



**University of Stuttgart**

Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE)

# Ultra-high temperature thermal insulation

First International Workshop on Ultra-High Temperature  
Thermal Energy Storage, Transfer and Conversion

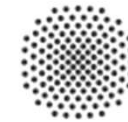
Madrid, 14. – 15. November 2019

Stephan Lang



**IGTE (established July, 2018)**

Formally known as ITW/TZS



**Universität Stuttgart**  
Institut für Energiespeicherung



**Institute for Building Energetics, Thermotechnology and Energy Storage**  
*Institut für Gebäudeenergetik, Thermotechnik und Energiespeicherung*

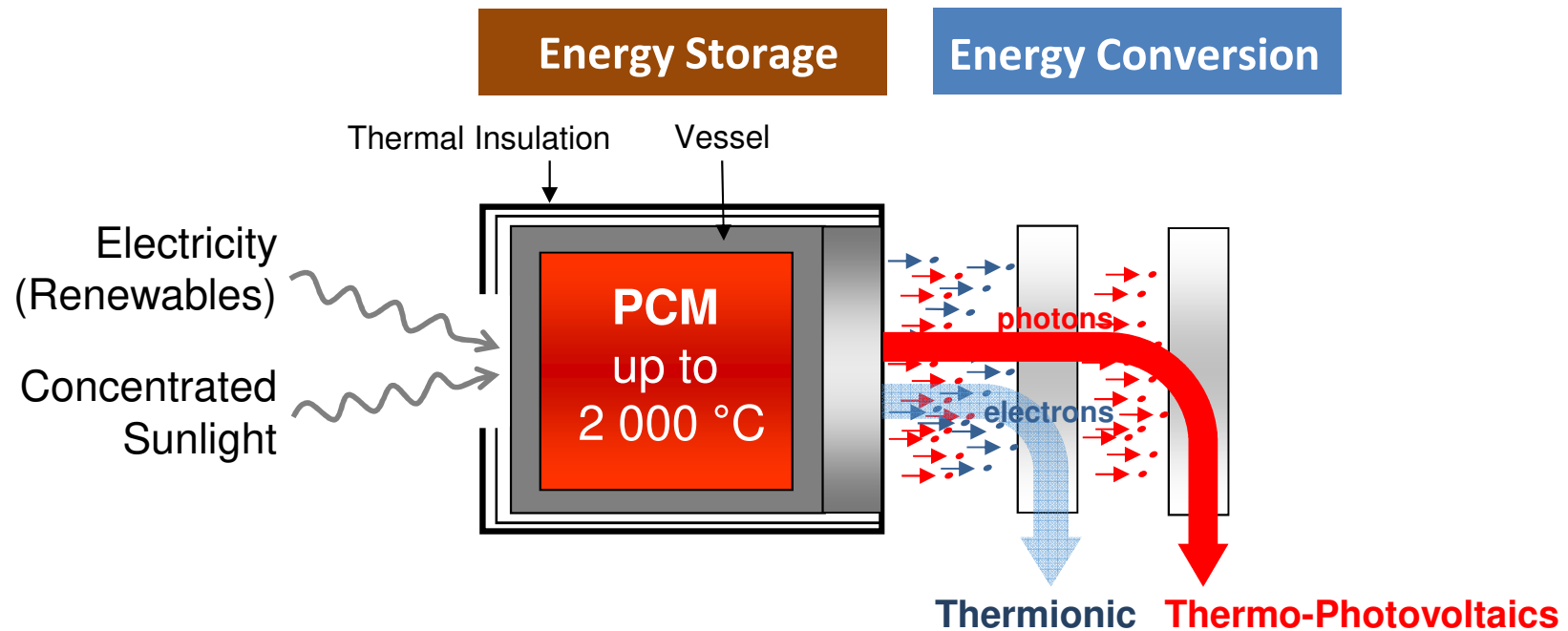
- Solar Technology
- Energy Storage
- Testing and Inspection
- Solar & Energy Efficient Buildings
- Smart Cities
- Energy Efficiency
- Cooling Technology

- Background, Aim, Motivation
- Thermal insulation techniques
- Market screening for UHT thermal insulation materials
- Cost-efficiency comparison of different thermal insulation techniques
- Optimization potential for the efficiency of thermal insulations

# Background, Aim and Motivation

## Background

Research project the presented work is part of



# Aim of presented thermal insulation research



- Finding the most cost-efficient thermal insulation for a thermal energy store with temperatures up to 2 000 °C
  - Screening for suitable commercially available thermal insulation materials for temperatures up to 2 000 °C
  - Comparison of different insulation techniques
  - Research on insulation optimization

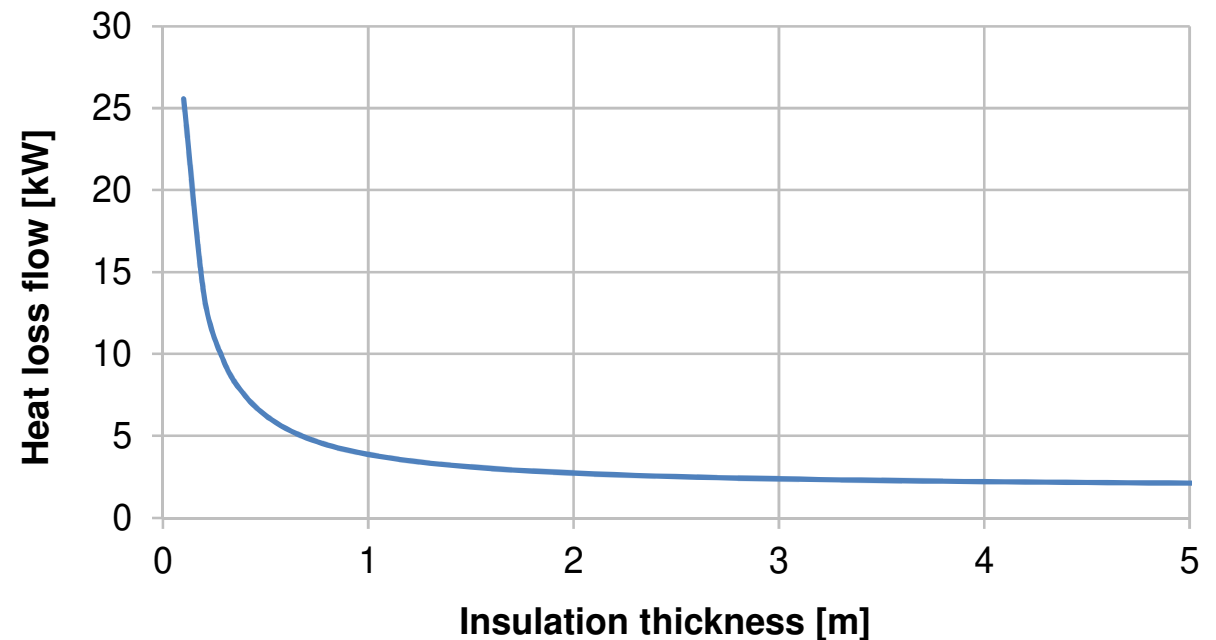
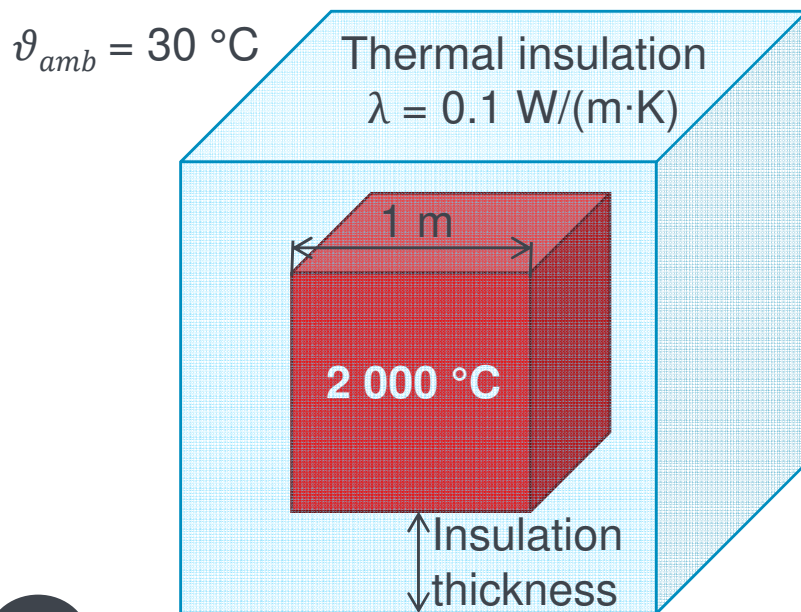
# Motivation for a high insulation performance



