Methods for Evaluation of Thermal Conductivity Increase of VIPs

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Standardization Efforts for VIPs in Buildings

European Standardization Organization CEN
Technical Committee TC 88
- Working Group WG 11 VIP

In Liaison with ISO TC 163 / SC 3 /WG 11

Major issue and discussion point:

„Declared Value of Thermal Conducitivity“
=
center of panel (COP) initial value
+
edge effects (depending on size and kind of film)
+
mean value of thermal conductivity increase during Service Life Time

Standardization: Reference Conditions

Methods should be similar for all prospective core materials

Buildings:

Reference Service Life Time t_{SLT} = **25 years**

Reference climate: **23 °C / 50%** (as for conventional insulation)

If increase of thermal conductivity $\lambda(t)$ is linear in time t,

declared value of thermal conductivity is given by the mean:

$$\lambda_{decl} = \lambda_{initial} + \Delta\lambda/\Delta t \cdot 12.5 \text{ years}$$

(upper limit, not including saturation effects)

Parameters influencing thermal conductivity increase

What influences change of thermal conductivity λ with time t:

1.) Increase of gas pressure p(t)

1a) air pressure $\mathbf{p_{air}(t)}$ <= air permeation rate P_{air} and panel thickness d

1b) water vapour pressure $\mathbf{p_{H2O}(t)}$ <= vapor permeation rate P_{H2O} and panel mass per area m‘‘

2.) Increase of liquid moisture content **X(t)** (for silica)

also:

water vapour pressure p_{H2O} is related to moisture content X by adsorption isotherm X(ϕ), with ϕ: rel. humidity

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3.) Increase of air permeation P_{air} rate with **temperature T**

4.) Increase of water vapor permeation P_{H2O} rate with

vapor pressure difference Δp_{H2O} <= **temperature T** and **rel. humidity ϕ**

and temperature T

Parameters Influencing Thermal Conductivity Increase

Simpliest approach:

Using linear relations with constants

$$\partial\lambda(p)/\partial p = \lambda_p \,,\; \partial\lambda(X)/\partial X = \lambda_X \,,\; \partial\phi(X)/\partial X = \phi_X$$

=> upper limit , actual increase of thermal conductivity will be lower

$$\Delta\lambda = \lambda_p \cdot \Delta p + \lambda_X \cdot \Delta X \qquad (1)$$

with $\Delta p = \Delta p_{air} + \Delta p_{H2O}$
and $\Delta p_{H2O} = p_s(T) \cdot \phi(X) = p_s(T) \cdot \phi_X \cdot \Delta X$
$p_s(T)$: vapor saturation pressure at temperature T

as function of air pressure increase Δp_{air}

$$\Delta\lambda = \lambda_p \cdot \Delta p_{air} + (\lambda_X + \lambda_p \cdot p_s(T_m) \cdot \phi_X) \cdot \Delta X \qquad (2)$$

Parameters Influencing Permeation Rate

with $\Delta p_{air} = P_{air}(T)/d \cdot \Delta t$ **d: panel thickness** **(3)**

$\Delta X = P_{H2O}(T) \cdot \phi \cdot p_s(T)/(\rho \cdot d) \cdot \Delta t$ **(4)**

and T_m: measurement temperature, T: storage temperature, ρ: silica density

permeation rate P_{air} : related to air pressure difference of 1000 mbar
permeation rate P_{H2O} : related to H_2O pressure difference of 1 mbar

$P(T) = a \cdot \exp(-b/T)$ Arrhenius type change of permeation with temperature T

<u>permeation units:</u>

air: P_{air} [mbar liter/(m² year)] (1000 mbar, m² of vacuum panel)
vapor: P_{H2O} [g/(m² year mbar)] (1 mbar, m² of vacuum panel)
thickness: d[mm]
typical values: λ_p= 0.04 mW/(m·K·mbar), approx. both for air and H_2O
λ_X = 0.5 mW/(m·K·%) and ϕ_X = 14%/%

Direct Measurements of Increase Δλ/Δt

10 years storage of va-Q-tec VIPs at EMPA at ambient conditions

20 mm thick silica VIPs „va-Q-vip“
Storage in climate chamber @23°C with
two different humidity conditions: **ϕ = 33%** and **ϕ = 80%**

