Barrier robustness of aluminium foil

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Outline

- Polymers, aluminium foil and other barriers
- Permeation in packaging laminates
- Transport model through laminates with pinholes in the foil
- Models to calculate permeation rate of pinholes in laminates
  - Area portion model
  - Permeator model (worst case calculation)
- How many pinholes are affordable with foil to safeguard barrier performance?
- Summary

Occasion

Aluminium foil in flexible packaging laminates has some competitors regarding barrier function like

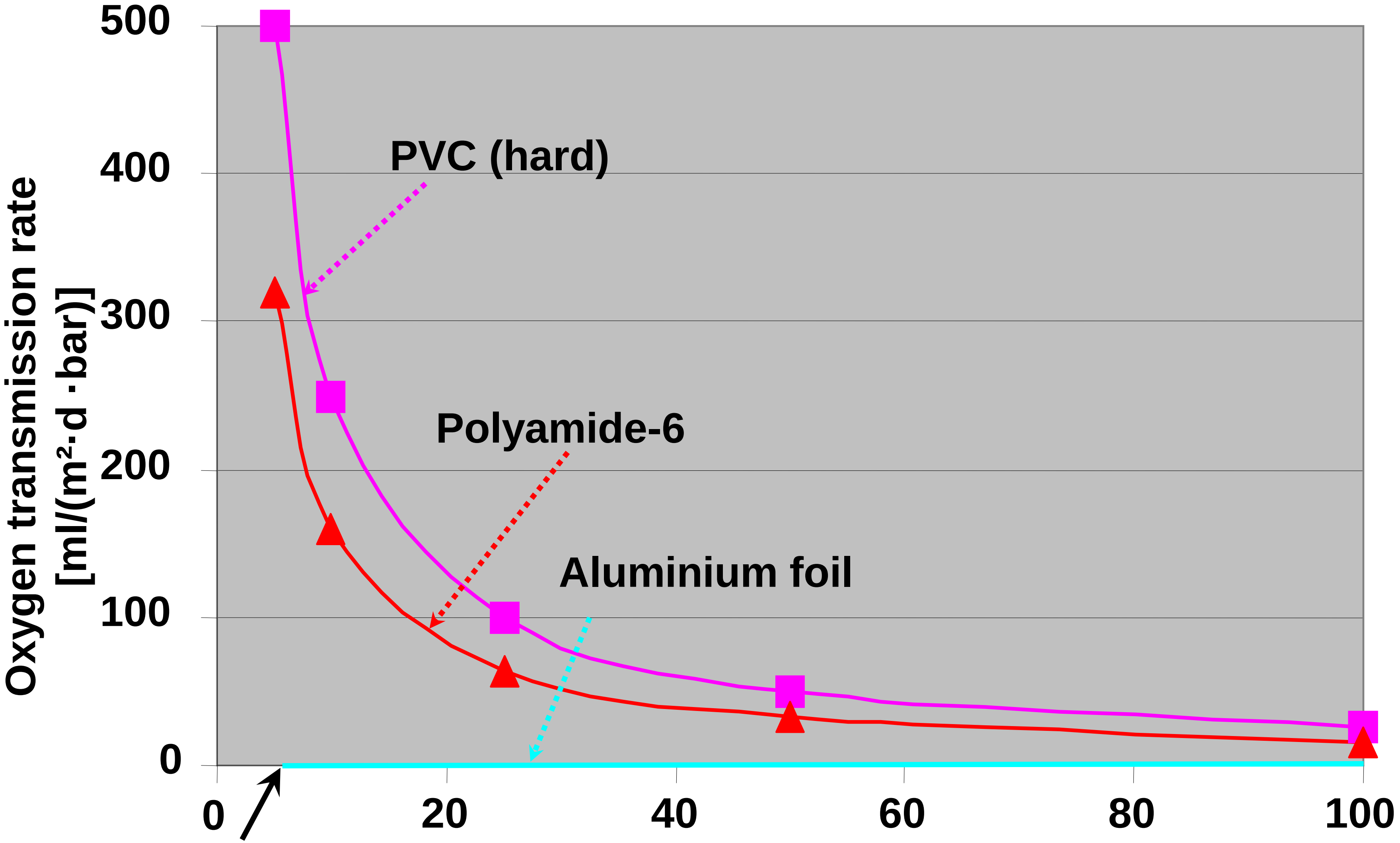
Metallised films	**AlO_x- or**	**SiO_x-coated films**	**Barrier polymers**
Polyamide	**EVOH**	**PVDC (still used)**	**Nano-barriers**

Aluminium has some advantage over these competitors:

- **No barrier loss during hot filling or retorting**
- **High stiffness and dead-fold**
- **No softening like plastics at high temperatures**
- **Excellent heat conductivity for sealing**
- **Can be heated by induction for sealing**
- **Unsurpassable light barrier**

