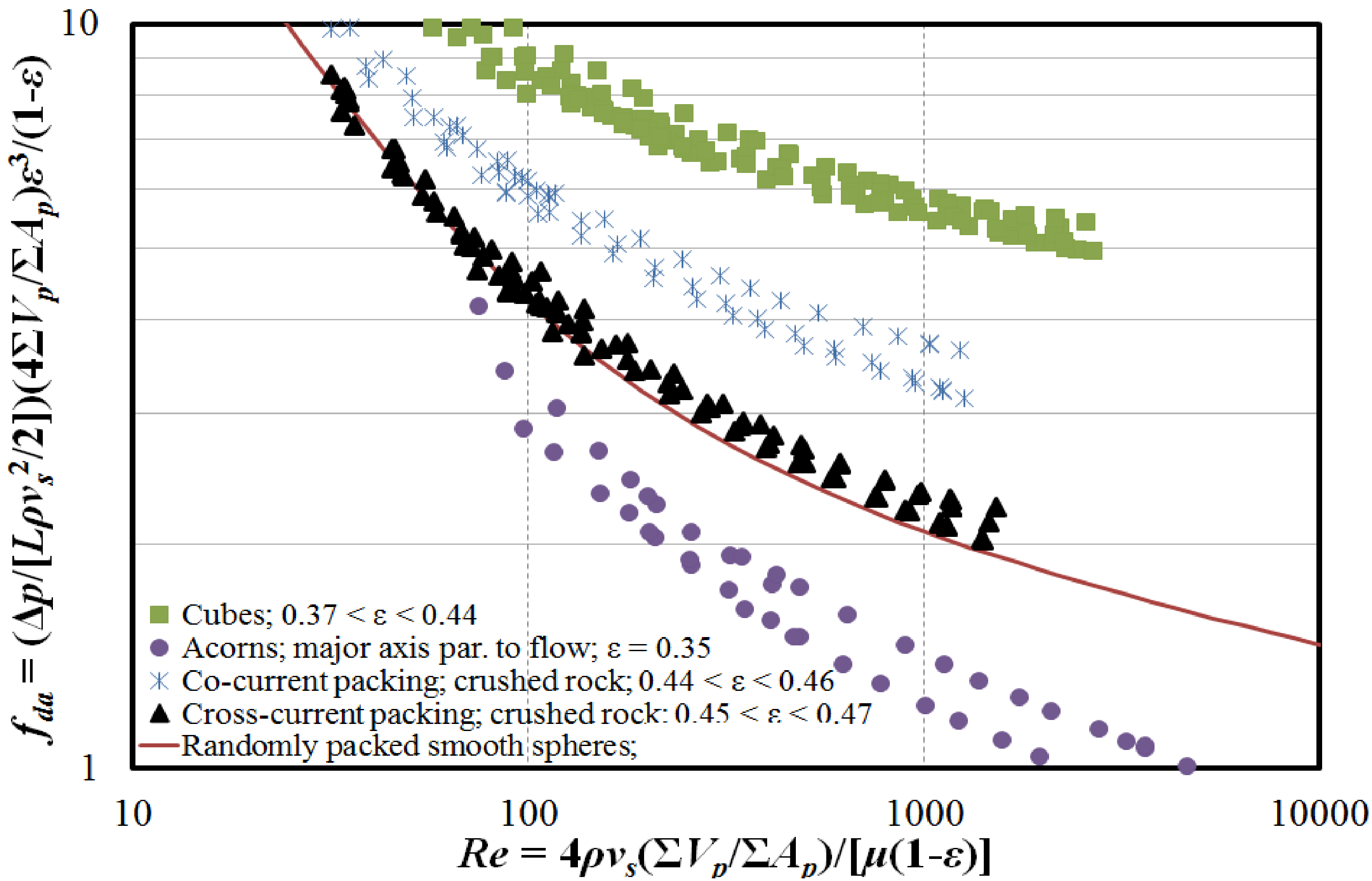
- Particle shape
- Alignment
- Packing arrangement
- Roughness