Measurement of increase of thermal conductivity Δλ/Δt:

mean yearly increase linearly extrapolated to 50% r.h.: **0.12 mW/(mKy)**
mean increase for 25 years extrapolated to 50% r.h.: **1.5 mW/mK**

condition	ϕ rel. hum.	λ initial	λ after 10 years	Δλ change	Δλ/Δt yearly rate	mean increase 25 years	@50% r.h. mean 25 years
	%	mW/mK	mW/mK	mW/mK	mW/mKy	mW/mK	mW/mK
high hum.	80	3.9	6.1	2.2	**0.22**	2.75	**1.5**
dry	33	3.9	4.5	0.6	**0.06**	0.75	

valid for va-Q-vip

10 Years Storage of Silica VIPs: Gas Pressure

Measurement of gas pressure increase Δp/Δt:

mean yearly increase rate linearly extrapolated to 50% r.h.: **1.0 mbar/y**
mean increase for 25 years extrapolated to 50% r.h.: **12 mbar**

condition	ϕ rel. hum.	p initial	p after 10 years	Δp change	Δp/Δt yearly rate	mean increase 25 years	@50% r.h. mean 25 years
	%	mbar	mbar	mbar	mbar/y	mbar	mbar
high hum.	80	1	18.5	17.5	**1.8**	22	**12**
dry	33	1	6	5	**0.5**	6	

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10 Years Storage of Silica VIPs: Moisture Content

Measurement of moisture content ΔX/Δt:

mean yearly increase rate extrapolated to 50% r.h.: **0.14 %/y**
mean increase for 25 years extrapolated to 50% r.h.: **1.8 %**

condition	ϕ rel. hum.	X initial	X after 10 years	ΔX change	ΔX/Δt yearly rate	mean increase 25 years	@50% r.h. mean 25 years
	%	%	%	%	%/y	%	%
high hum.	80	0.1	3.1	3	**0.3**	3.8	**1.8**
dry	33	0.1	0.6	0.5	**0.05**	0.63	

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10 Years Storage of Silica VIPs: Comparison

From the yearly change rates of gas pressure $\Delta p/\Delta t$
and moisture content $\Delta X/\Delta t$
the change rate of thermal conductivity $\Delta\lambda/\Delta t$
can be calculated according to (eq. 1) $\mathbf{\Delta\lambda = \lambda_p \cdot \Delta p + \lambda_X \cdot \Delta X}$ and compared to the measured one.

With the parameters λ_p = 0.04 mW/(mK mbar) and λ_X = 0.5 mW/(mK %)

the calculated change of thermal conductivity is **0.11 mW/mK per year**
whereas the measured one is **0.12 mW/mK per year**

condition	ϕ rel. hum.	Δλ/Δt measured	Δp/Δt measured	ΔX/Δt measured	Δλ/Δt calculated
	%	mW/mKy	mbar/y	%/y	mW/mKy
reference	50	**0.12**	1.0	0.14	**0.11**

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Measurements of Silica VIPs with Accelerated Aging

- **Accelerating air permeation P_{air}** by storing VIP at higher temperature
- **Accelerating vapor permeation P_{H2O}** by storing VIP at higher temperature and humidity

=> Accelerated thermal conductivity increase $\Delta\lambda/\Delta t$

Procedure:

Climate proposed by CEN Committee: **50 °C / 70% r.h.**

Storage time: half a year

Regular measurements of thermal conductvity λ, gas pressure p and mass m of sample (at least every two months)

Temperature difference to reference climate **23°C/50% r.h.**:

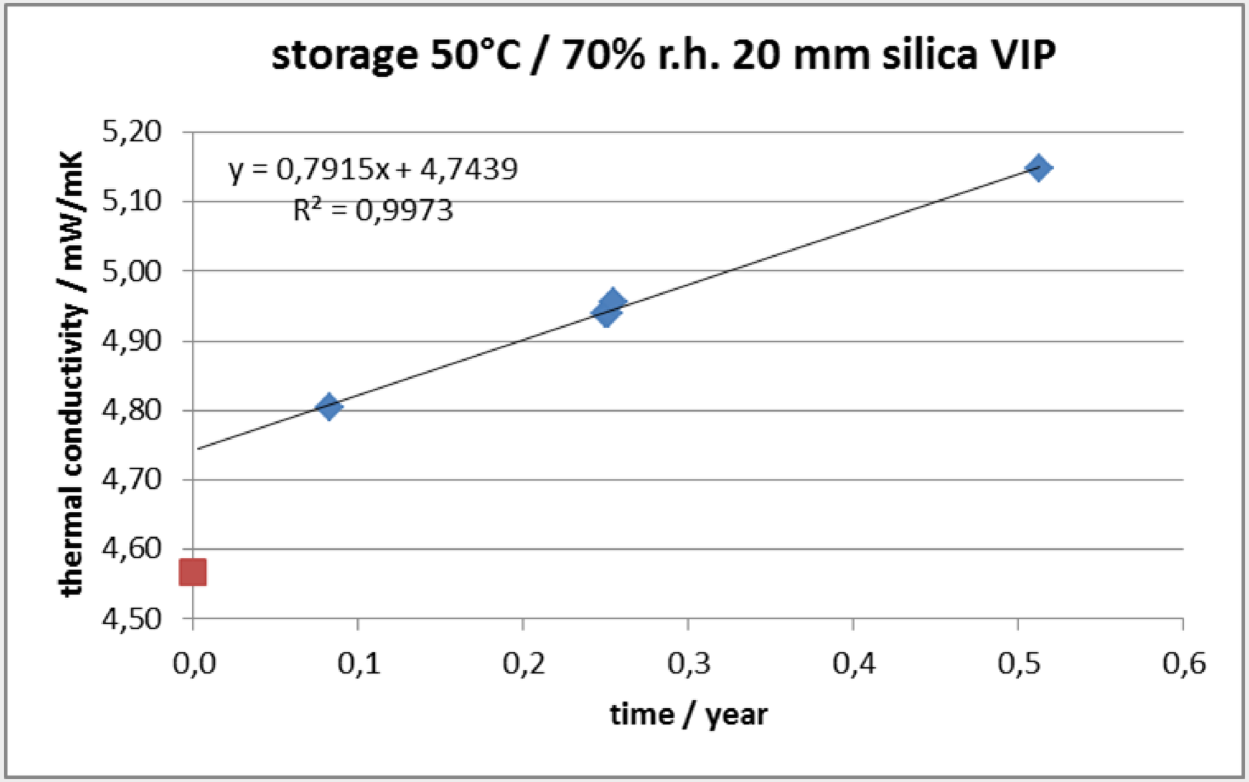
$$\Delta T = 27\ K$$

Water vapour pressure @50°C/70%: 86 mbar

Water vapour pressure @23°C/50%: 14 mbar

Measurement Results Accelerated Aging Silica VIPs

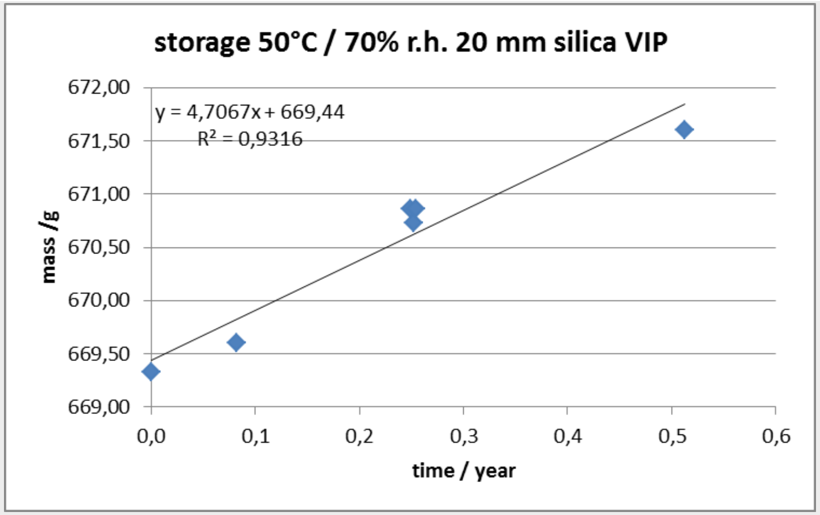
Mean thermal conductivity increase λ(t) of three silica VIPs 400 mm x 400 mm x 20 mm:

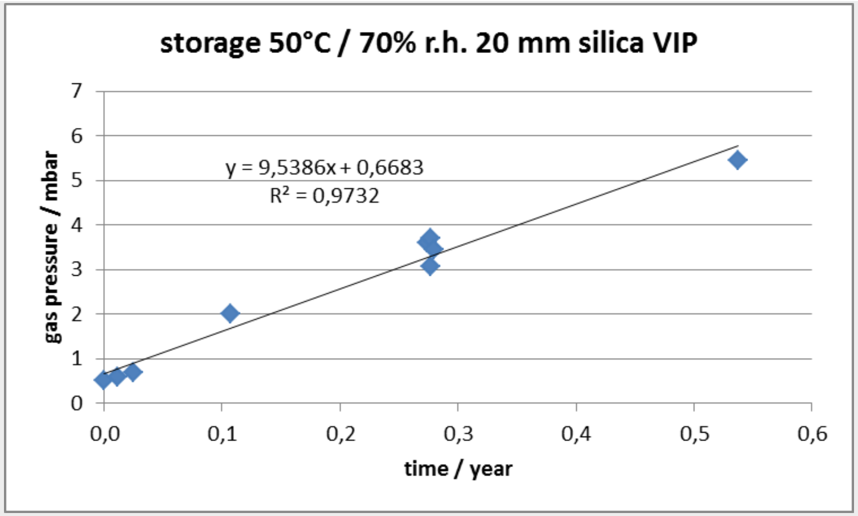


valid for va-Q-vip

Initial increase of $\Delta\lambda_i$ = 0.2 mW/mK
Steady increase of $\Delta\lambda/\Delta t$ = **0.79 mW/(mK year)** after 1 month

Accelerated Aging: Gas Pressure and Water content





Increase of mass m $\Delta m/\Delta t = (4.7 +/- 0.7)$ g/year =>

relative water content X $\mathbf{\Delta X/\Delta t = (0.90 +/- 0.13)}$ **%/year**

and total gas pressure p: $\mathbf{\Delta p/\Delta t = (9.5 +/- 1.4)}$ **mbar/year**

with eq.(1) $\mathbf{\Delta\lambda = \lambda_p \cdot \Delta p + \lambda_X \cdot \Delta X}$ **:**

=> $\mathbf{\Delta\lambda/\Delta t = 0.04 \cdot 9.5 + 0.5 \cdot 0.9 = 0.38 + 0.45 = (0.83 +/- 0.16)}$ **mW/(mK year)**

direct measurement: ⇔ 0.79 mW/(mK year)

Determining Acceleration Factors f

Accelerating factor f: test climate T_1 = **50°C/70%** r.h. in comparison to reference climate T_{ref} = **23°C/50% r.h.**?

Acceleration factor f_{H2O} for water vapor permeation P_{H2O}

Diffusion rate of water vapor is proportional to partial vapor difference inside and outside
Assumption: inside vapor pressure = 1 mbar

partial vapor pressures climate chamber:	86 mbar ⇔ 14 mbar @ reference
partial vapor pressure differences	83 mbar ⇔ 13 mbar @ reference

=> ratio f_1 = 83 mbar/ 13 mbar = 6.4

Change of water vapor permeation **per mbar** with temperature T => f_2:

Measurements of vapor permeation at different temperatures of metallized films by Hanita indicate a relative small variation with temperature, typically : $f_2 \approx 1.2$

in total: $\mathbf{f_{H2O} = f_1 \cdot f_2 \approx 8}$

Measuring Air Permeation Rates P_{air} of VIP Envelope

For evaluation of acceleration factor of air permeation f_{air} measurements of P_{air} (T) are needed

Method:
Measurement of small changes of thermal conductivity $\Delta\lambda/\Delta t$ of a sample VIP with barrier film envelope and coarse core material (high value λ_p^*) instead of silica core (low λ_p)

