Thermo-mechanical behavior of titanium beryllide pebble beds at elevated temperatures

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The thermomechanical behavior of titanium beryllide pebble beds was investigated experimentally at temperatures between 200 and 500°C in helium atmosphere at atmospheric pressure. The pebbles consist of a mixture of $TiBe_{12}$ and Ti_2Be_{17} titanate beryllide phases and a small residual amount of Be phase, denominated as Be-7.7Ti.

Like previous experiments at ambient temperature [1], the pebble beds were compressed uniaxially up to 4.5MPa and the effective thermal conductivity k was measured using the hot wire technique.

Compared to ambient temperature, the stress-strain curves do not differ significantly in investigated temperature range. Because the thermal conductivity of solid $TiBe_{12}$ is fairly constant in a wide temperature range [2], k increases moderately with increasing temperature because of the increasing thermal conductivity of helium.

Compared to beryllium pebble beds, the k of the Be-7.7Ti pebble beds increases again much lesser because of the significantly smaller thermal conductivity of the solid material and the mechanically harder behavior resulting in smaller contact surfaces.

[1] J. Reimann et al, Fusion Eng. Des. 165 (2021) 112249
[2] M. Uchida, E. Ishitsuka, H. Kawamura, Fusion Eng. Des. 69 (2003) 499-503.

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Outline

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- Introduction
  - Modelling parameters of the thermo-mechanical behaviour of pebble beds
  - Previous investigations at ambient temperature
- Experimental set-up
- Results
  - A) Uniaxial Stress-Strain dependence
  - B) Effective thermal conductivity of pebble beds
  - C) Thermal creep
- Discussion/Conclusions

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General Remarks

- *This paper is an extension of recent investigations at ambient temperature T_a [1]. In all experiments, a simple experimental facility was used, therefore, the experimental results should be considered as screening exps.*
- *The beryllium-titanate pebbles (d=0.8-1.2mm) were produced with the stoichiometric composition of Be and 7.7at% Ti, ideally resulting in single phase Be12Ti pebbles. However, it was found that the used pebbles have also a Be13Ti2 and a Be phase, for details, see [1]. Therefore, the denomination Be-7.7Ti was chosen.*

[1] Reimann et al, FED 165 (2021) 112249

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Main Parameters for the modelling of the thermo-mechanical behaviour of blanket pebble beds, pbs

BOL:

- stress-strain relationship $\sigma = f(\varepsilon, T, \ldots)$,
- pebble bed effective thermal conductivity $k_{eff} = f(\varepsilon, T, \ldots)$,
- thermal creep ε_{cr}.

EOL: Irradiation effects,

- Same parameters as above, see e.g. [2] analyses of Be-based materials from the ADOBE exps.

Previous investigations

Exps at ambient temperature, Ta, [1]

[2] Chakin et al, JNM 559 (2022) 153430

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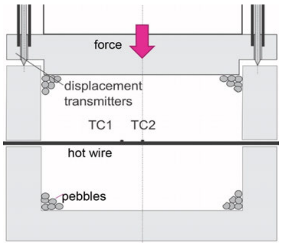
Experimental set-up

Uniaxial Compression Test facility combined with a Hot Wire, HW, set-up.



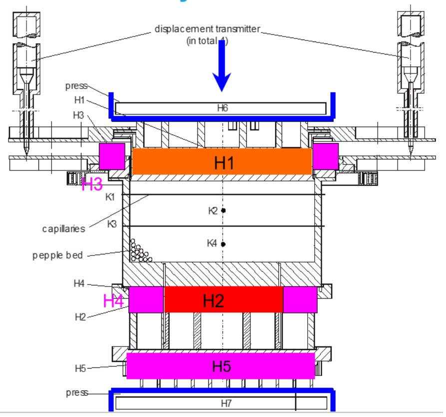
Set-up used for exps at Ta [1] . For details of the HW-system, see also [1].