Goal:

- ➢ Prediction of rock bed pressure drop

  (pumping power and cost)

Variation of apparent friction factor



From Allen *et al.*, 2013. Powder Tech. 246:590-600

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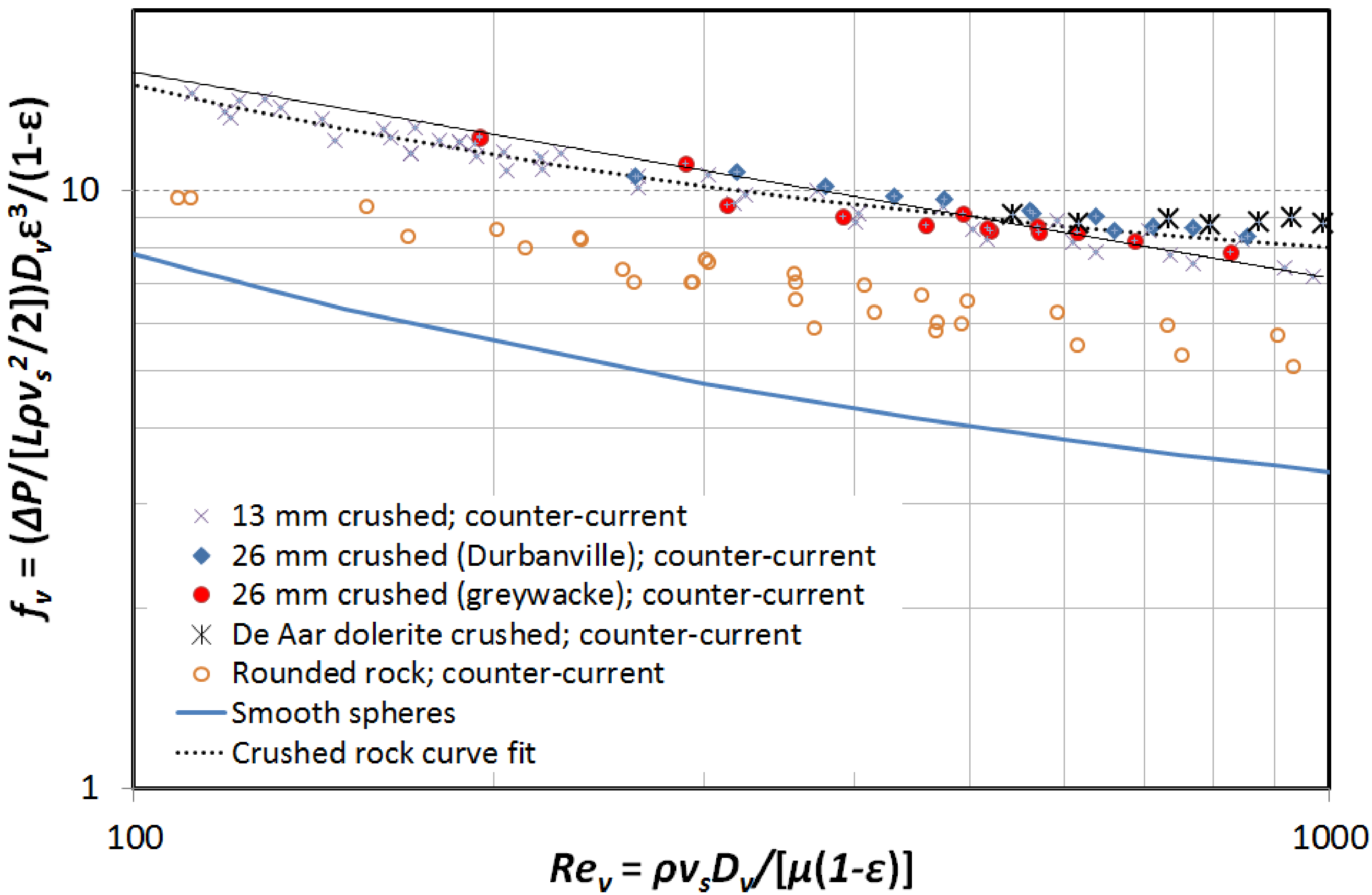
Field use: the volume-equivalent sphere diameter



