ENERGY.
FUTURE.
ZAE.

Vacuum Super Insulation at High Temperatures

Development of a Highly Efficient Thermal Insulation for Applications in the Aluminium Industry

Matthias Demharter, M.Sc.

ZAE BAYERN

Structure

ZAE BAYERN

1. Preface | Introduction of ZAE Bayern
2. Vacuum Super Insulation (VSI) | Functionality & Example Projects
3. Vacuum Insulation Panels (VIP) | Functionality & Applications
4. VSI at High Temperatures | Potential & Possible Applications
5. Profitability of VSI | Costs & Amortisation
6. Conclusion and Outlook

Introduction of ZAE Bayern

ZAE BAYERN

ZAE Bayern – Mission and Vision

Main fields of activity (since 1991):

- Research
- Practical implementation
- Training and education
- Consulting and information

in all areas of energy technology and related sciences

Objective:
Realisation of a **carbon-neutral energy supply** using **renewable energies** and **energy- efficient technologies**

ZAE Bayern: Overview in Numbers

ZAE BAYERN

261 projects

3 locations

2 branches

1 info center

93 universities and institutes

304 partners

211 companies

16,5 million €
revenue per year

231 employees

1 registered association

37 members

120 publications

4 million €
Institutional support by

Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

Scientific Departments

ZAE BAYERN

Scientific Departments

RENEWABLE ENERGIES (RE)	ENERGY STORAGE (ES)	ENERGY EFFICIENCY (EF)
Erlangen | Nürnberg | Hof	Garching	Würzburg
Scientific Director: Prof. Brabec Divisional Director: Dr. Hauch	Scientific Director: Prof. Spliethoff Divisional Director: Dr. Hauer	Scientific Director: Prof. Dyakonov Divisional Director: Dr. Ebert
FAU Friedrich-Alexander Universität Erlangen-Nürnberg	TUM Technische Universität München	Julius-Maximilians-Universität Würzburg

Department Energy Storage (ES)

ZAE BAYERN

~85 Employees

~5,5 million € funds per year

Technische Universität München

Lehrstuhl für Energiesysteme

Lehrstuhl für Technische Elektrochemie

EES Lehrstuhl für Elektrische Energiespeichertechnik

Energy Storage

Flexibility for heat and power

System Engineering

Solar Thermal and Geothermal

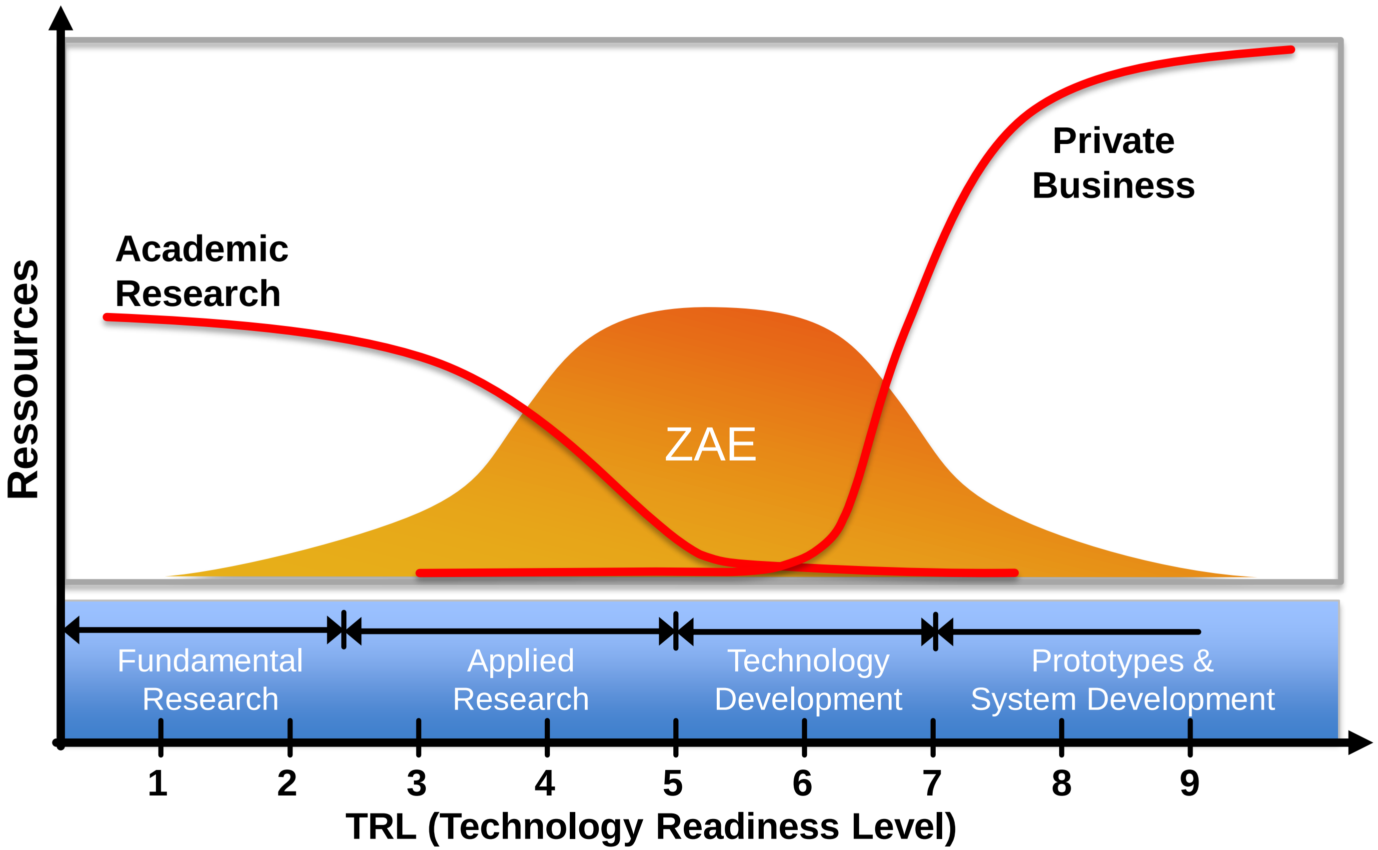
Thermal Energy Storage

Electrical Energy Storage

Heat Transformation

ZAE Bayern – Applied Research for the Industry

From basic research to prototypes



ZAE Bayern bridges the gap between fundamental research and commercialization of new technologies.