- Decreasing energy losses
- Increasing storage time
- Increasing temperature homogeneity of energy store

# Motivation for a very efficient thermal insulation (low thermal conductivity)

- Decreasing total volume of device
- Heat losses  $\sim$  surface of heat transfer to ambient





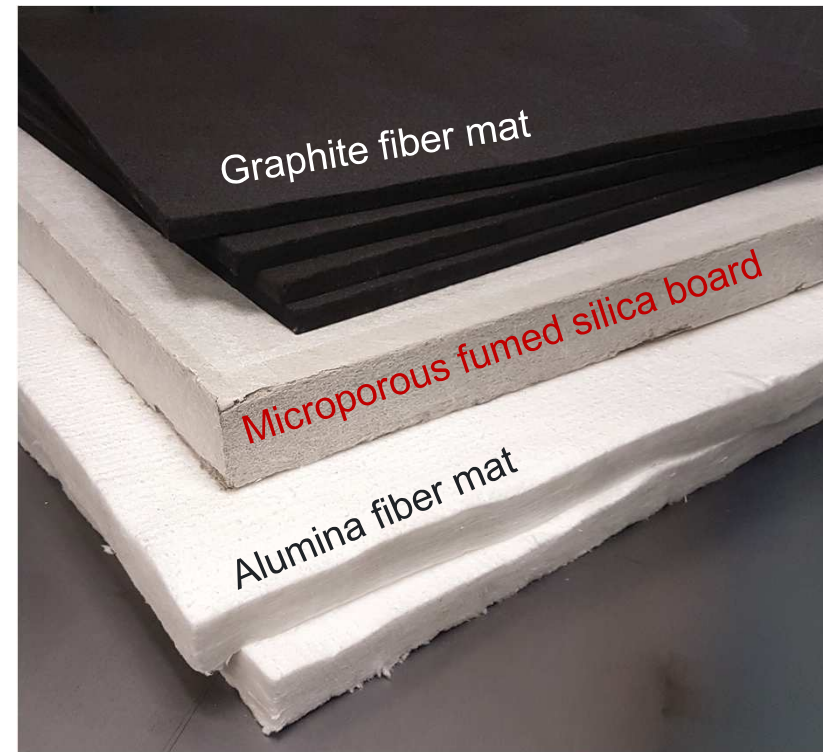
# **Thermal insulation techniques**

# Thermal insulation techniques

## Infrared radiation shields (IRS)



## Porous thermal insulation materials (TIM)



10

Source: Triangle Refractory Materials: "Molybdenum Infrared radiation shields", URL: <https://trmaterial.com/wp-content/uploads/2018/12/Mo-heat-shield-10x8.jpg>, accessed 25.09.2019.

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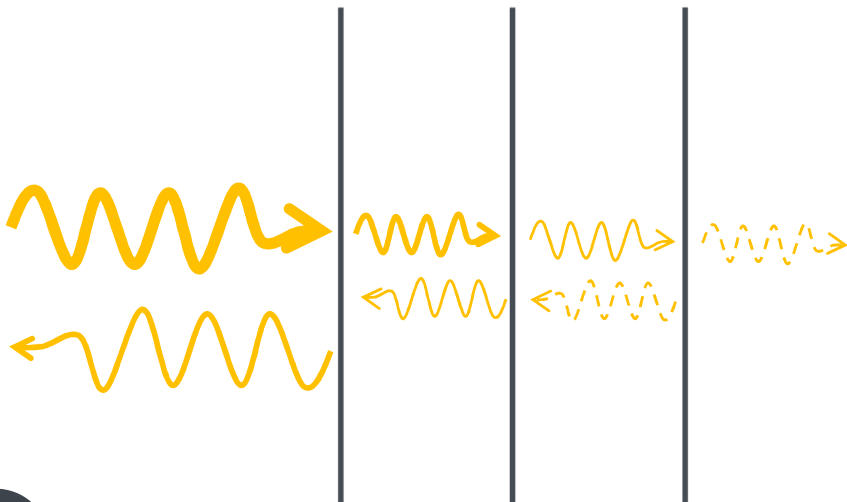
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# Thermal insulation techniques

## Working principles – Thermal radiation

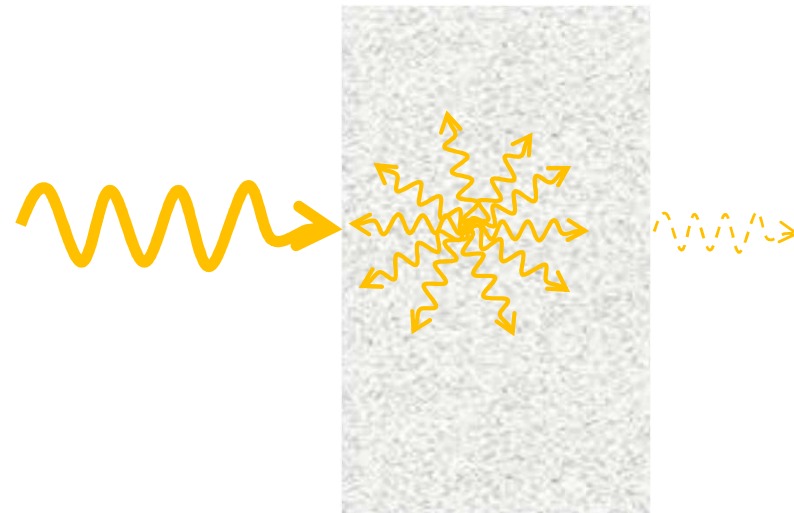
### Infrared radiation shields (IRS)

- Reflection
- Absorption
- Emission



### Porous thermal insulation materials (TIM)

- Scattering (incl. reflection, absorption, emission)



# Thermal insulation techniques

## Working principles

### Infrared radiation shields (IRS)

- Heat transfer mechanisms:
  - Thermal radiation
  - solid conduction (via spacers)
  - gas conduction
  - convection
- Characteristic material parameter:
  - Emissivity  $\varepsilon$  [-]

### Porous thermal insulation materials (TIM)

- Heat transfer mechanisms:
  - Thermal radiation
  - solid conduction
  - gas conduction
- Characteristic material parameter:
  - Effective thermal conductivity  $\lambda$  [W/(m·K)]