Now: Use of the container with additional heating on cylindrical part and the heating system of HECOP facility [3]

Parameter range:

- max. pressure (uniaxial stress): 6MPa
- max. T: 500°C

HECOP facility



[3] Reimann et al, FED 81 (2006) 449-454

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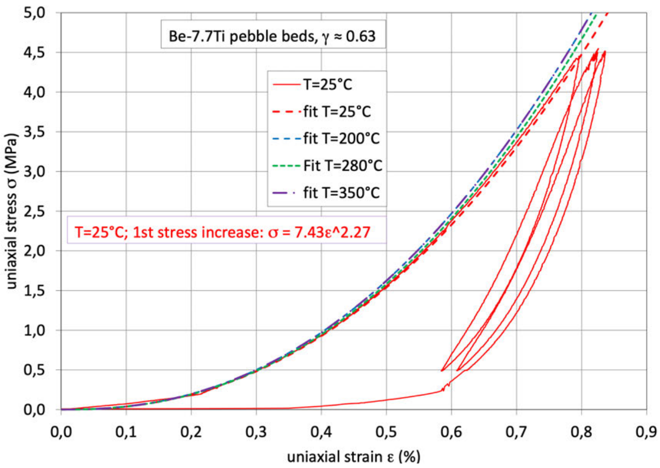
Results: A) σ–ε relationship



- Besides the first stress increase curve, the subsequent stress release and following cycles are also blanket relevant.
- As already observed for Be pbs [3], the σ–ε dependence of 1st σ-increase curve is negligibly dependent on T as long as thermal creep is of no concern.
- The cycling curves curves indicate an elastic pebble material.

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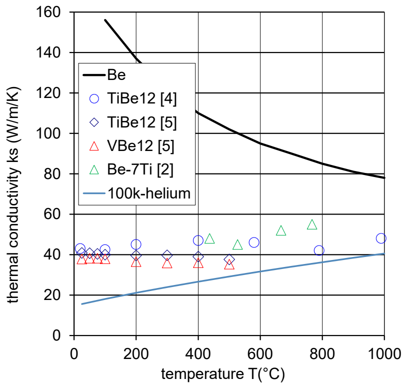
Results: B) Thermal conductivity of solid materials, ks, and helium, k-he



Beryllide pbs, are superior to Be pbs in many aspects (irradiation, compatibility, oxidation…)

However, there is a significant drawback: the thermal conductivity of the solid materials, k_s, is significantly smaller than that of Be [2,4,5].

Because the present Be-7.7Ti pebbles consist of several phases, the exact ks value is not known. In the following, a constant value of ks = 40 W/(mK) is assumed.

The thermal conductivity of helium increases with T.

[4] Uchida et al, FED 69 (2003) 499-503

[5] Reimann et al, SOFE 2009, IEEE CFP09SOF-PRT, 305-309

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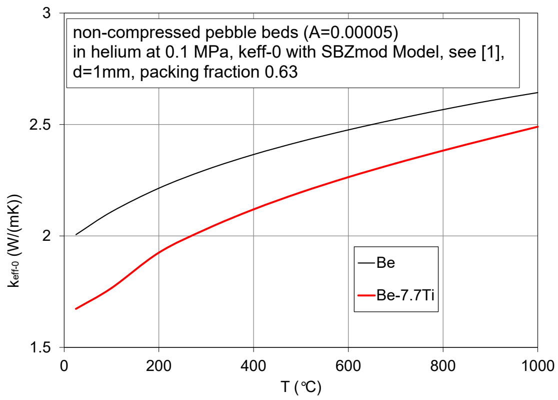
B) Non-compressed pbs, k_{eff-0} = f(T)



- Pebble bed thermal conductivities much smaller than solid material conductivities.
- k_{eff-0} for Be-7.7Ti at 600C about 10% lower than that of Be (although $k_{s\text{-}Be7.7} \approx 0.5k_{s\text{-}Be}$).
- However: for Be pbs, k_{eff} increases drastically with compression (uniaxial stress); how about Be-7.7Ti?