Counter-current packing

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Crushed rock friction factor correlations

Using the volume-equivalent sphere diameter:

- Co/counter-current packing

$$f_v = \frac{\Delta p}{L(\rho v_s^2/2)} \frac{\varepsilon^3}{(1-\varepsilon)} D_v \approx 76.47 \left(\frac{1-\varepsilon}{Re_{pv}}\right)^{0.343}$$

- Cross-current packing

$$f_v = \frac{\Delta p}{L(\rho v_s^2/2)} \frac{\varepsilon^3}{(1-\varepsilon)} D_v \approx 80.94 \left(\frac{1-\varepsilon}{Re_{pv}}\right)^{0.41}$$

Where $50 < Re_{pv} < 500$ and

$$Re_{pv} = Re_v(1-\varepsilon) = \frac{\rho v_s D_v}{\mu}$$

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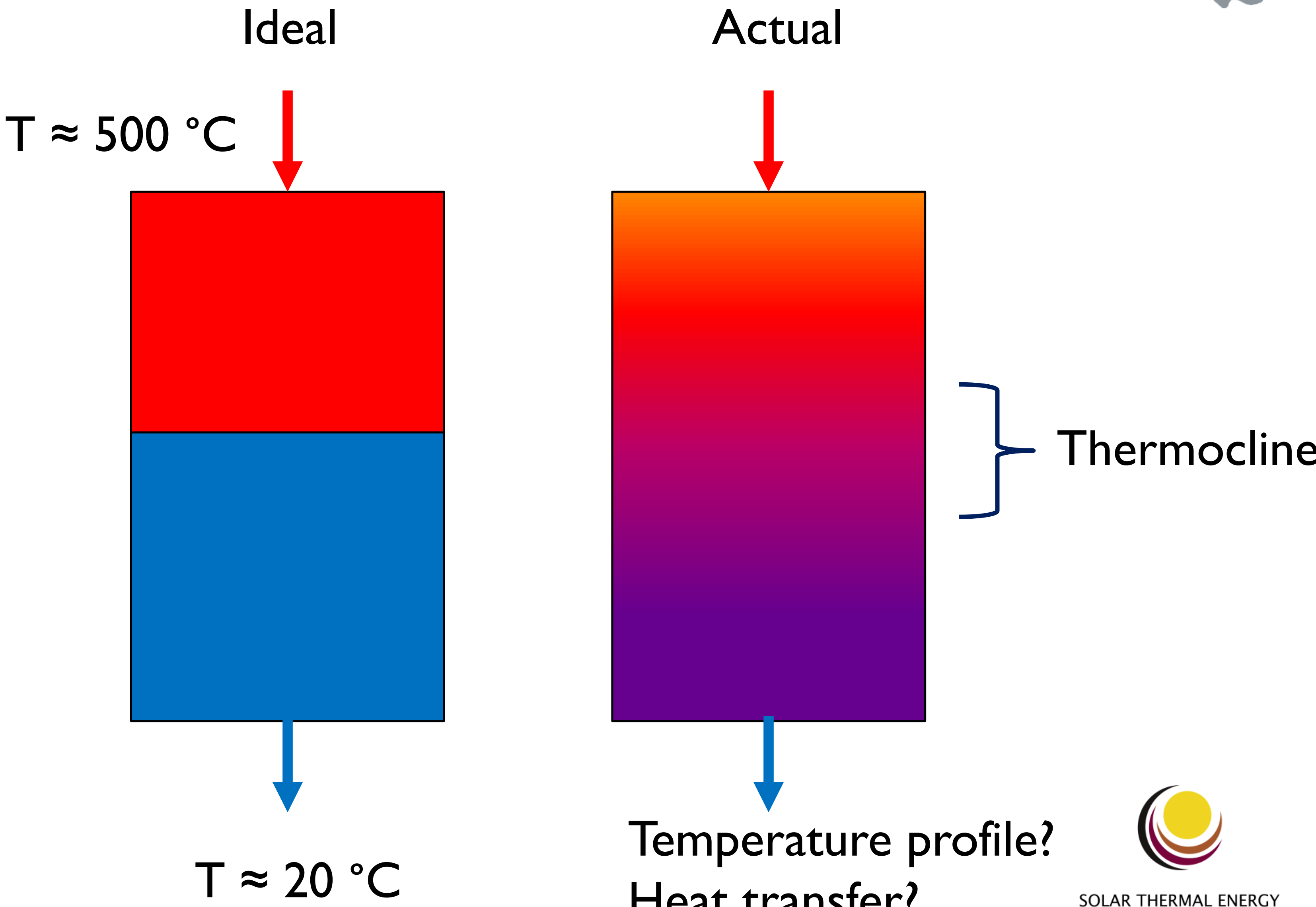
4 Thermal characteristics, sizing and cost estimate