# **Market screening for porous thermal insulation materials (TIM)**

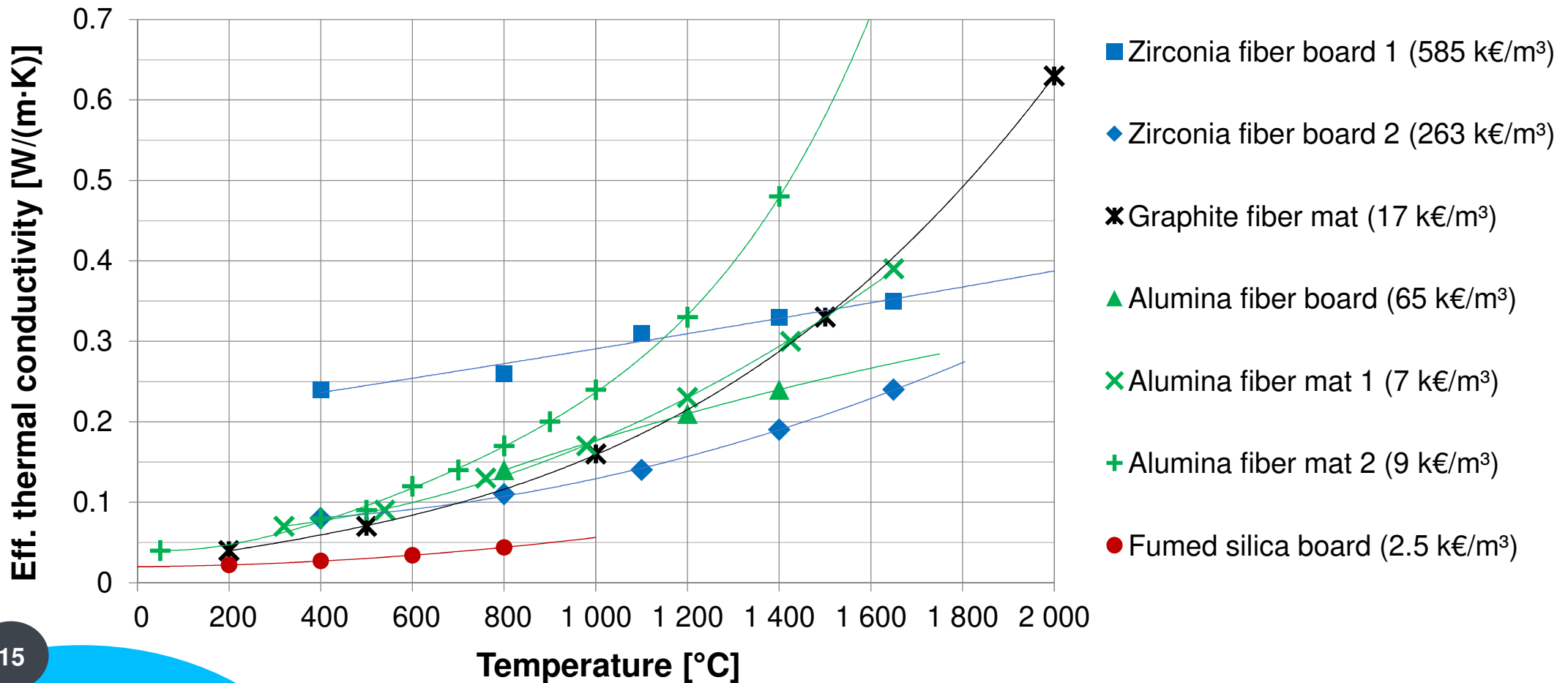
# Market screening for porous thermal insulation materials (TIM)



- Main criteria:
  - Permanent temperature stability
  - Costs
  - Eff. thermal conductivity

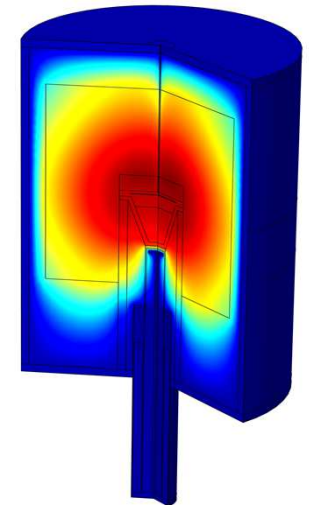
# Market screening for porous thermal insulation materials (TIM)

Thermal conductivities of TIMs in air/ nitrogen (manufacturer data)



# Choice of most cost-efficient thermal insulation materials (TIM)

- Conductivity-costs-product:  $CCP(\vartheta) = \lambda(\vartheta) \cdot \text{specific costs}$ 
  - $CCP_{ZFB2}(1\,400\,^{\circ}\text{C}) = 0.19\,\text{W}/(\text{m}\cdot\text{K}) \cdot 263\,\text{k}\text{€}/\text{m}^3 = 49.97\,\text{k}\text{€}\cdot\text{W}/(\text{m}^4\cdot\text{K})$
  - $CCP_{GFM}(1\,400\,^{\circ}\text{C}) = 0.29\,\text{W}/(\text{m}\cdot\text{K}) \cdot 17\,\text{k}\text{€}/\text{m}^3 = 4.93\,\text{k}\text{€}\cdot\text{W}/(\text{m}^4\cdot\text{K})$
  - Only significant for a flat wall
  - Higher heat transfer surface with higher insulation thickness not considered
- Thermal simulations for indicated application recommended
  - Evaluation of heat losses and costs
- Combination of different TIM
  - Insulation volume and cost reduction potential
  - Thermal simulations and tests necessary to prevent damage for TIM with lower max. temperatures than max. application temperature





# **Market screening for infrared radiation shield (IRS) materials**

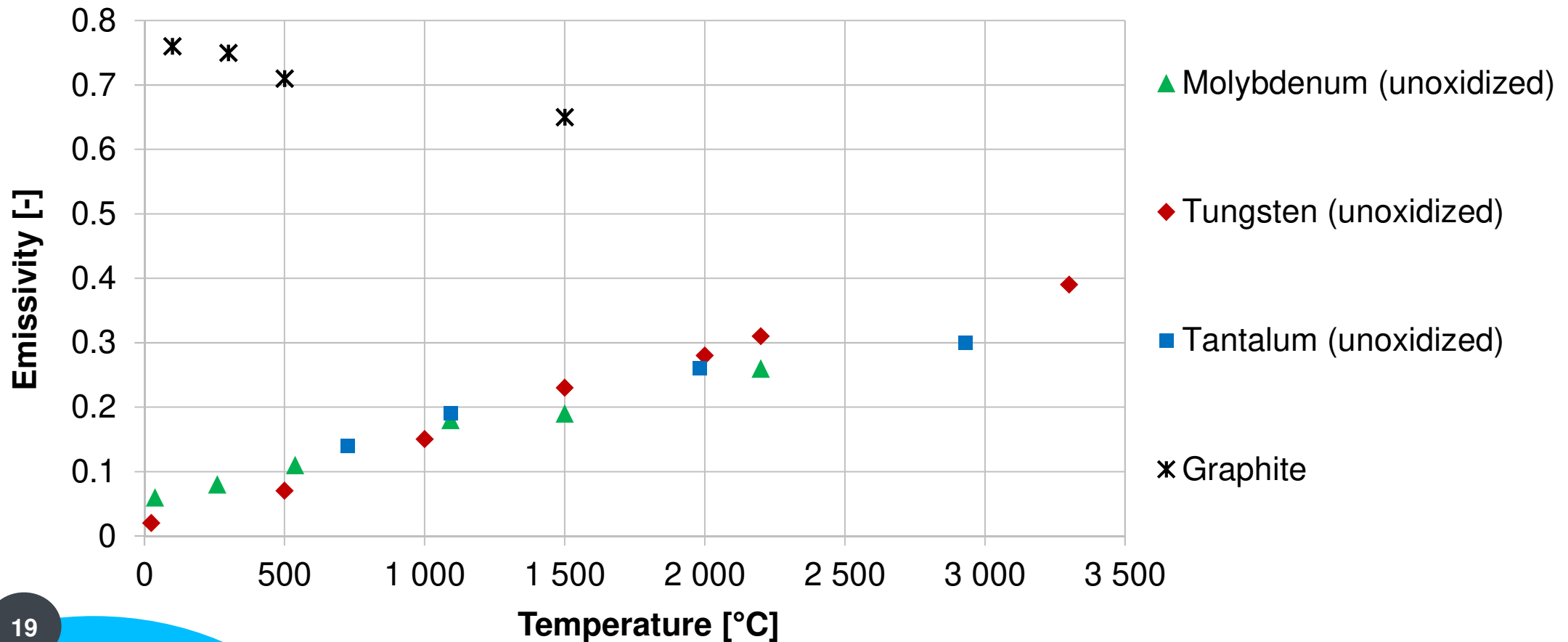
# Market screening for infrared radiation screen (IRS) materials