Partners of ZAE Bayern

From SMEs to big corporations

AREVA
BASF The Chemical Company
BAYER
BMW
BOSCH
Continental
Dow®
DU PONT®
EnBW
e.on
EVONIK INDUSTRIES
GDF SUEZ
Heineken®
KNAUF Gips
LEONI
MERCK
REHAU® Unlimited Polymer Solutions
Rolls-Royce®
SAINT-GOBAIN
SGL GROUP THE CARBON COMPANY
SIEMENS
Vaillant
VARTA
VATTENFALL
WACKER

Partners of ZAE Bayern

From SMEs to big corporations

ALTANA BELECTRIC® BGT DMG MORI SEIKI AKTIENGESELLSCHAFT Endress+Hauser People for Process Automation

GRAMMER GRENZEBACH HEUNISCH GUSS QUALITÄTSGIESSEREIEN HIGHTEX IBC SOLAR

Lindner MAHLE manz OSRAM Rauschert

Roto SAFRAN AEROSPACE · DEFENCE · SECURITY SMA STIEBEL ELTRON SWM

uponor Valeo va-Q-tec warema Webasto

ZAE Bayern: Prize-Winning

ZAE BAYERN

Awards and Prizes

Bayerischer Energiepreis 2014

GESTALTER der Energiewende 2014

DESIGN+ TECHNOLOGY AWARD MATERIALICA 2013

GHTC® AWARD

UMWELTPREIS SCHWEIZ PRIX SUISSE ENVIRONNEMENT

Bayerischer Staatspreis
63. Internationale Handwerksmesse München 2011

Deutscher Kältepreis

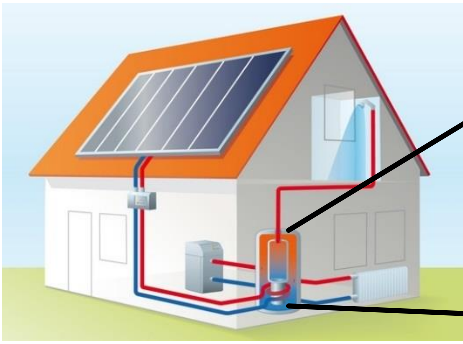
Der Innovationspreis für Klima und Umwelt

Deutschland Land der Ideen
Ausgewählter Ort 2009

Vacuum Super Insulation (VSI)

History of VSI storage development at ZAE Bayern

ZAE BAYERN



solar thermal system

storage with high thermal losses

insulation with mineral wool

liquid gas storages with vacuum super insulation

90 °C

technology transfer

-200 °C

Example Project: „Super-Insulated Long-Term Hot Water Storage“ (2012)

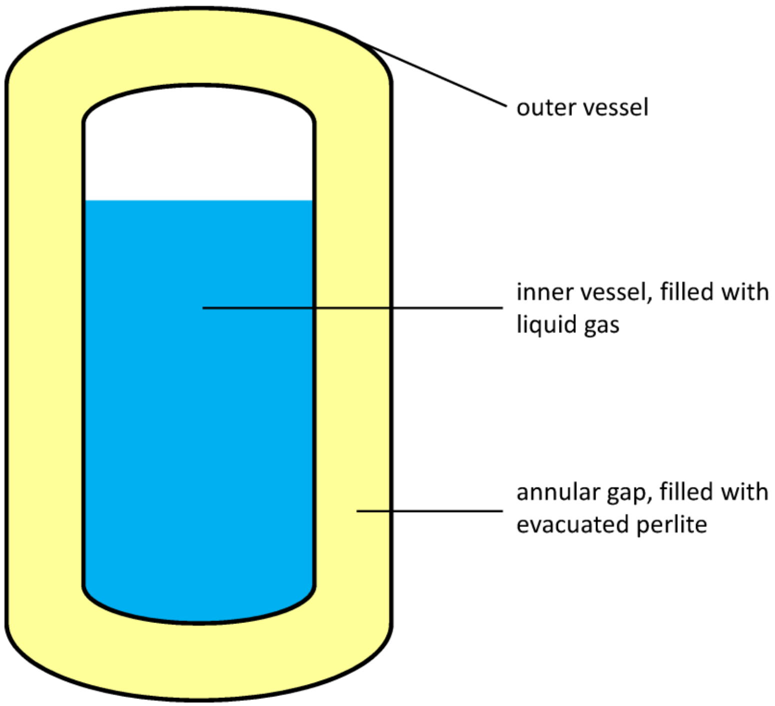
- BMU grant number 0325964A
- **16 m³** storage within the heating system of an office building
- Outer diameter: **2.4 m**
- T_{in}: **87 °C**, T_{out}: **- 4 °C**
- Measured cooling rate: **0,23 °C pro Tag**
  conventional storage: 1–3 °C pro Tag

Improvement by factor 4 – 10

Construction of VSI Containers

ZAE BAYERN

- Double-walled steel container
- Annular gap filled with microporous powder
- Evacuation of the insulation (≈ 0.01 mbar)



Total thermal conductivity:

≈ 0,003 … 0,005 W/mK for cryogenic applications (-200 °C)

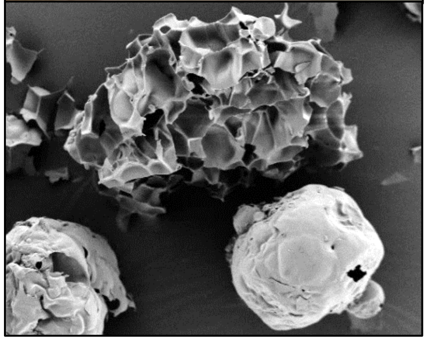
≈ 0,007 … 0,009 W/mK for hot water storage (100 °C)

≈ 0,02 … ? 0,05 W/mK for molten aluminium applications (750 °C)

VSI Powder Material: Expanded Perlite

- Raw Perlite
  - Volcanic glass, water content: 2–5 %
  - Main deposit: Greece, Turkey, USA
  - Chemical composition: SiO_2 (65–75 %), Al_2O_3 (10–15 %), K_2O, Na_2O, Fe_2O_3, CaO, MgO
- Expansion process
  - Heating (≈ 1000 °C)
  - Softening of the glassy material
  - Evaporation of contained water
  - Development of pores due to volume expansion
- Expanded Perlite
  - Density: 50–75 kg/m³
  - Porosity: ≈ 98 %
  - Mean pore diameter: 10–100 µm
  - Price: 50–75 €/m³

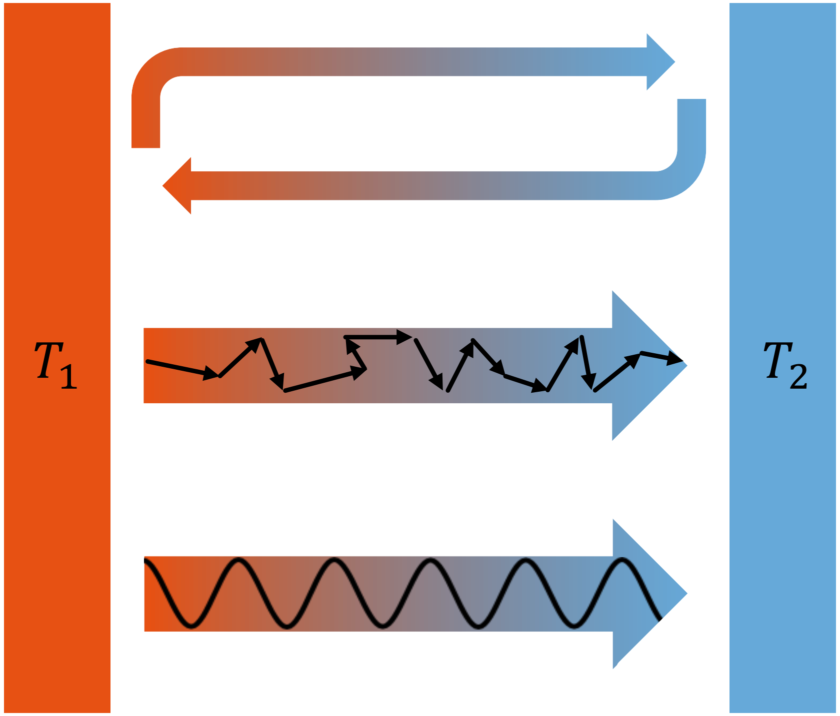
Bergama



Basics of Heat Transfer

Heat Transfer Mechanisms:

- Convection:
  Net mass transport (free or forced) within a fluid
- Conduction:
  Diffusion process, usually caused by collisions between particles
- Radiative transfer:
  Irradiation of thermal energy (photons)



Why is thermal insulation with VSI powders better than with conventional materials?