Increase of thermal conductivity with time **$\Delta\lambda/\Delta t$** is proportional to change of gas pressure with time **$\Delta p/\Delta t$** :

$$\Delta\lambda/\Delta t = \lambda_p^* \cdot \Delta p/\Delta t = \lambda_p^* \cdot P_{air}/d$$

$$\Rightarrow P_{air}(T) = (\Delta\lambda/\Delta t)_T \cdot d/\lambda_p^*$$

Permeation of dry air P_{air} is proportional to thermal conductivity change with time $\Delta\lambda/\Delta t$, if dryer is inserted and there is no additional outgassing from envelope or core material

Measurement of P_{air} of Metallized Film

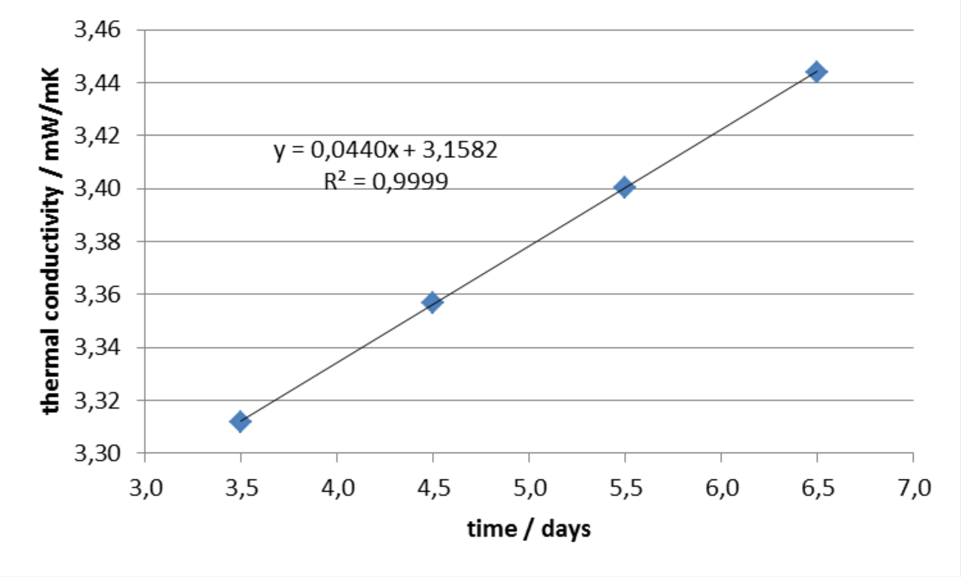
Measurement of glass fiber VIP with same metallized barrier film as used for va-Q-vip

Apparatus: heat flow meter, T_1 = 37 °C, T_2 = 20 °C, T_{mean} = 28.5 °C

⇒ **change of thermal conductivity λ:** 480 % per year or **16 mW/mK per year**

due to inside dryer material
only air permeation is responsible
for thermal conductivity increase:

P_{air} = 6 mbar liter/(m² year)
(@ T_{mean} = 28.5 °C)



Determining Acceleration Factor f_{air} for Air

Change of air permeation P_{air} with temperature T is measured for metallized barrier film envelope, which is the same as for the silica VIP:

temperature T °C	air permeation P_{air} mbar liter/(m² year)
29	6,2
45	13,5
70	33,5