- Main criteria:
  - Permanent temperature stability
  - Costs
  - Emissivity

# Market screening for infrared radiation screen (IRS) materials

## Emissivities of IRS materials



# Market screening for infrared radiation screen (IRS) materials

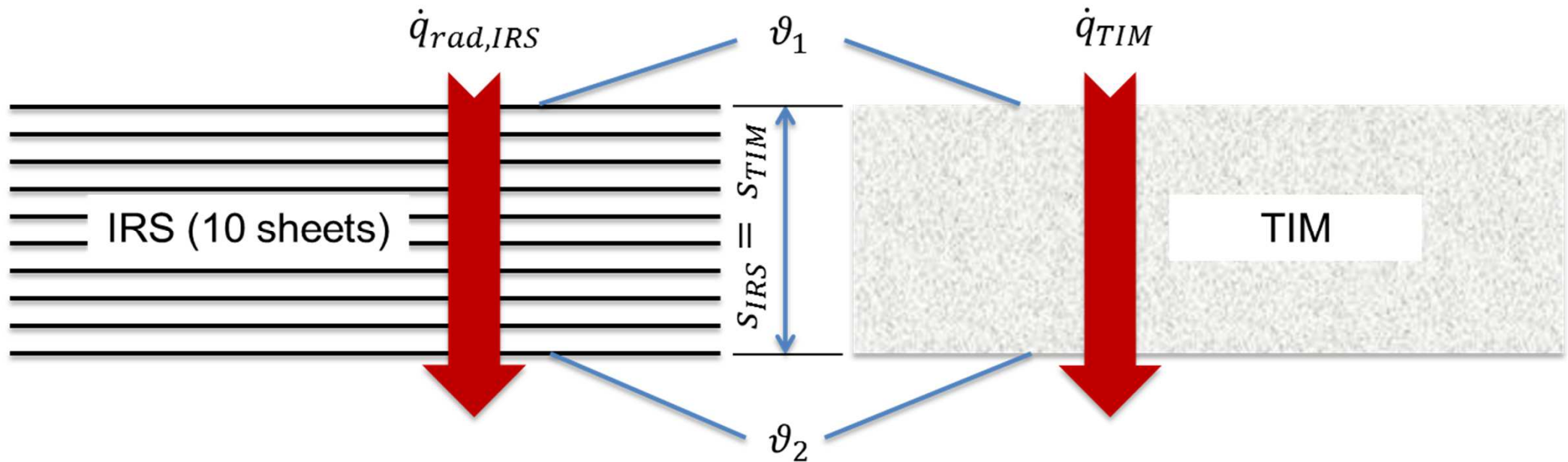
## Emissivities and Prices of IRS materials



Material	Manufacturer/ Provider	Max. Temp. in vacuum [°C]	Emissivity [-]	Thickness [mm]	Price [€/m <sup>2</sup> ]
Molybdenum (Mo)	WHS Sondermetalle (D)	1 500	ca. 0.2 @ 1 500 °C	0.5 0.05	900 700
Tungsten (W)	WHS Sondermetalle (D)	2 200	ca. 0.2 @ 1 500 °C	0.5 0.05	2 400 2 600
Tantalum (Ta)	WHS Sondermetalle (D)	2 400	ca. 0.2 @ 1 500 °C	0.5	5 600
Graphite (C)	SGL Carbon (D)	2 200	ca. 0.65 @ 1 500 °C	1 – 3	100 – 400

# **Cost-efficiency comparison of IRS and porous TIM**

## Cost-efficiency comparison of porous TIM and IRS

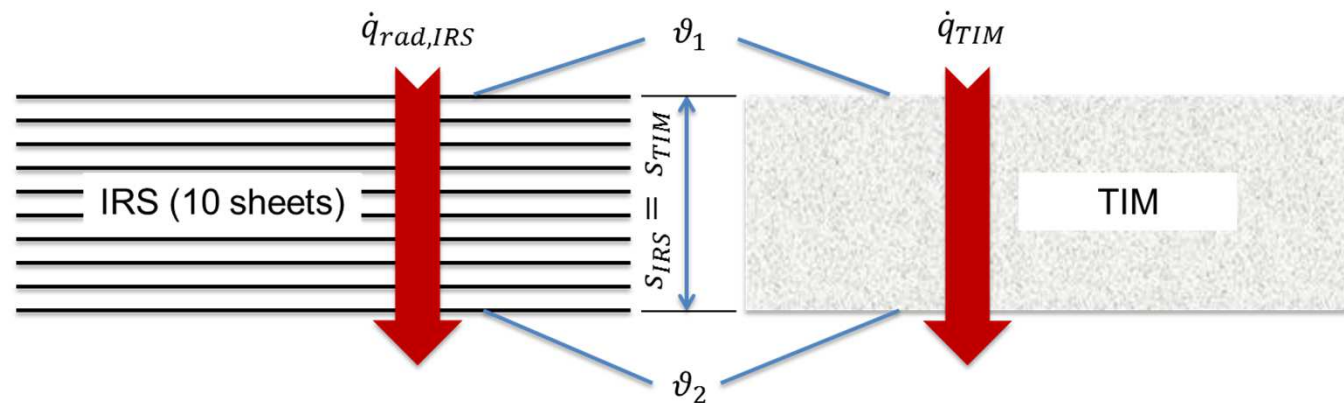


# Cost-efficiency comparison of porous TIM and IRS

## Boundary conditions

### General conditions:

- Heat transfer through flat wall
- $\vartheta_1 = 1\,500\text{ °C}$ ;  $\vartheta_2 = 1\,000\text{ °C}$
- $S_{IRS} = S_{TIM}$
- Only material costs considered (no construction costs)



# Cost-efficiency comparison of porous TIM and IRS

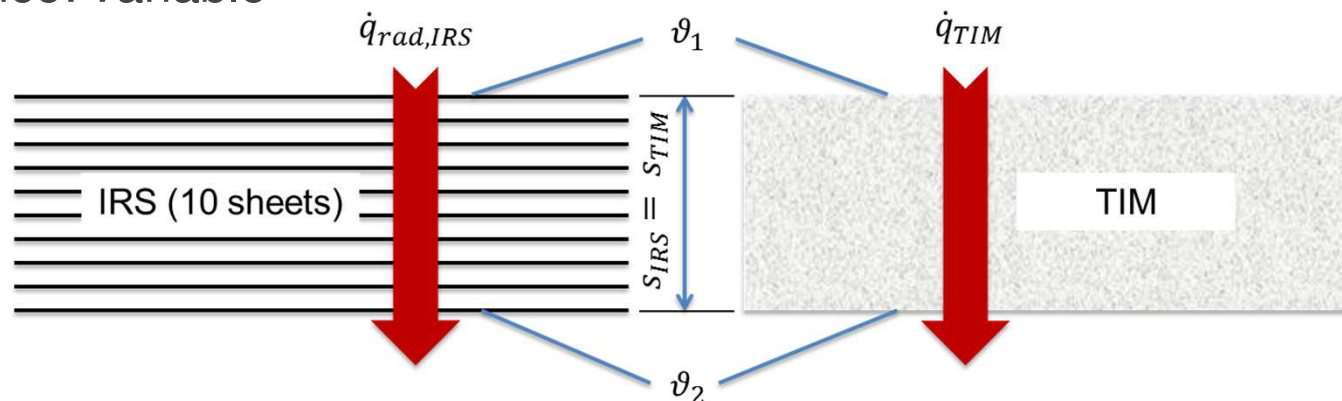
## Boundary conditions

### Infrared radiation shields (IRS):

- IRS Material: unox. molybdenum (900 €/m<sup>2</sup>)
- $\varepsilon_{IRS}(1250\text{ }^{\circ}\text{C}) = 0.175$
- Perfect vacuum (no gas heat transfer)
- No spacers (no solid heat transfer)
- Sheet thickness: 0.3 mm
- Sheet distance: variable