Comparison of heat transport mechanisms	 **VSI powder**	 **conventional insulation**
Inhibition of convection due to confinement of air in pores	✓	✓
Reduction of radiative transfer by absorption and scattering	✓	✓
Low solid conduction due to high porosity and small contact areas	✓	✓
Suppression of gas conduction due to evacuation	✓	✗
Total thermal conductivity	$\lambda = 0{,}007$ W/mK	$\lambda \geq 0{,}030$ W/mK

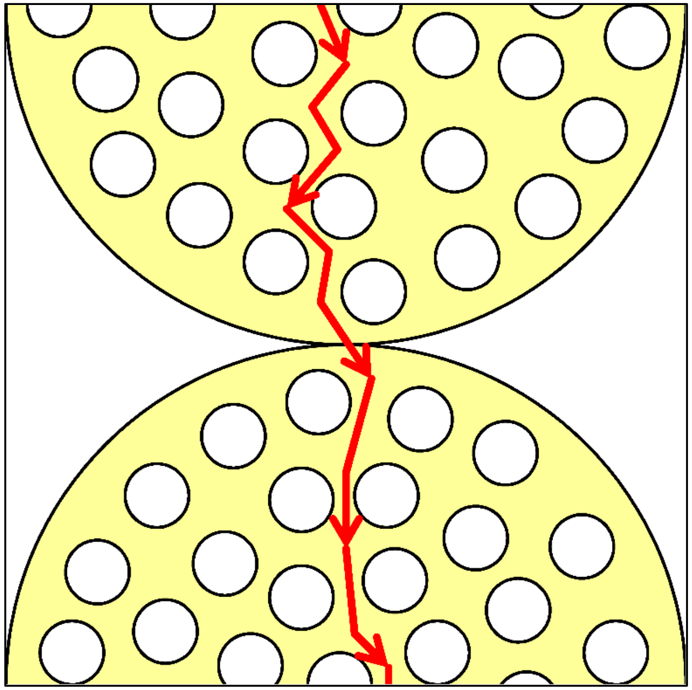
Radiative Transfer and Infrared Opacifiers

Extinction coefficient *E*: measure for attenuation of thermal radiation by absorption and scattering

Material	*E* [1/m]
mineral wool (HT-optimised)	2.000 – 5.000
perlite	2.000 – 4.000
perlite + opacifier	**5.000 – 10.000**

Examples for opacifiers: SiC, Fe_3O_4, soot

Solid Heat Conduction and Contact Resistances

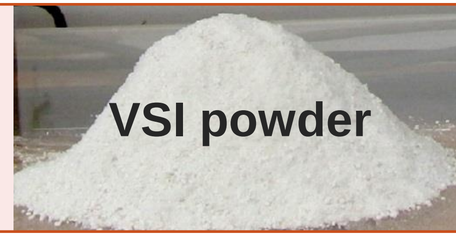
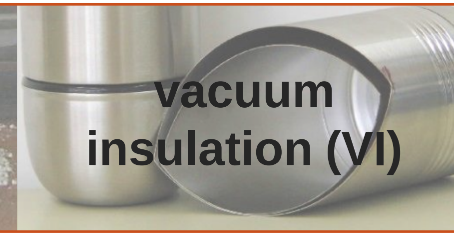


Thermal conductivity of the massive material fraction: ≈ 1 W/mK

Solid thermal conductivity of VSI powders: ≈ 0,001 W/mK

→ **reduction by factor 1000**

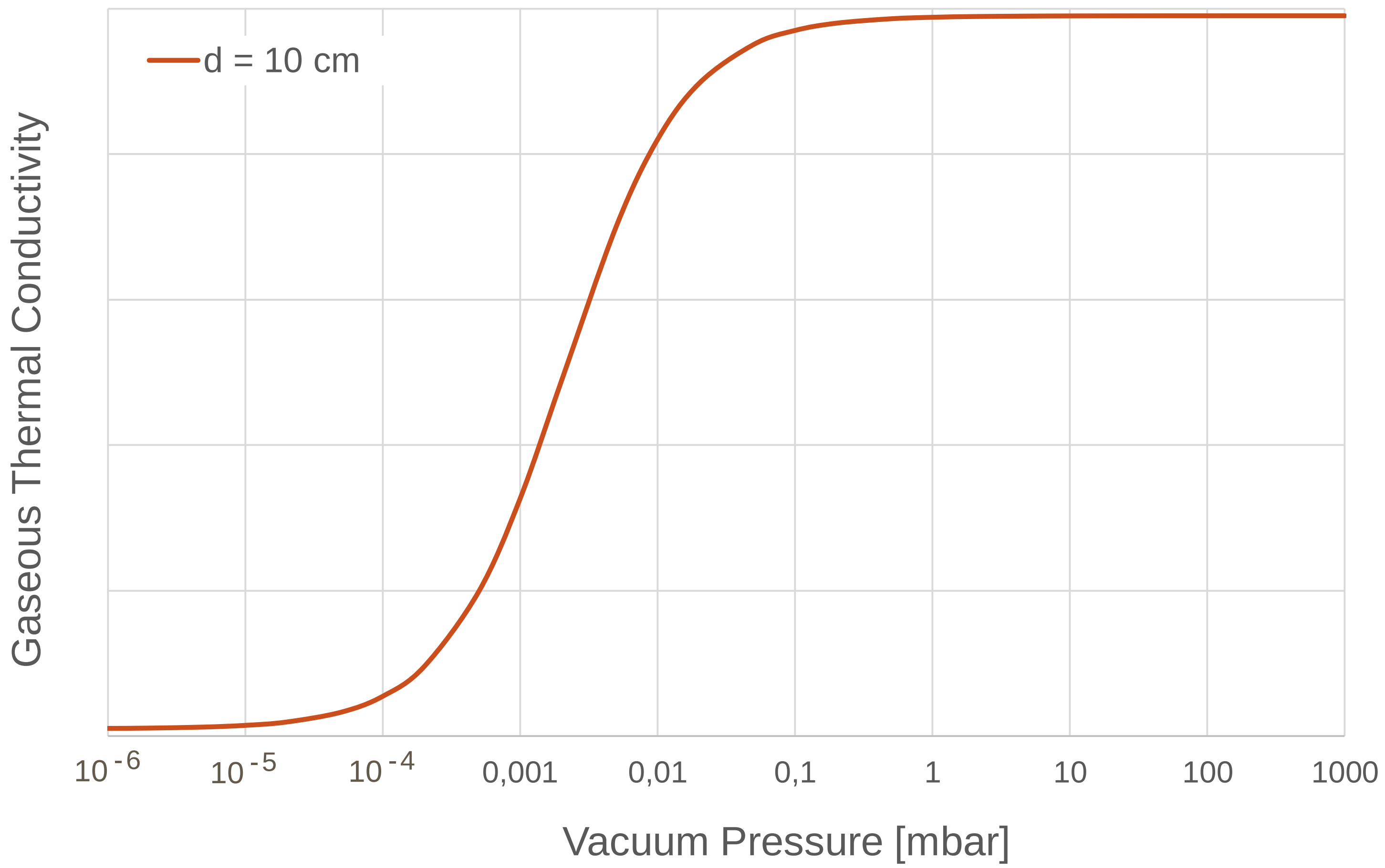
Why is thermal insulation with VSI powders better than classical vacuum insulation (Thermos flask)