Temperature profile?
Heat transfer?

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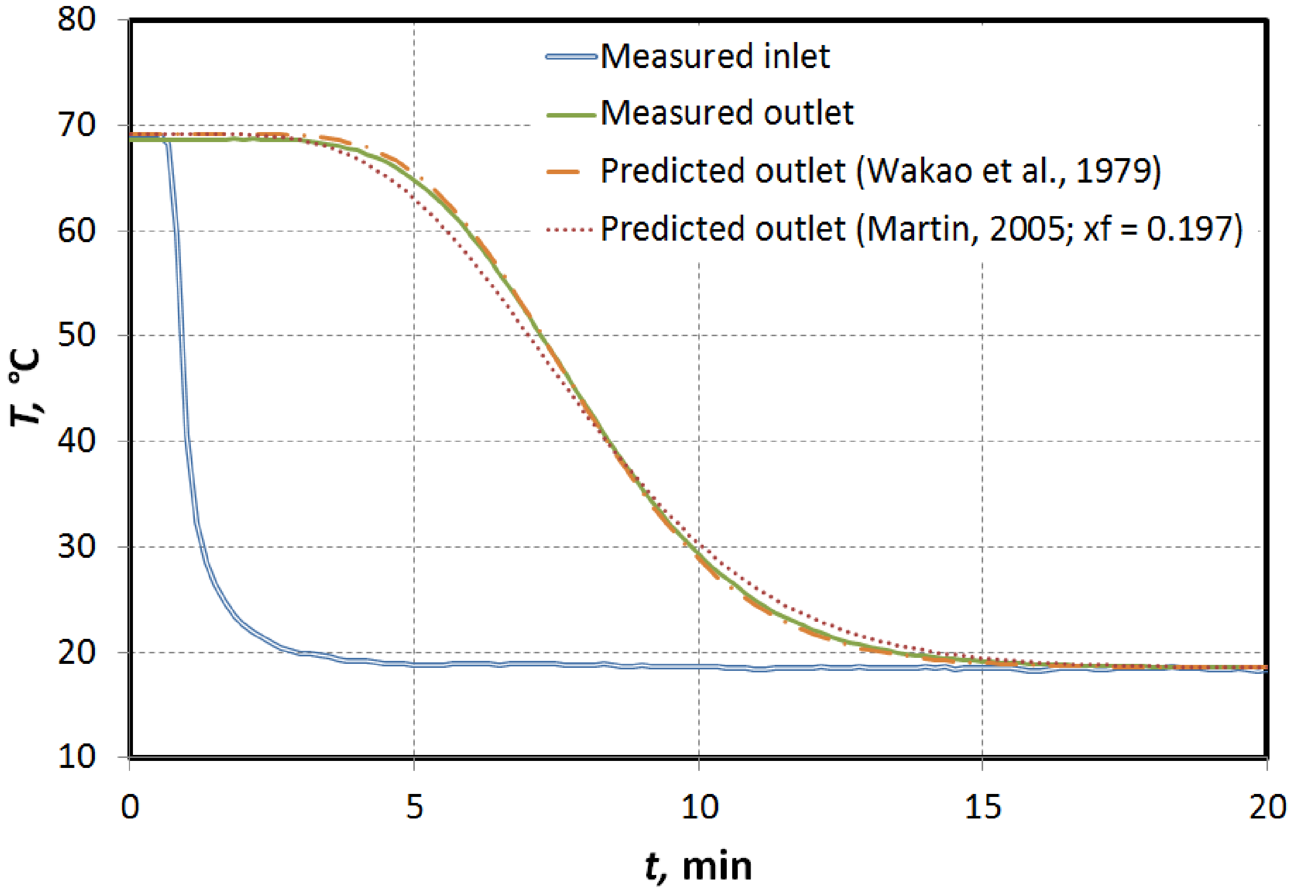
E-NTU Temperature prediction (< 75 °C)