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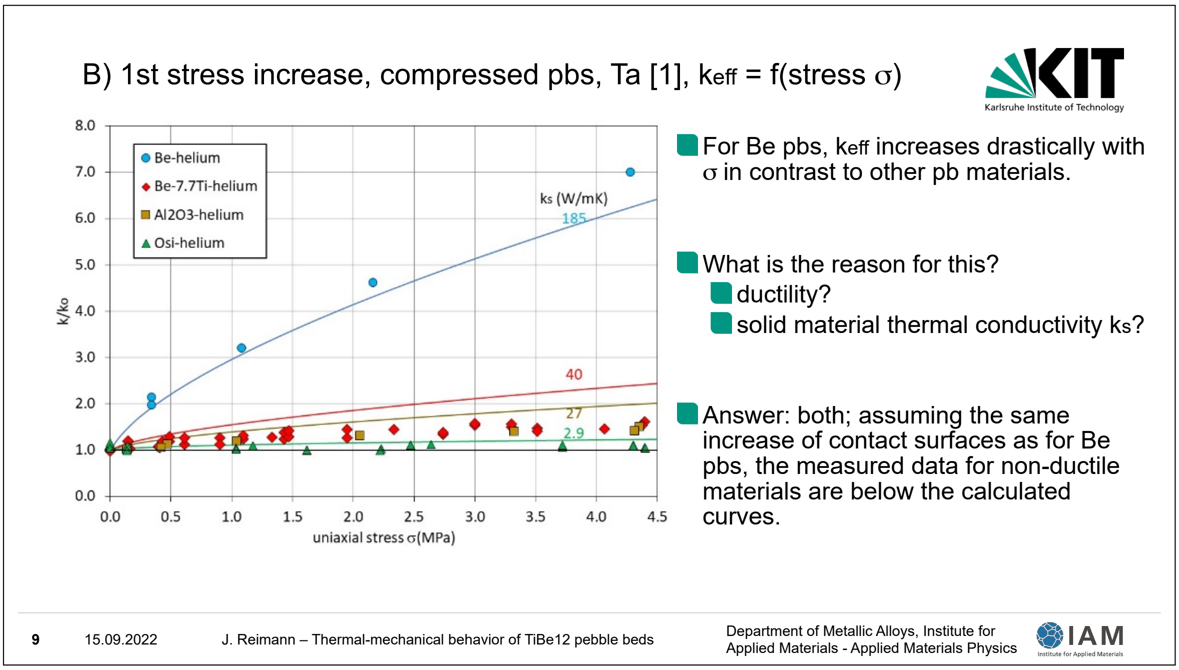
B) 1st stress increase, compressed pbs, Ta [1], keff = f(stress σ)
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Be-helium
Be-7.7Ti-helium
Al2O3-helium
Osi-helium
ks (W/mK)
185
40
27
2.9
k/ko
uniaxial stress σ(MPa)
For Be pbs, keff increases drastically with σ in contrast to other pb materials.
What is the reason for this?
ductility?
solid material thermal conductivity ks?
Answer: both; assuming the same increase of contact surfaces as for Be pbs, the measured data for non-ductile materials are below the calculated curves.
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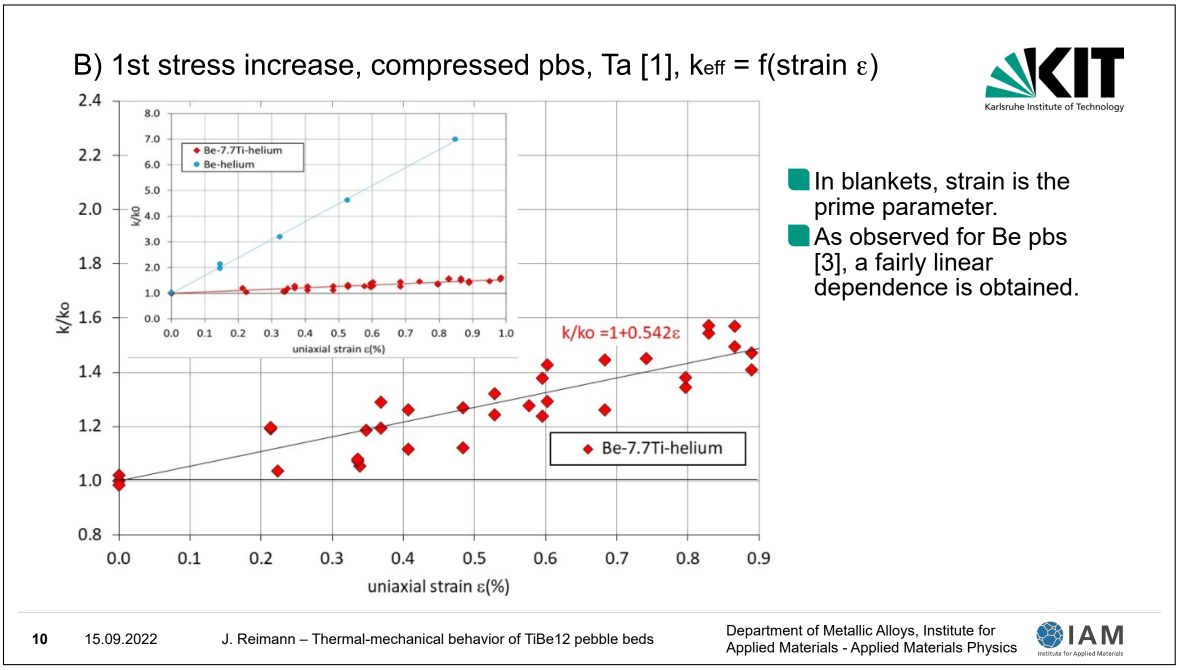
B) 1st stress increase, compressed pbs, Ta [1], keff = f(strain ε)
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Be-7.7Ti-helium
Be-helium
k/ko
uniaxial strain ε(%)
k/ko =1+0.542ε
Be-7.7Ti-helium
In blankets, strain is the prime parameter.
As observed for Be pbs [3], a fairly linear dependence is obtained.
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B) Temperature dependence of keff for first stress increase