Comparison of heat transport mechanisms	 **VSI powder**	 **vacuum insulation (VI)**
Suppression of air conduction and convection due to evacuation	✓	✓
Absence of solid material as a medium for conduction	✗	✓
Reduction of radiative transfer by absorption and scattering	✓	✗
Total heat flow	q = 0,14 W/m²K	q = 0,4 W/m²K

(d = 5 cm, T_1 = 90 °C, T_2 = 10 °C, ε = 0,1)

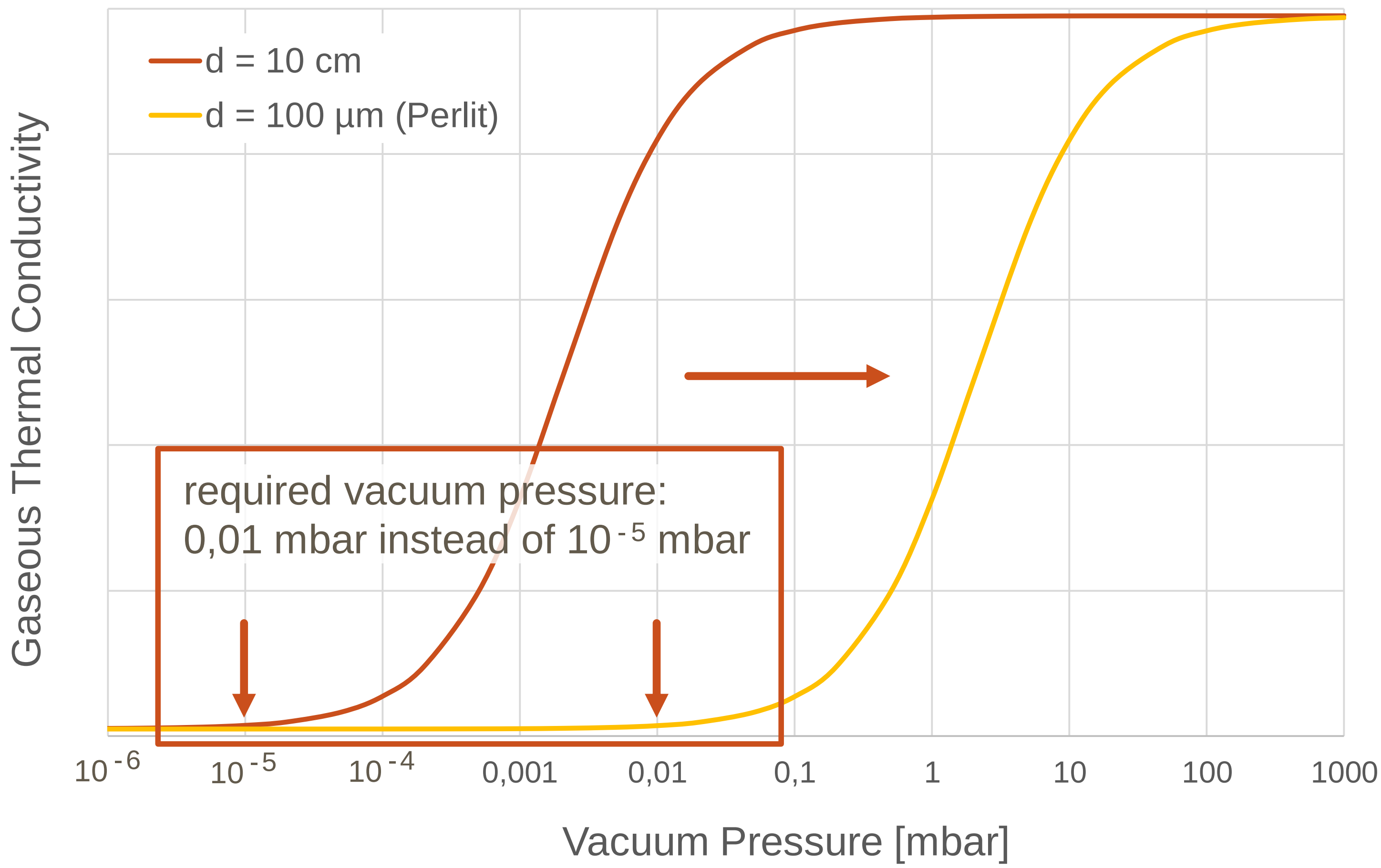
VI vs. VSI: Vacuum Requirements

Gaseous thermal conductivity as a function of vacuum pressure at different void dimensions d