$\Sigma V_p / \Sigma A_p$ = 1.3 mm; *Bi* ≈ 0.15; *Re* ≈ 410; Counter-current crushed greywacke

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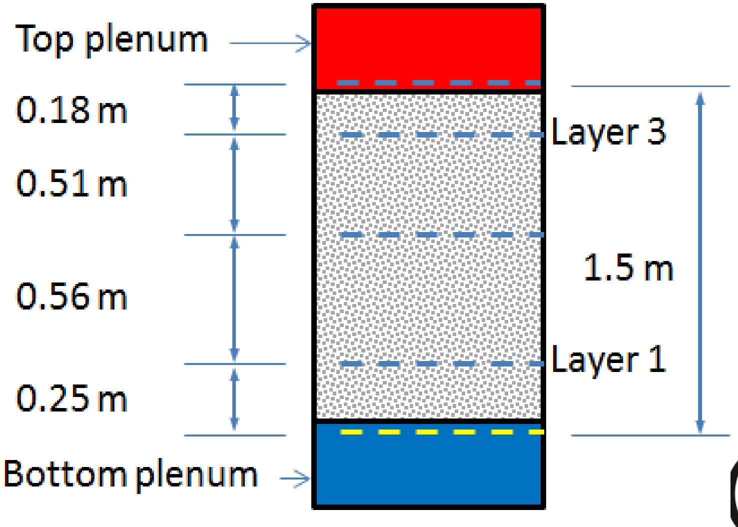
High temperature test facility (500 - 600 °C)