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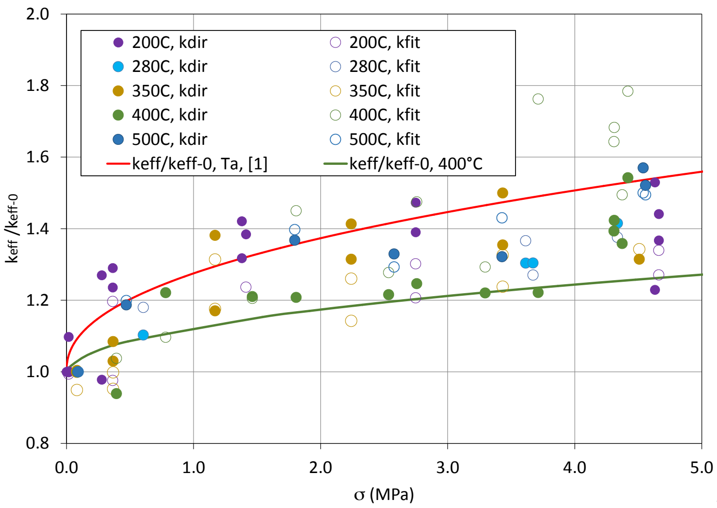

- With increasing temperature, the data are generally below the curve for Ta. The reason is that keff-0 increases with T because of the increasing helium thermal conductivity.
- Additionally, the contribution of contact surfaces decreases also with increasing gas thermal conductivity.