### Porous thermal insulation materials (TIM):

- TIM: graphite fiber mat (GFM, 17 k€/m<sup>3</sup>)
- $\lambda_{TIM}(1250\text{ }^{\circ}\text{C}) = 0.23\text{ W}/(\text{m}\cdot\text{K})$
- Atmosphere gas: nitrogen
- Thickness: variable





# Cost-efficiency comparison of porous TIM and IRS

## Calculation of heat flux density

### Infrared radiation shields (IRS):

$$\dot{q}_{rad,IRS} = \sigma \cdot \frac{T_1^4 - T_2^4}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 + n \cdot \left( \frac{2}{\varepsilon_{IRS}(\vartheta_m)} - 1 \right)}$$

$\dot{q}_{rad,IRS}$ : Heat flux density through IRS via radiation [W/m<sup>2</sup>]

$\sigma$ : Stefan-Boltzmann constant [W/m<sup>2</sup>·K<sup>4</sup>]

$T_1$ : Temperature of hot side [K]

$T_2$ : Temperature of cold side [K]

$n$ : Number of IRS sheets

$\varepsilon_1$ : Emissivity of hot side = 0.95

$\varepsilon_2$ : Emissivity of cold side = 0.95

$\varepsilon_{IRS}(\vartheta_m)$ : Emissivity of IRS at arithm. mean temperature  $\vartheta_m$

### Porous thermal insulation materials (TIM):

$$\dot{q}_{TIM} = \frac{\lambda_{TIM}(\vartheta_m)}{s_{TIM}} (\vartheta_1 - \vartheta_2)$$

$\dot{q}_{TIM}$ : Heat flux density through TIM [W/m<sup>2</sup>]

$\lambda_{TIM}(\vartheta_m)$ : Eff. thermal conductivity of TIM at arithm. mean temperature  $\vartheta_m$  [W/m·K]

$s_{TIM}$ : Thickness of TIM [m]

$\vartheta_1$ : Temperature of hot side [°C]

$\vartheta_2$ : Temperature of cold side [°C]

# Cost-efficiency comparison of porous TIM and IRS

## Rating of cost-efficiency

- Area-specific heat flux density-costs-product  $HCP$  [ $\text{k€} \cdot \text{W}/\text{m}^2$ ] :

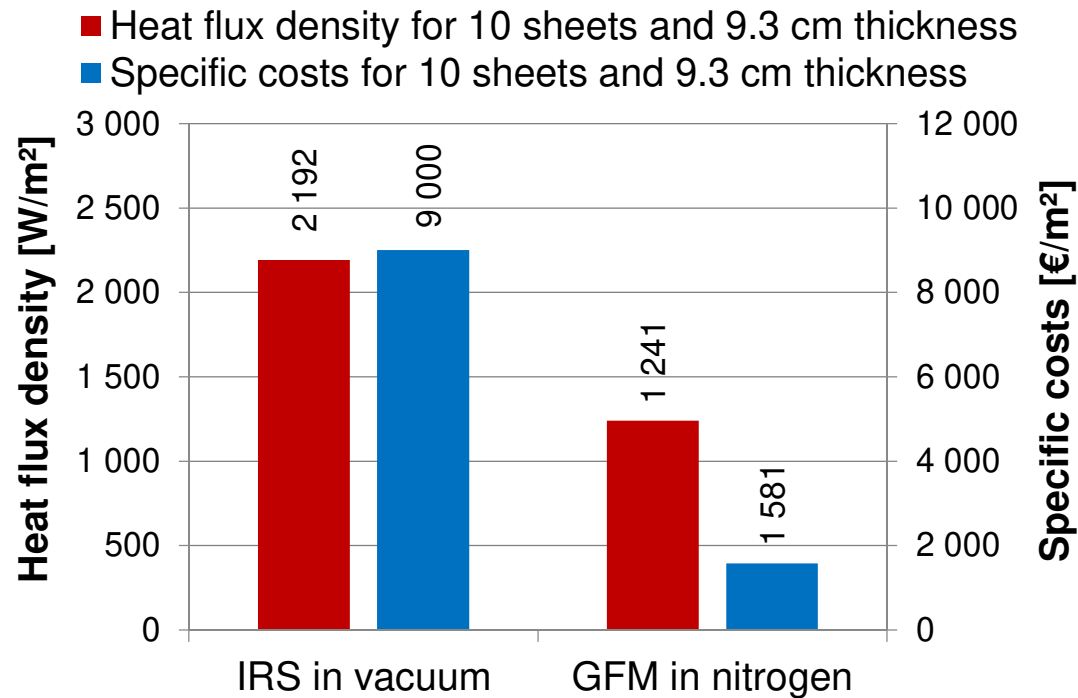
$$HCP = \dot{q} \cdot \text{specific costs}$$

$\dot{q}$ : Heat flux density [ $\text{W}/\text{m}^2$ ]

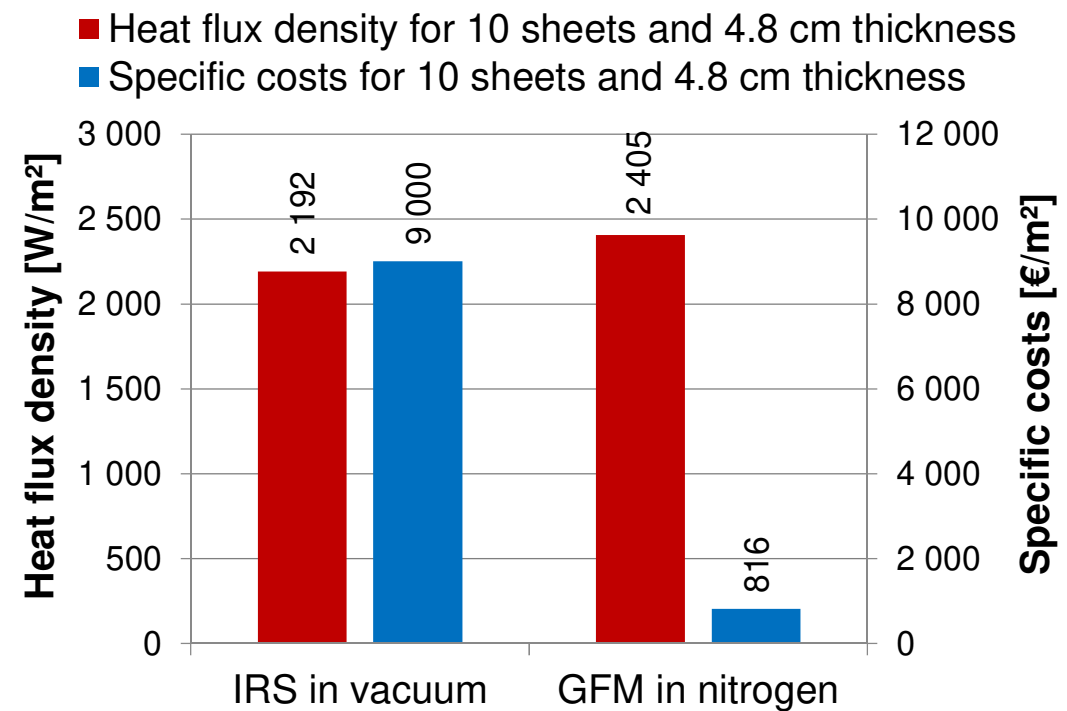
# Cost-efficiency comparison of porous TIM and IRS