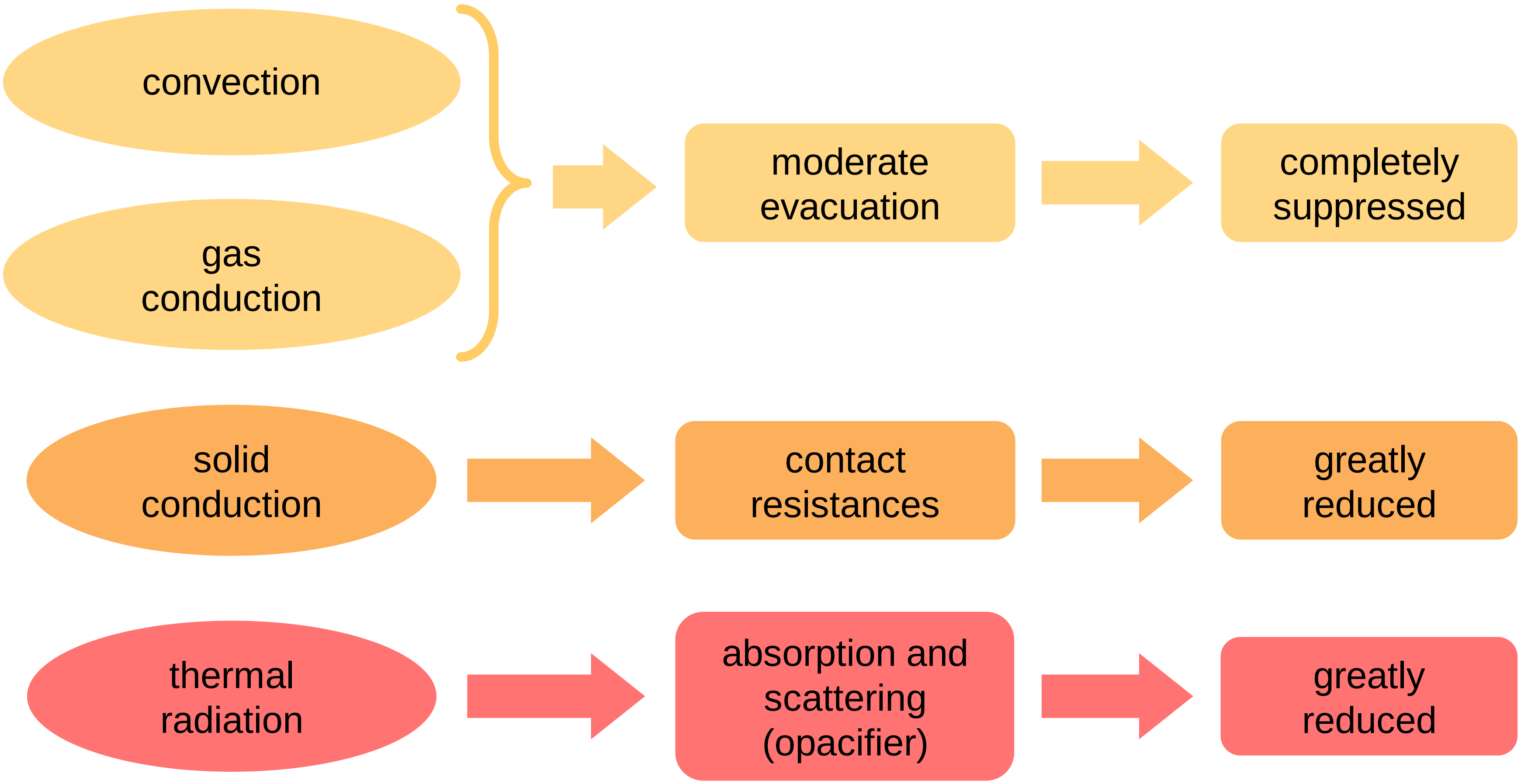
VI vs. VSI: Vacuum Requirements

Gaseous thermal conductivity as a function of vacuum pressure at different void dimensions d



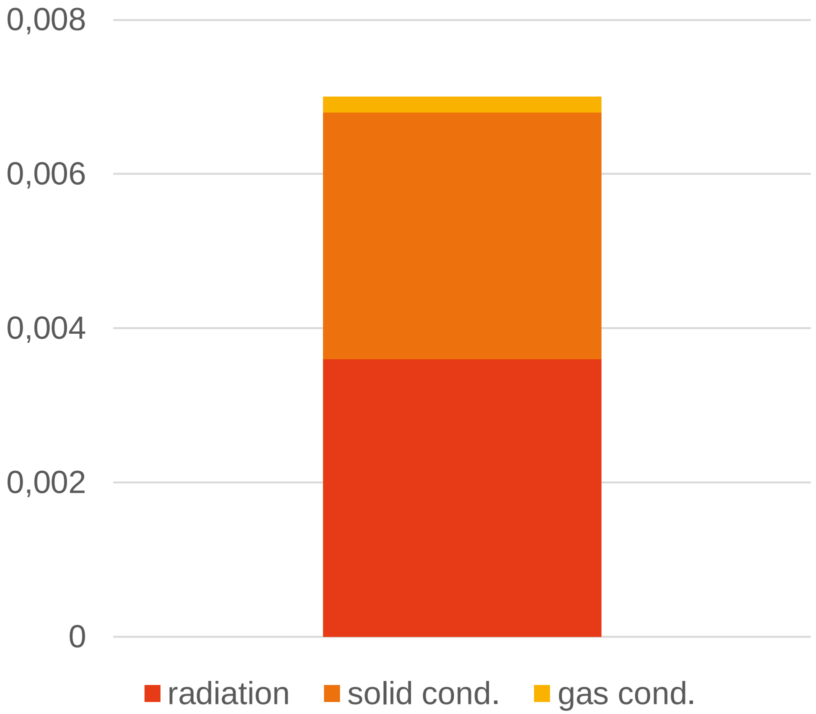
Summary: Heat Transport in VSI Powders

The exceptionally low thermal conductivities of VSI powders can be explained as follows:

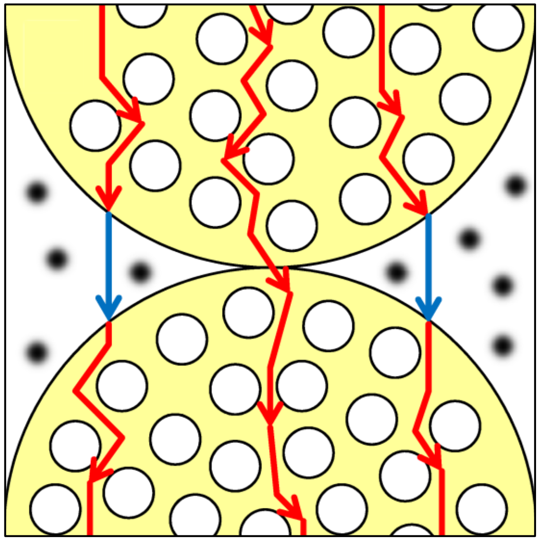


Modelling of the Heat Transport and Its Individual Mechanisms

optimisation for
hot water storages:
T = 40 °C
p = 0,01 mbar
ρ = 65 kg/m³
λ = 0,007 W/mK



Heat Transport in Evacuated Perlite Powders for Super-Insulated Long-Term Storages up to 300 °C



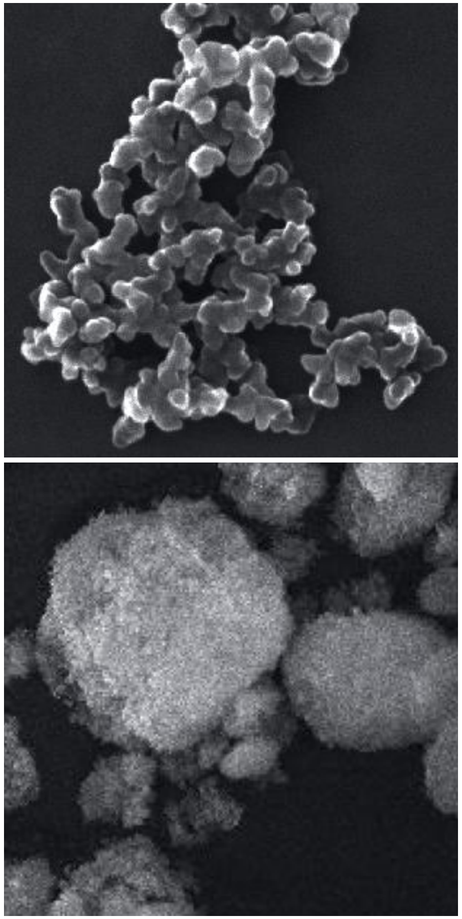
Beikircher T., Demharter M.
Journal of Heat Transfer, 135, 051301. (2013)