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B) Temperature dependence of keff during mech. cycling

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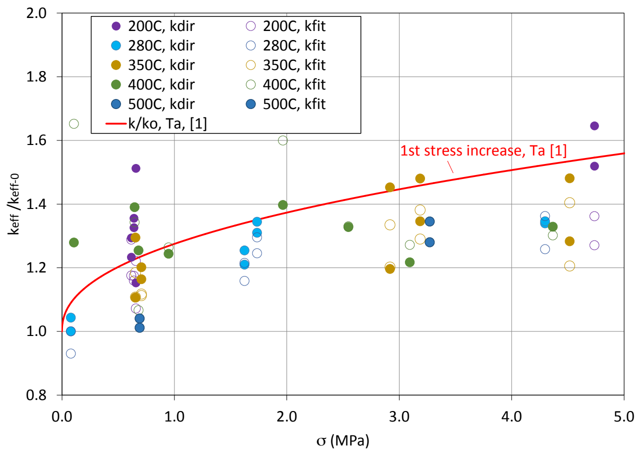

- For ductile pb materials, e.g. Be, keff does not decrease significantly with stress decrease in a wide σ-range.
- For Be-7.7Ti, this effect is not expressed, indicating again the elastic pebble behavior.

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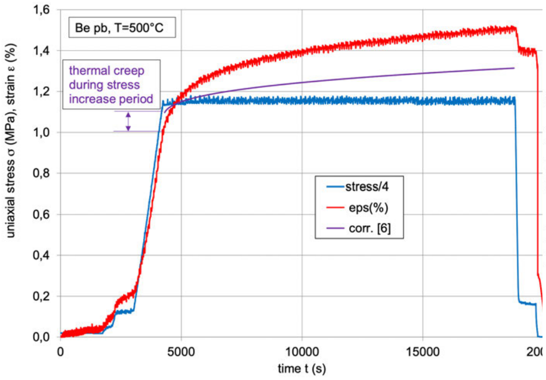
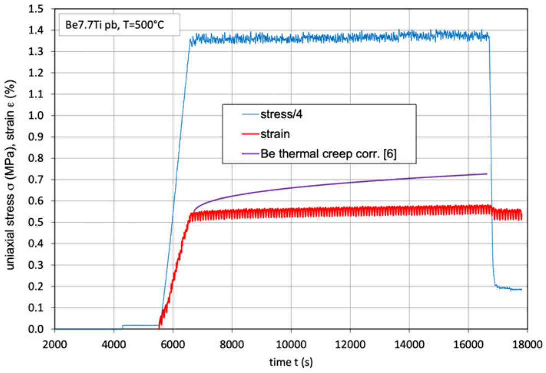
C) Thermal creep strain ε_{cr}





[6] Reimann et al, FED 75-79 (2005) 1043-1046

- Thermal creep increases contact surfaces and with this increases effectively keff.
- At 500°C, thermal creep is significant for Be pbs [6] and negligible for Be7.7Ti pbs. (Corresponding keff results can not be shown because of HW failure).

Discussions/Conclusions

- The thermo-mechanical behavior of beryllium titanate Be-7.7Ti pbs was investigated at temperatures up to 500°C.
- Compared to Be pbs, Be-7.7Ti pbs have a considerably smaller keff during compression because of the smaller ductility and the smaller solid material conductivity.
- Thermal creep effects, causing also an increase of contact surfaces, are marginal for Be-7.7Ti in the investigated temperature range.
- keff can be impoved by using binary pbs instead of monosized pbs [7].
- Beryllide pbs can be superior to Be pbs, if mixed breeder and neutron multiplyer pbs are a viable option, requiring irradiation exps.
- Recent analyses of the HIDOBE irradiation programme showed much smaller swelling of Be5Ti and Be7Ti disks compared to Be disks, and smaller swelling rates for Be pebbles compared to Be disks. Again, irradiation exps with non-constrained/ constrained beryllide pebbles are required.
- First thermal creep results on irradiated Be pebbles were presented by [8].

[7] Reimann et al, BeWS 13
[8] Chakin et al, BeWS 15