## Results

### Distance between IRS sheets: 10 mm



### Distance between IRS sheets: 5 mm



$$HCP_{IRS} = 19\,728 \text{ k€} \cdot \text{W/m}^2; \quad HCP_{GFM} = 1\,962 \text{ k€} \cdot \text{W/m}^2$$

# **Optimization potential for the efficiency of thermal insulations**

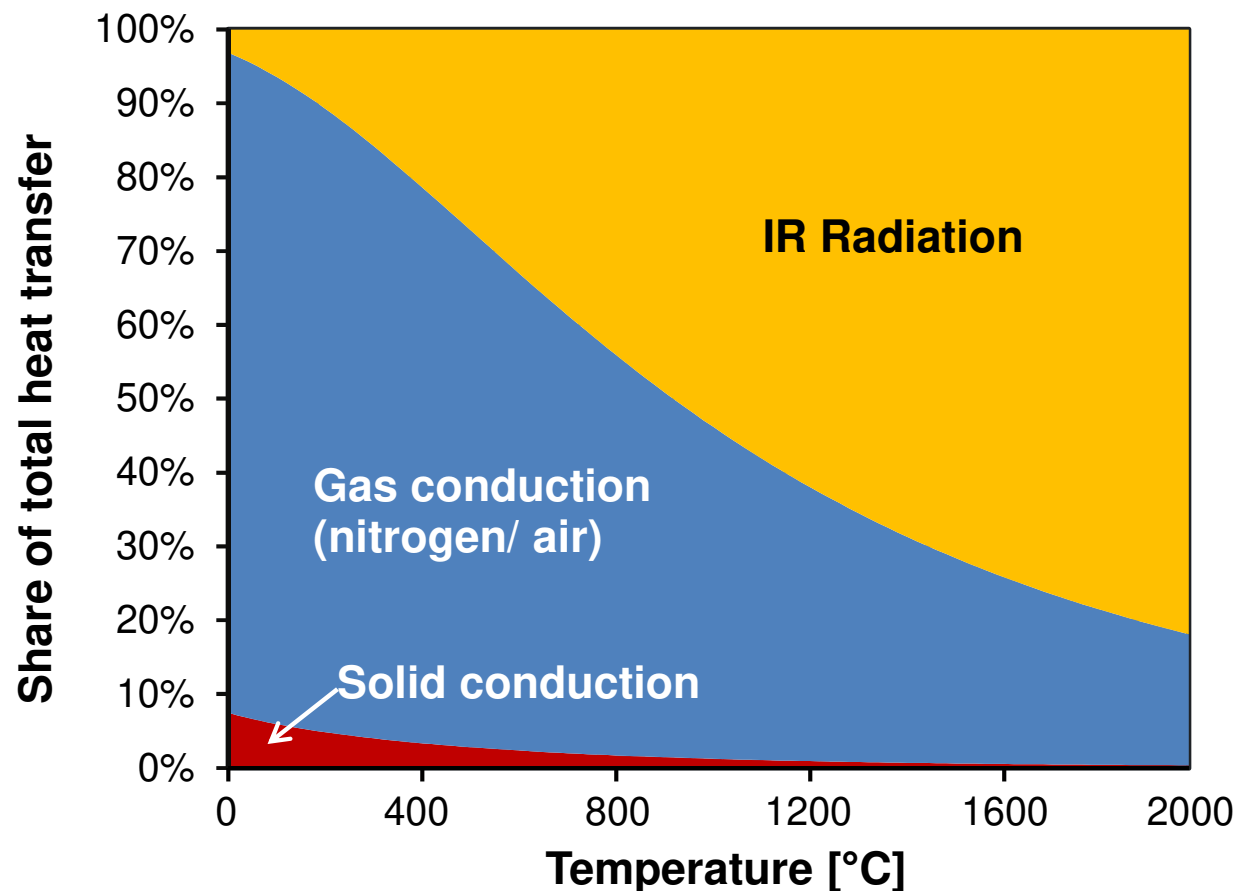
# Optimization potential for the efficiency of thermal insulations