Vacuum Insulation Panels (VIP)

ZAE BAYERN

Alternative VSI Powder Material: Fumed Silica

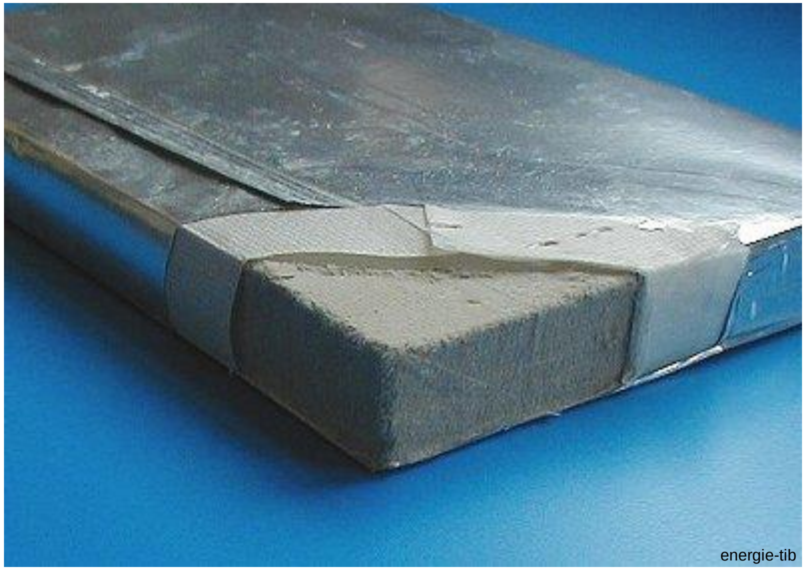
- Synthesis: flame hydrolysis of $SiCl_4$
  - SiO_2 droplets (primary particles)
  - Merging of aggregates
  - Agglomeration
- Chemical components: pure SiO_2 (>99,8 %)
- Properties:
  - Density: 50–120 kg/m³
  - Porosity ca. 98 %
  - Mean pore diameter: 10–100 nm
  - Price: 250–350 €/m³



Evonik Industries

VIP Structure

- Core: pressed panel of fumed silica (possibly with added opacifier)
- High barrier laminate (diffusion-tight): 2 alternatives
  - 7 µm Al-foil with PE coating
  - PE or PET foils with Al coating (30nm), several layers



VIP Applications

Thermal conductivity: $\lambda \approx 0{,}005$ W/mK

- Building insulation
  - Refurbishment of old buildings
  - Energetically optimised new buildings (low-energy and passive house)
- Transport, e.g. cooled drugs
  → space savings
- Refrigeration technology

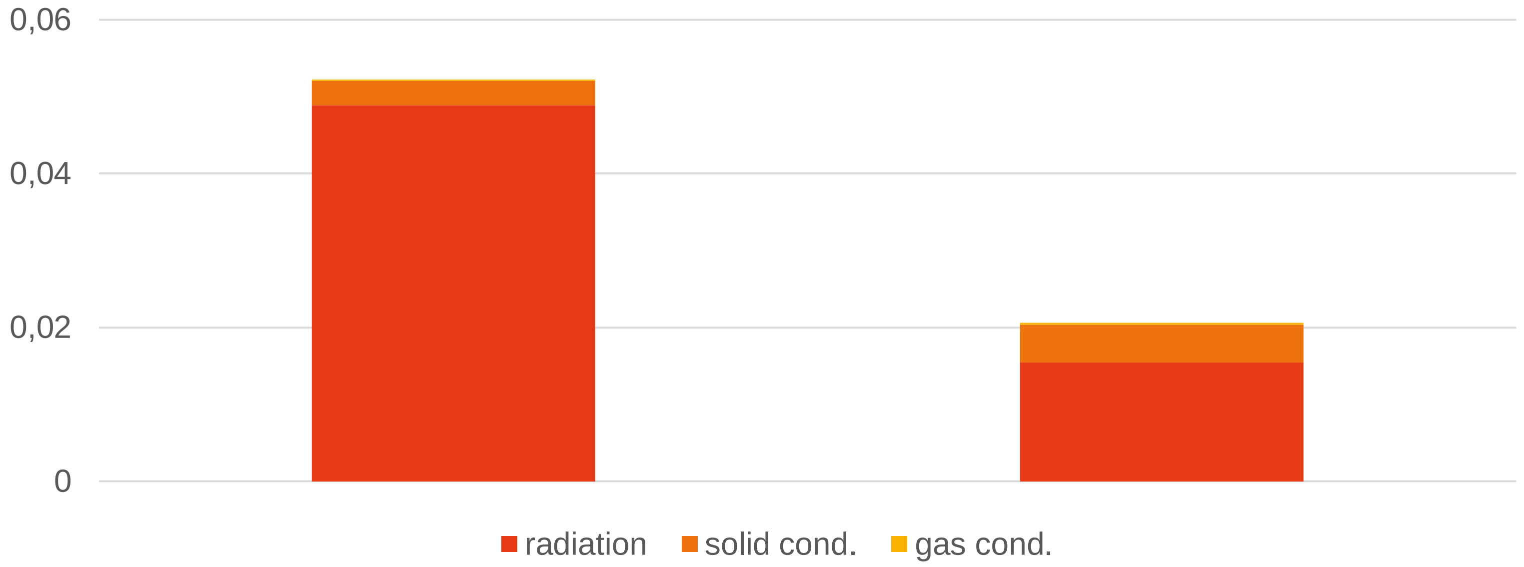
VSI at High Temperatures

Material Optimisation for High Temperatures (200 – 1000 °C)

ZAE BAYERN

non-optimised VSI powder:
expanded perlite
T = 380 °C (mean temp.)
p = 0,01 mbar
ρ = 65 kg/m³
without opacifier
λ ≈ 0,05 W/mK

optimised VSI powder:
perlite (or fumed silica)
T = 380 °C (mean temp.)
p = 0,01 mbar
ρ = 90 kg/m³
with added opacifier
λ ≈ 0,02 W/mK



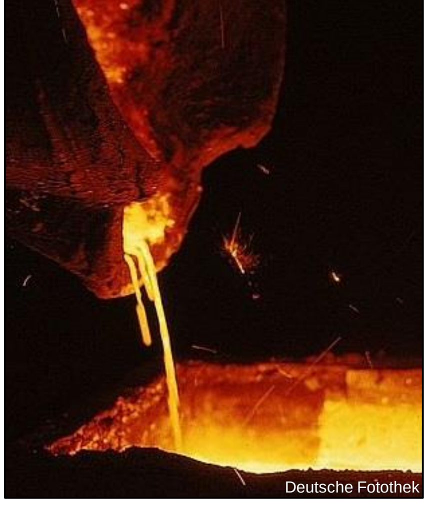
These values are extrapolated and estimated, not measured!