=> Interpolation to T_1 = 50 °C and T_{ref} = 23 °C

Acceleration Factor f_{air}

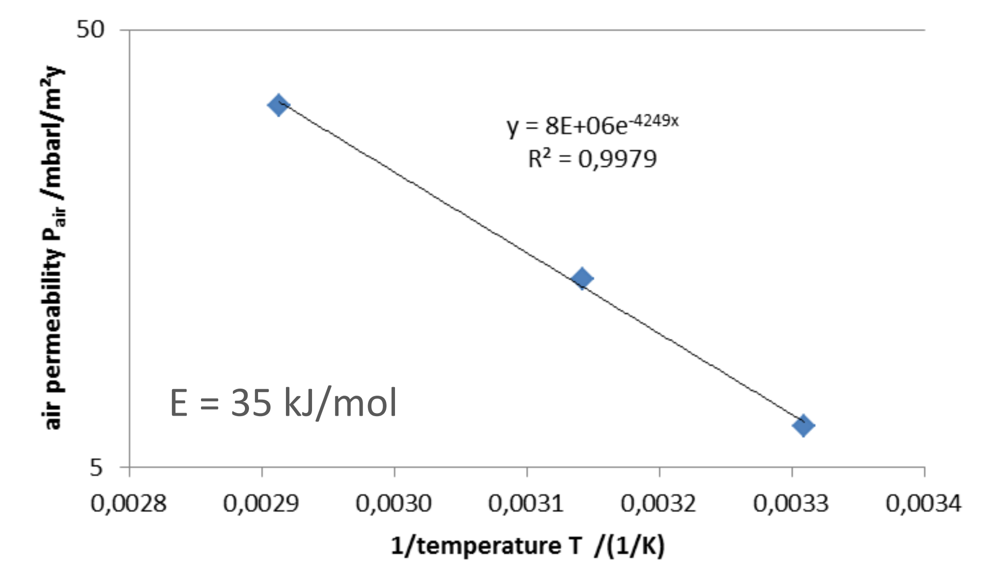
Air permeation P_{air} for the metallized barrier film shows a typical Arrhenius type variation with absolute temperature T:

$\Rightarrow$ **Acceleration Factor f_{air}** $= P_{air}(T_1)/P_{air}(T_{ref})$

$= \exp(-a/T_1)/\exp(-a/T_{ref}) = \exp(-a\cdot(1/T_1 - 1/T_{ref}))$

with T_1 = 323 K, T_{ref} = 296 K and a = 4249 K:

=> f_{air} = 3.3



Calculation of Thermal Conductivity@Reference Climate

Increase of thermal conductivity λ at reference climate 23°C/50%:

$$(\Delta\lambda/\Delta t)_{23} = (1 - f_{air}/f_{H2O}) \cdot \underbrace{(P_{air,23}/d)\cdot\lambda_p}_{\Delta\lambda_{air,23}/\Delta t} + (\Delta\lambda/\Delta t)_{50}/f_{H2O} \qquad (5)$$

with $P_{air,23}$ = 5 mbar liter/(m² year) (from Arrhenius plot)

f_{air} = 3.3, f_{H2O} = 8, d = 20 mm, λ_p = 0.04 mW/mK

$(\Delta\lambda/\Delta t)_{23}$ = ((1 – 3.3/8) · 5/20 · 0.04 + 0.79/8) mW/(mK year)
= (0.006 + 0.099) mW/(mK year)

$(\Delta\lambda/\Delta t)_{23}$ = 0.105 mW/(mK year)

=> **mean thermal conductivity increase during 25 years: 1.3 mW/mK**

Comparison of Results va-Q-tec silica VIPs

Results extrapolated to reference climate **23 °C / 50 % r.h.**:

method	measured quantity	measured quantity	parameters to be known	yearly increase λ mW/mKy	mean increase λ 25 years mW/mK
Accel. aging	$(\Delta\lambda/\Delta t)_{50}$	$P_{air,28}$	f_{H2O} , f_{air}	0.105	1.3
Accel. aging	$(\Delta m/\Delta t)_{50}$	$(\Delta p/\Delta t)_{50}$	λ_X, λ_p, f_{H2O} , f_{air}	0.110	1.4
10 years	$(\Delta\lambda/\Delta t)_{23}$	-	direct	0.12	1.5
10 years	$(\Delta m/\Delta t)_{23}$	$(\Delta p/\Delta t)_{23}$	λ_X, λ_p	0.11	1.4

valid for va-Q-vip

Ten years real aging and half year accelerated aging extrapolated to 23°C/50% yield similar results

Conclusions

- Accelerated aging results @ 50 °C/ 70% r.h. extrapolated to reference climate 23 °C / 50 % are in accordance with results of 10 years aging of silica VIPs @ 23 °C.
- Proposed procedure: Silica VIP manufacturer shall measure thermal conductivity increase during storage of VIP @ standard climate 50°C/70%.
- The accelerating factors of air and vapor permeation and the absolute air permeation at room temperature should be provided by the film manufacturer / institutes
- Shown procedure for extrapolation results to standard climate 23°C/50% rh. is only valid for silica VIPs
- Other core materials: time until getter/dryer saturate is important

Thank you for your attention

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