- Atmosphere gas for thermal insulations
- Construction of IRS

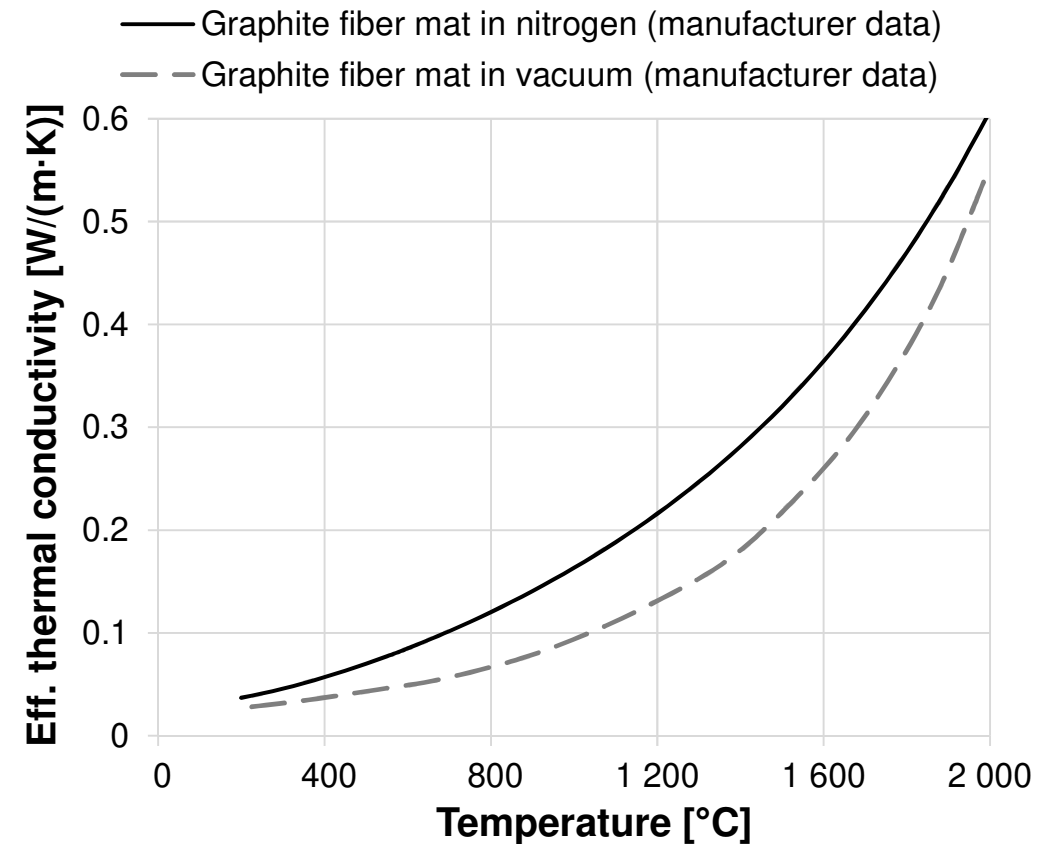
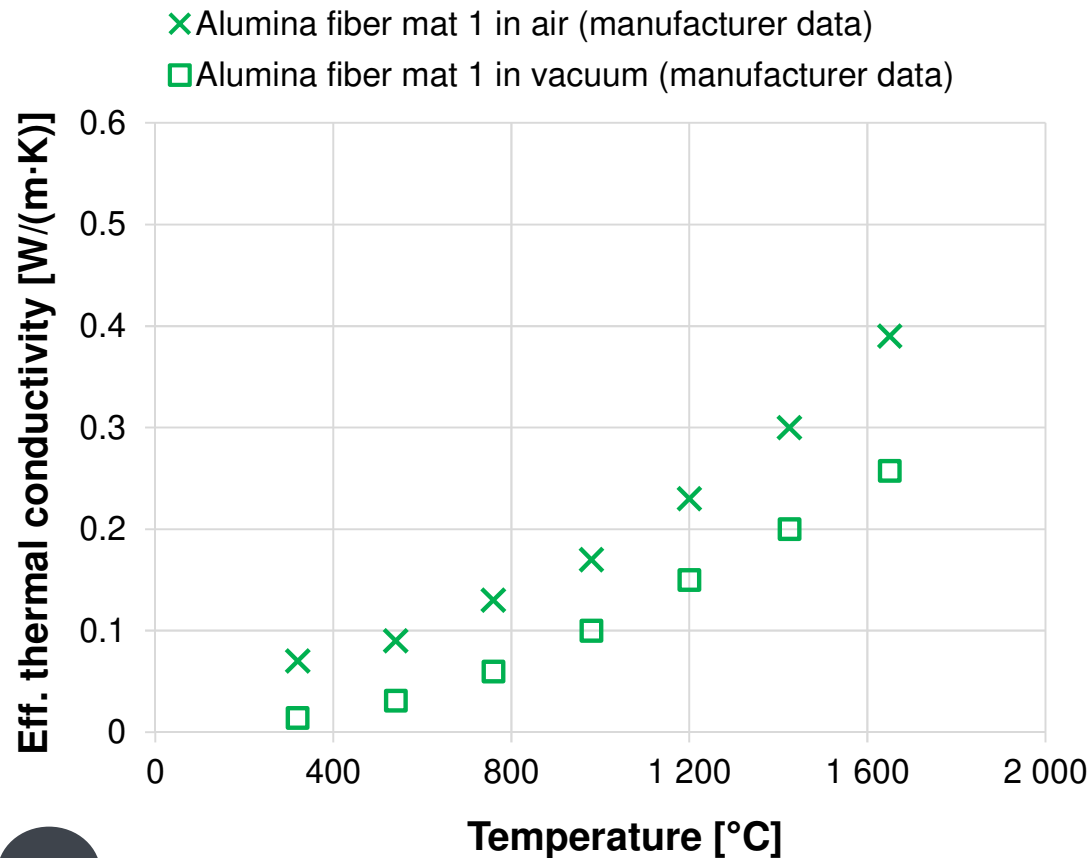
# Optimization potential for the efficiency of thermal insulations

Potential of vacuum atmosphere for open porous TIMs



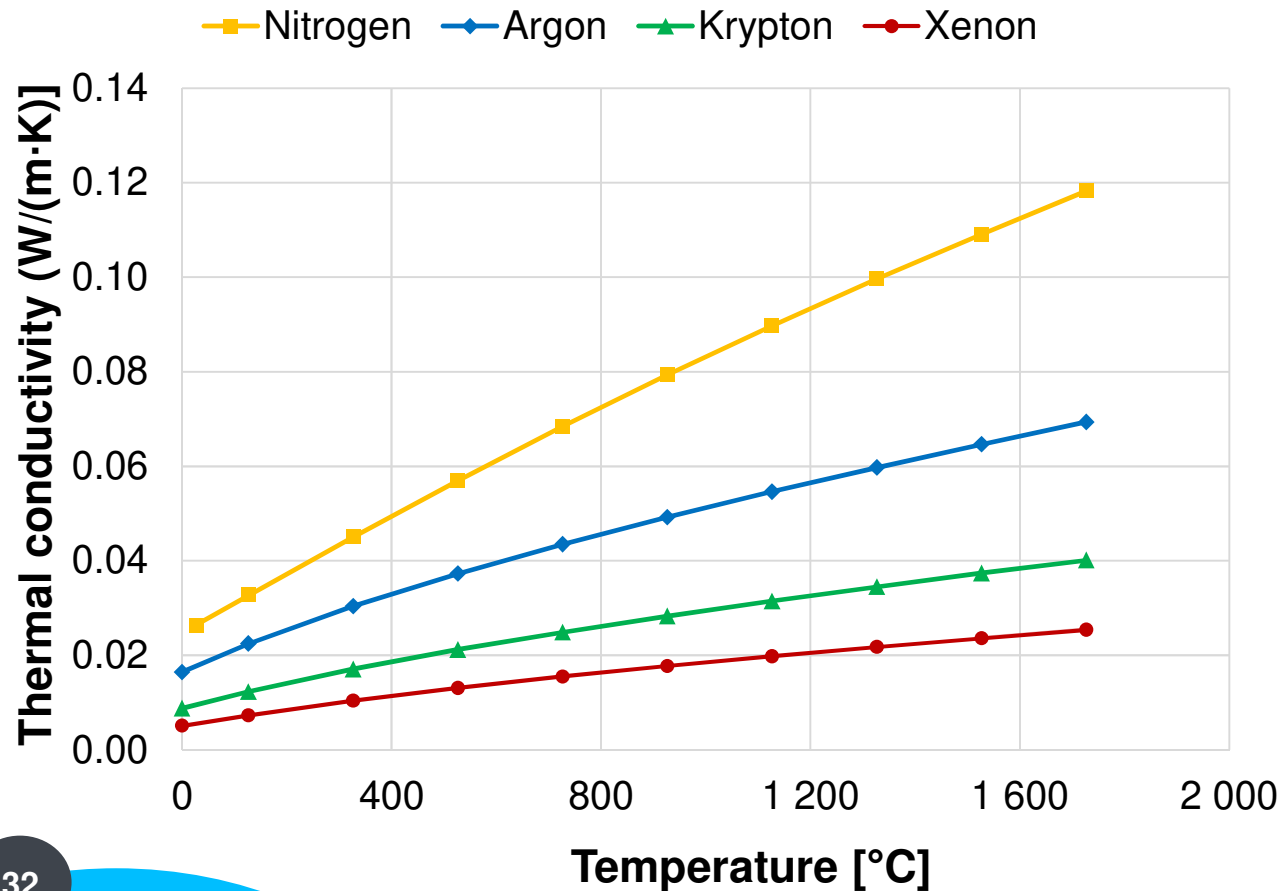
# Optimization potential for the efficiency of thermal insulations

## Eff. thermal conductivities of TIMs in vacuum



# Optimization potential for the efficiency of thermal insulations

## Choice of inert gas for thermal insulations' atmosphere



### Prices of inert gases (2017 – 2018):

Nitrogen: ca. 0.15 €/m<sup>3</sup>

Argon: ca. 12.5 €/m<sup>3</sup>

Krypton: ca. 100 €/m<sup>3</sup>

Xenon: ca. 11 000 €/m<sup>3</sup>

*(Source: Elsner, H., "Edelgase – Versorgung wirklich kritisch? – DERA Rohstoffinformationen 39," Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Berlin, Germany, 2018.)*