Applications for HT-VSI

- Transport crucibles for molten aluminium
  - Increase of transport range
  - Decrease of energy demand
  - Decrease of outside temperature
  - Increase of usable volume

- Industrial high-temperature processes
  - Furnaces and processing chambers
  - High-temperature waste heat storages
  - Insulation of pipelines

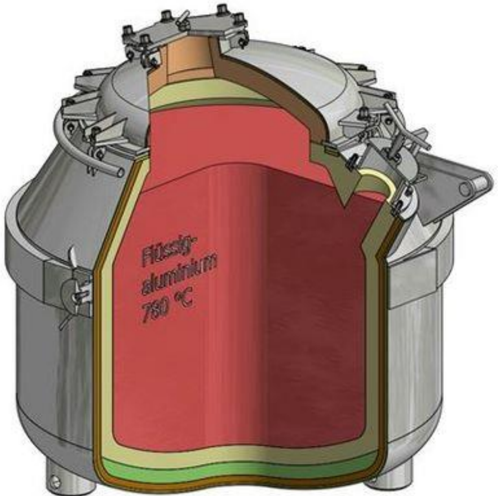

Bartz Maschinenbau


Deutsche Fotothek

Example Calculation for Molten Aluminium Transport Crucibles

Current insulation of crucibles:

- Temperature loss of 6 °C per hour (at best)
- Container capacity: 6 t aluminium ≈ 2,5 m^3
- Surface: ≈ 9 m^2
- **U-value: ≈ 2 W / m^2 K**



Bartz Maschinenbau

Potential of powder VSI:

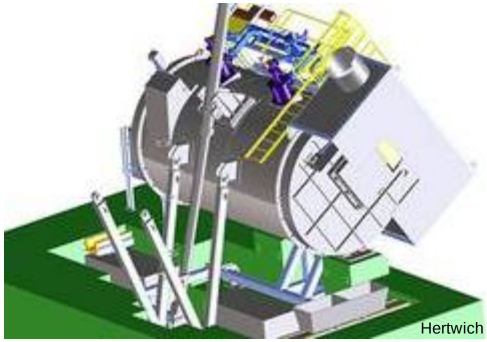
- Thermal conductivity: 0,02 – 0,05 W/mK
- 10 cm insulation thickness (→ usable volume)
- **U-value: 0,2 … 0,5 W / m^2 K**

Temperature loss approx. 1–2 °C per hour (without lid)

Aluminium Furnaces

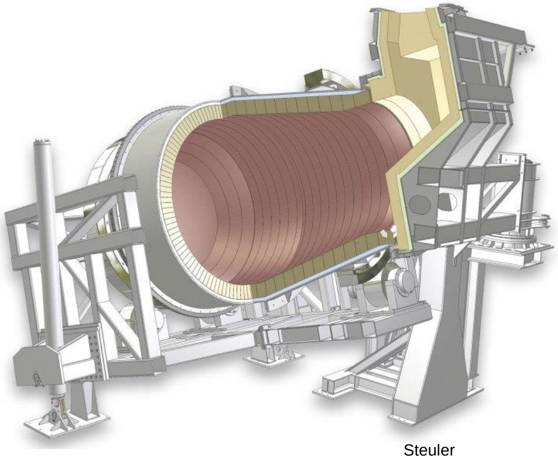
ZAE BAYERN

- E.g. casting furnaces, rotary drum furnaces, heat treatment furnaces
- Challenge: constructive realisation of an evacuable void
- potential: increase of energy efficiency by considerable reduction of thermal losses