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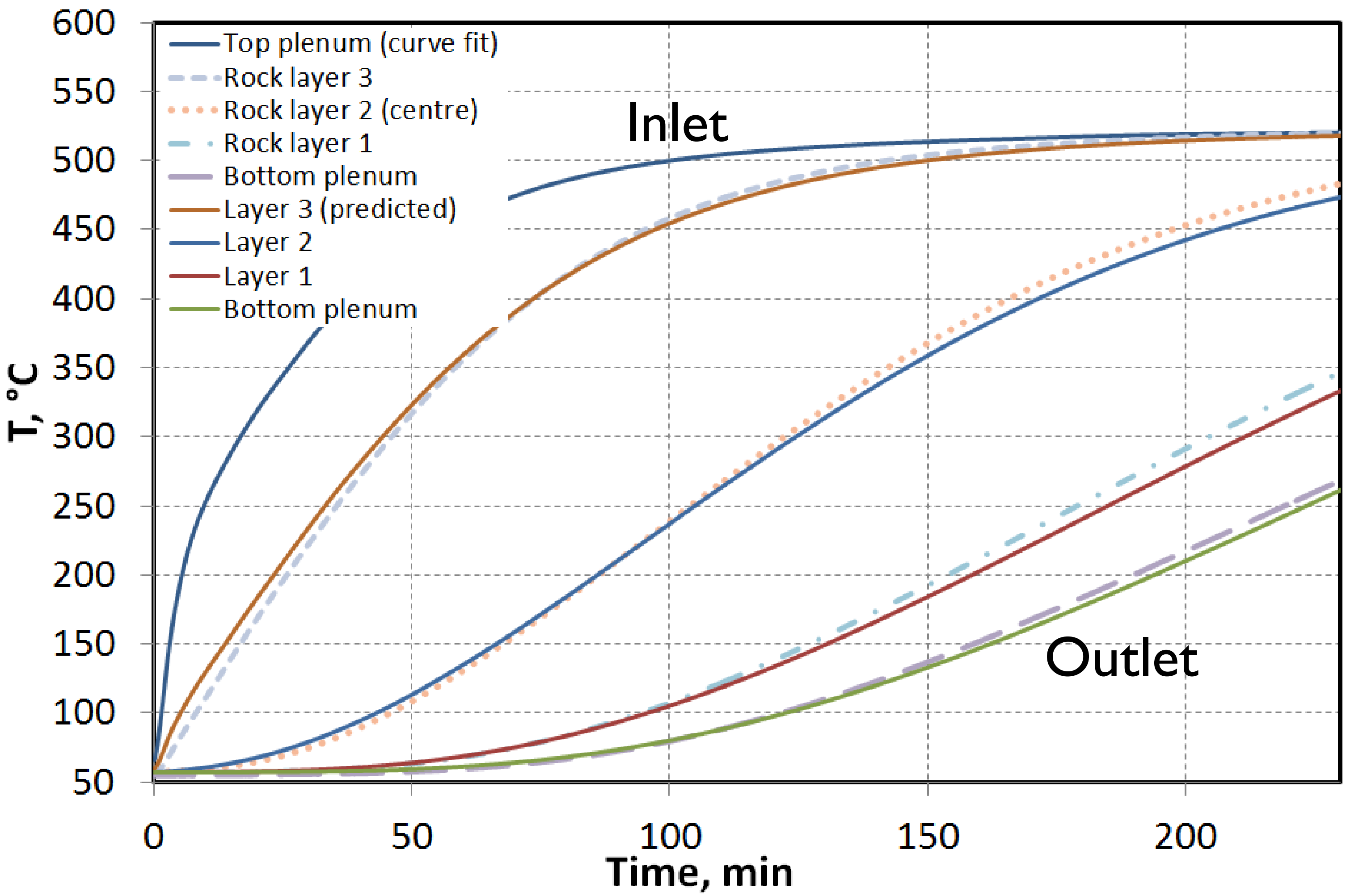
Sample measurements and E-NTU predictions



- Importance of taking into account varying c_p
- Friction factor alteration with thermal cycling

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Size and cost estimates for D = 0.02 m, L = 7 m

Bed sizes for different steam cycle outputs (12 hr)

Steam cycle, MW_e	Required A_{cs}, m^2	Bed volume, m^3	Rock volume, m^3	Rock mass, 10^3 kg
1 (3.03 MW_{th})	76 (8.7x8.7)	532	319	845
10	760 (28x28)	5320	3190	8450
100	7600 (87x87)	53 200	31 900	84 535

Storage system cost estimate

Steam cycle, MW_e	Rock cost, 10^6 R	Bed cost (10x), 10^6 R	Bed cost (3x), 10^6 R	Molten salt, 10^6 R
1 (3.03 MW_{th})	0.17	1.7	0.51	8.0
10	1.7	17	5.1	80
100	17	170	52	800

Conclusions

- Ratcheting and air volumetric flow through storage
  - Problems can be minimised by design
- Pressure drop prediction
  - Importance of particle shape, roughness, arrangement
  - No general correlation
  - Correlation for specific material and packing arrangement
  - For irregular asymmetric particles – packing & air flow direction crucial
- Thermal characteristics, sizing and cost estimate
  - Lower cost than molten salt (est. factor of 4 - 5 for scale)

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