# Optimization potential for the efficiency of thermal insulations

## Ultra-high temperature multifoil (IRS) insulation



### Advantages compared to rigid IRS:

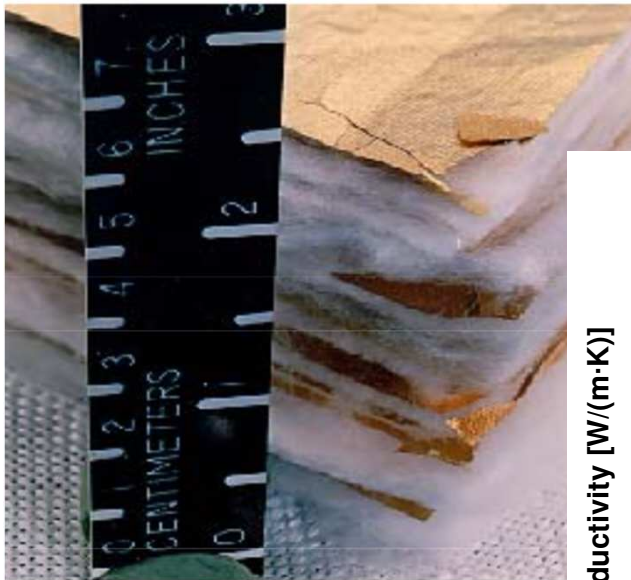
- Thinner IRS sheets
  - Less material costs
- Smaller distances between sheets
  - Less space requirement for more IRS sheets
  - Higher volume-related efficiency

Sources: AerospaceEd.org (Rossie J.), "Multifoil IRS," 2006. URL: [www.rossie.com/layer4x.jpg](http://www.rossie.com/layer4x.jpg);

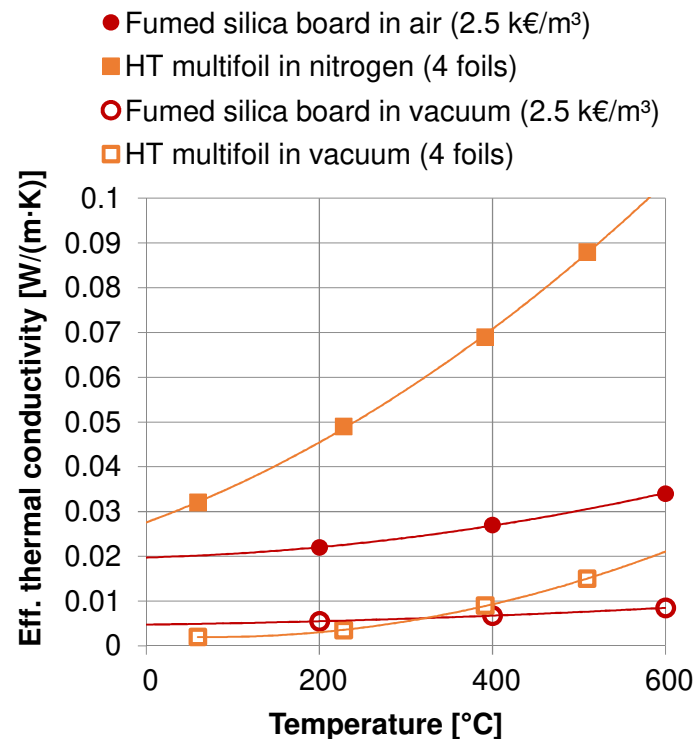
NASA, "Mars Reconnaissance Orbiter insulated with multifoil IRS". URL: [https://upload.wikimedia.org/wikipedia/commons/5/59/Mars\\_Reconnaissance\\_Orbiter\\_fully\\_assembled.jpg](https://upload.wikimedia.org/wikipedia/commons/5/59/Mars_Reconnaissance_Orbiter_fully_assembled.jpg)

# Optimization potential for the efficiency of thermal insulations

## Ultra-high temperature multifoil (IRS) insulation



Source: K. Daryabeigi, NASA, 2007



### Availability for UHT:

- Multifoil for up to 1 450 °C has been used for heat shields of spacecraft objects (for atmosphere re-entry)
  - Materials:
    - Foils: flexible alumina sheets coated with gold (up to 1 000 °C) or platinum (up to 1450 °C)
    - Spacers: low density alumina fiber mat
  - Effective thermal conductivity: s. Graph
  - Costs  $\approx$  100 k€/m<sup>3</sup>
  - Eff. thermal conductivity and costs could be decreased by (e. g.):
    - thinner spacers
    - other foil materials (Molybdenum, Graphite, ...)

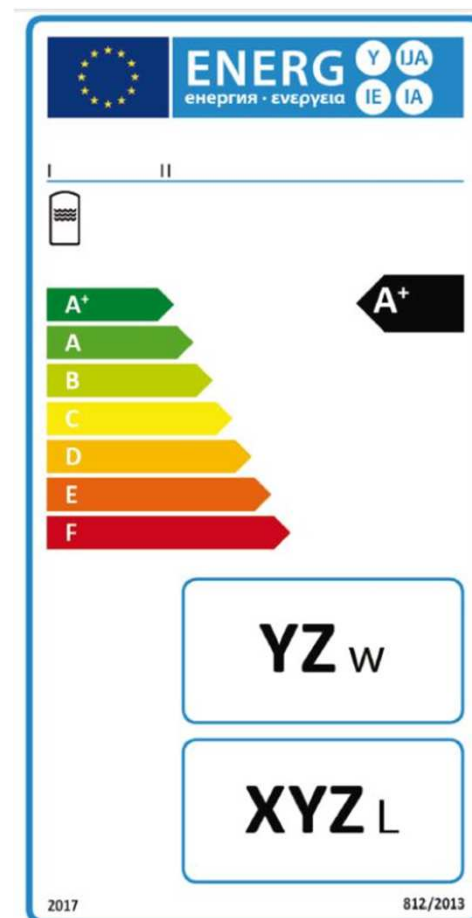
## Summary

- Porous thermal insulation materials (TIM) for temperatures  $> 1\,000\text{ °C}$  have significantly higher prices and eff. thermal conductivities than TIM for  $< 1\,000\text{ °C}$
- Combination of TIM for higher and lower temperatures can save space and costs
- Porous TIM have significantly higher cost-efficiency than infrared radiation shields (IRS) at ultra-high temperatures
- Vacuum or low- $\lambda$  inert gases can reduce heat transfer through thermal insulations
- UHT multifoil insulation could be a promising thermal insulation for UHT-TES

## Further research on thermal insulation for UHT-TES

- Classifying the energy losses of UHT-TES
  - Adaption of available standards for hot water stores to UHT-TES

PCM volume [dm <sup>3</sup> ]	Energy class @1 000 °C	Energy class @1 200 °C	Energy class @1 300 °C	Energy class @1 500 °C	Energy class @2 000 °C
0.48	A+	A+	A+	A+	A
7.5	A+	A+	A	B	C
60	A+	A	B	C	E
202.5	A+	B	B	C	E
480	A+	B	C	D	F





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# Thank you!



**Horizon 2020**

FUTURE EMERGING TECHNOLOGIES



**AMADEUS**  
ultra high temperature energy storage



[www.amadeus-project.eu](http://www.amadeus-project.eu)

The project AMADEUS (Next GenerAtion MateriAls and Solid State DevicEs for Ultra High Temperature Energy Storage and Conversion) has received funds from the European Union's Horizon2020 research and innovation program, FET-OPEN action, under grant agreement No 737054. The sole responsibility for the content of this presentation lies with the authors. It does not necessarily reflect the opinion of the European Union. Neither the REA (Research Executive Agency) nor the European Commission is responsible for any use that may be made of the information contained therein





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# Ultra-high temperature thermal insulation



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