Hertwich

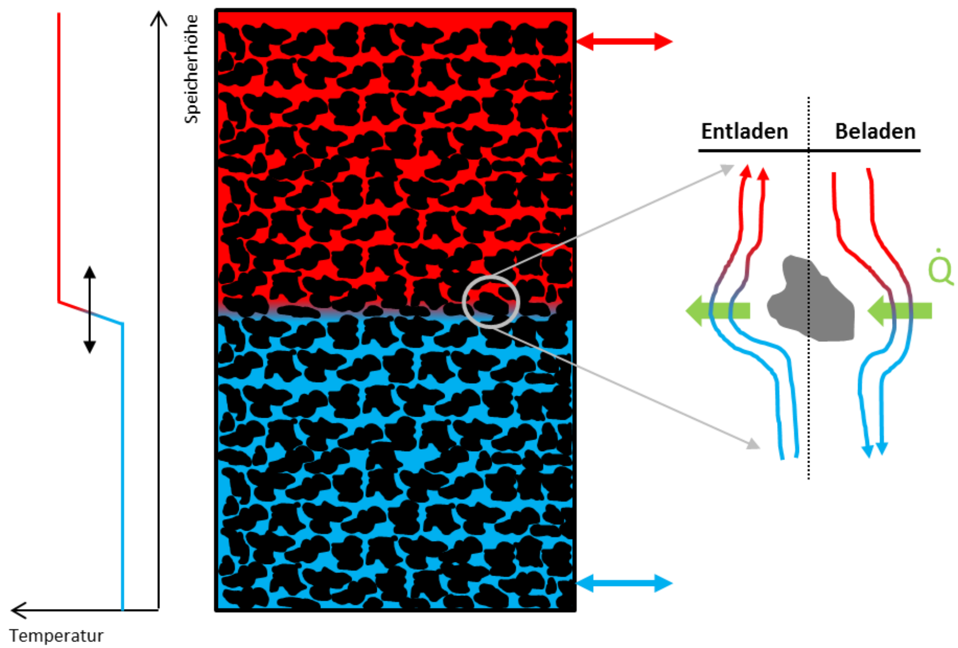
Seco/Warwick



Steuler

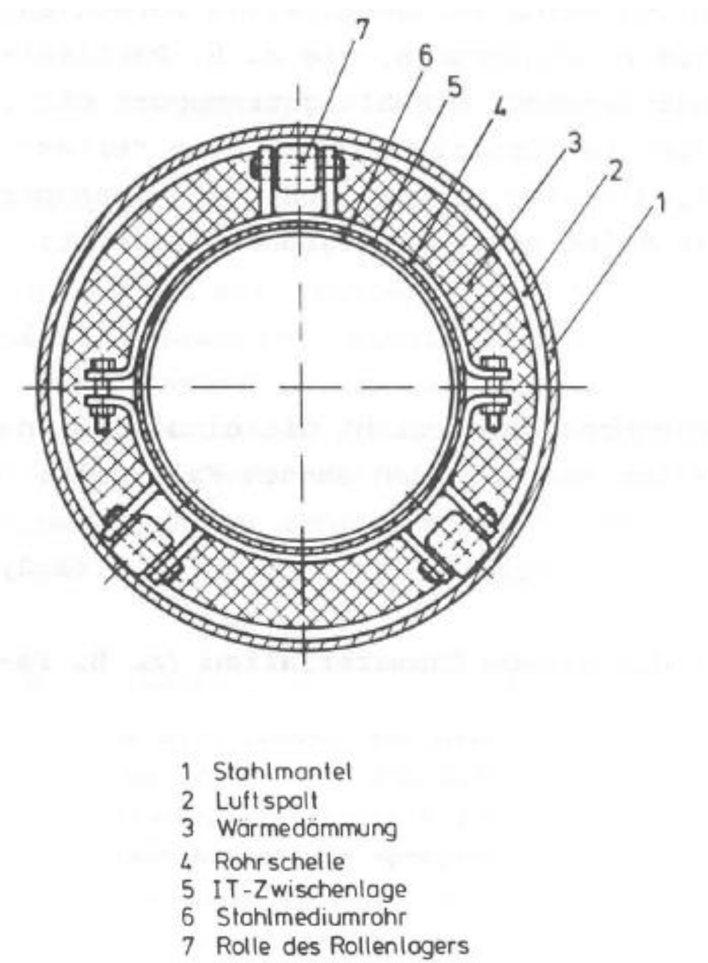
Storages for Waste Heat

- Example Project „Usage of Industrial Waste Heat at a Foundry“
- Storage of discontinuous waste heat from flue gas
- Two-component storage (thermal oil + solid medium) with T = 300 °C
- Usage of the stored heat in a drying process



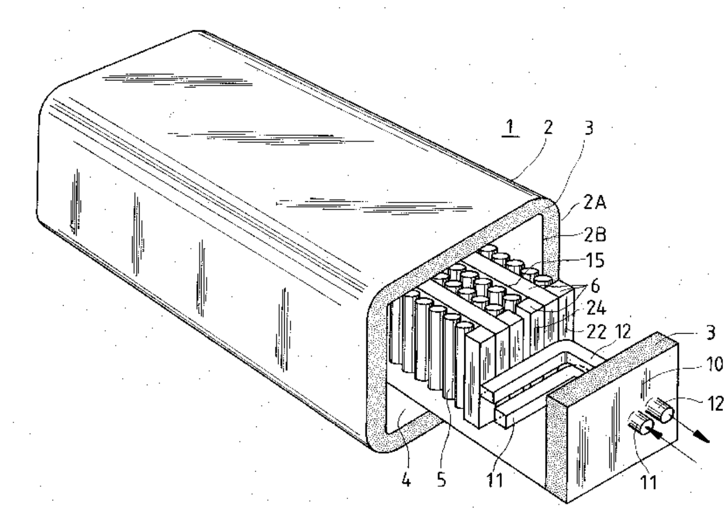
High-Temperature Pipelines

- Heat transfer media: steam, thermal oil, air
- Construction of double-walled VSI pipelines is known from district heating (up to 180 °C)



High-Temperature VIPs

- Laminates containing PE and PET, which are currently used for almost all produced VIPs, are generally not applicable above 100 °C
- Envelopes from steel (or other metals) are necessary
  - Steel foils (75 µm) already in 1990
  - Current approaches: reduction to 25 µm



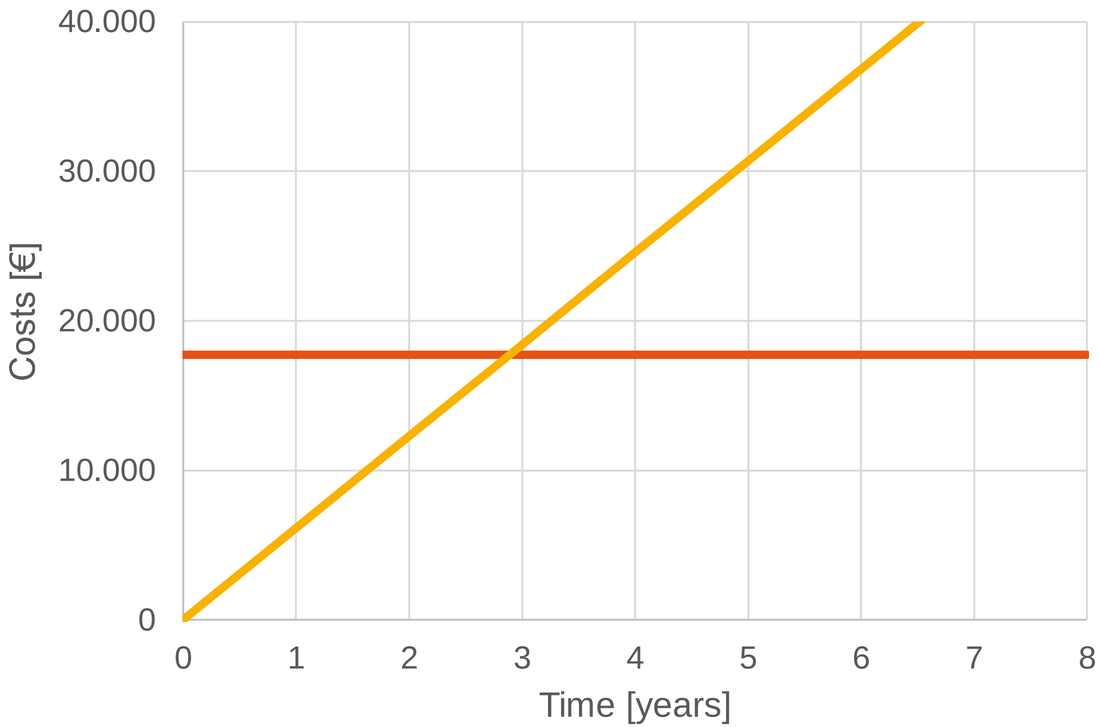
US patent 4517263 A

Profitability of VSI

Estimated Amortisation Period of a VSI Storage

ZAE BAYERN

- Comparison: 25 m³ VSI storage vs. Conventional storage with mineral wool (insulation thickness 20 cm in both cases)
- Storage temperature 600 °C, outside temperature 0 °C



- Initial investment: 17.750 €
- Annual savings: 6.140 €
- **Amortisation period: approx. 3 years**

Conclusion and Outlook

Conclusion and Outlook

- For hot water storages, VSI reaches thermal conductivities which are lower by a factor of approx. 5 compared to conventional insulation materials (state of the art).
- Using an infrared opacifier, we expect values which are lower by a factor of approx. 4 to 10 compared to high-temperature insulation or refractory materials at 750 °C.
- The experimental proof of these thermal conductivities has not been carried out yet (need for research).
- For some applications, the vacuum-tight encapsulation of VSI powders may be technically challenging (need for technology development).
- ZAE Bayern is looking for industry partners with specific applications for HT-VSI to apply for a federally-granted R&D project, planned to start in autumn 2017.

Thank you for your attention!

Matthias Demharter, M.Sc.
Dr. Thomas Beikircher

ZAE Bayern
Bavarian Center for Applied Energy Research e. V.
Department Energy Storage (ES)

Walther-Meißner-Str. 6
D-85748 Garching

Tel.: +49 89 329442-51
Fax: +49 89 329442-12

matthias.demharter@zae-bayern.de
thomas.beikircher@zae-bayern.de
http://www.zae-bayern.de

ZAE BAYERN