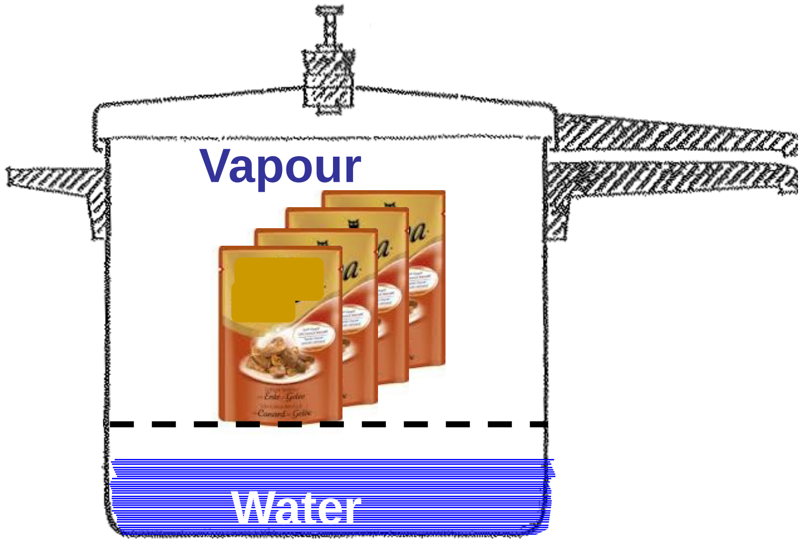
But rivals claim that aluminium pinholes cause foil to have poor barrier It is worth taking a closer look at this…..

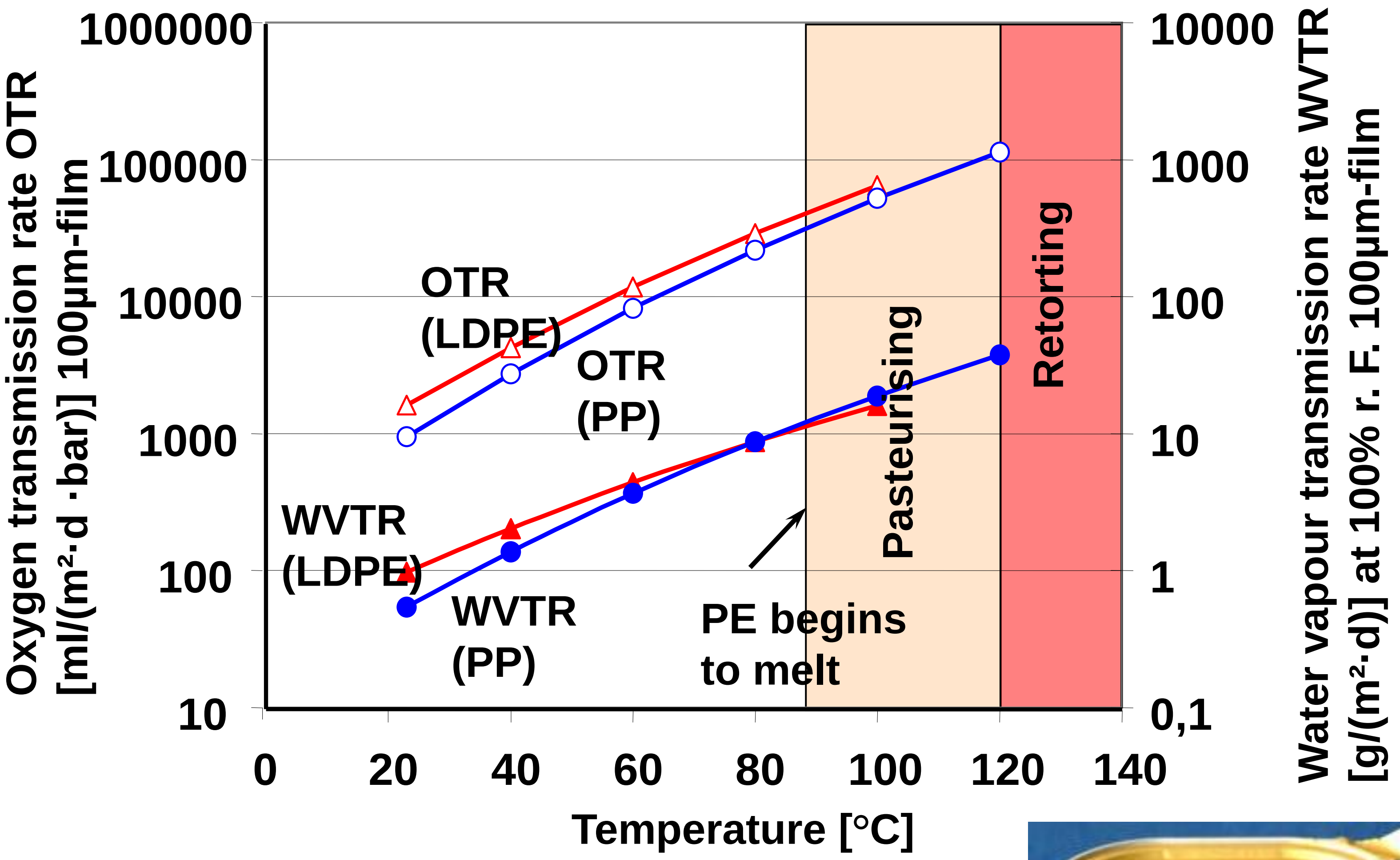
Aluminium foil and polymer films – What makes them different?



6,0 µm (thinnest industrially manufactured aluminium foil)

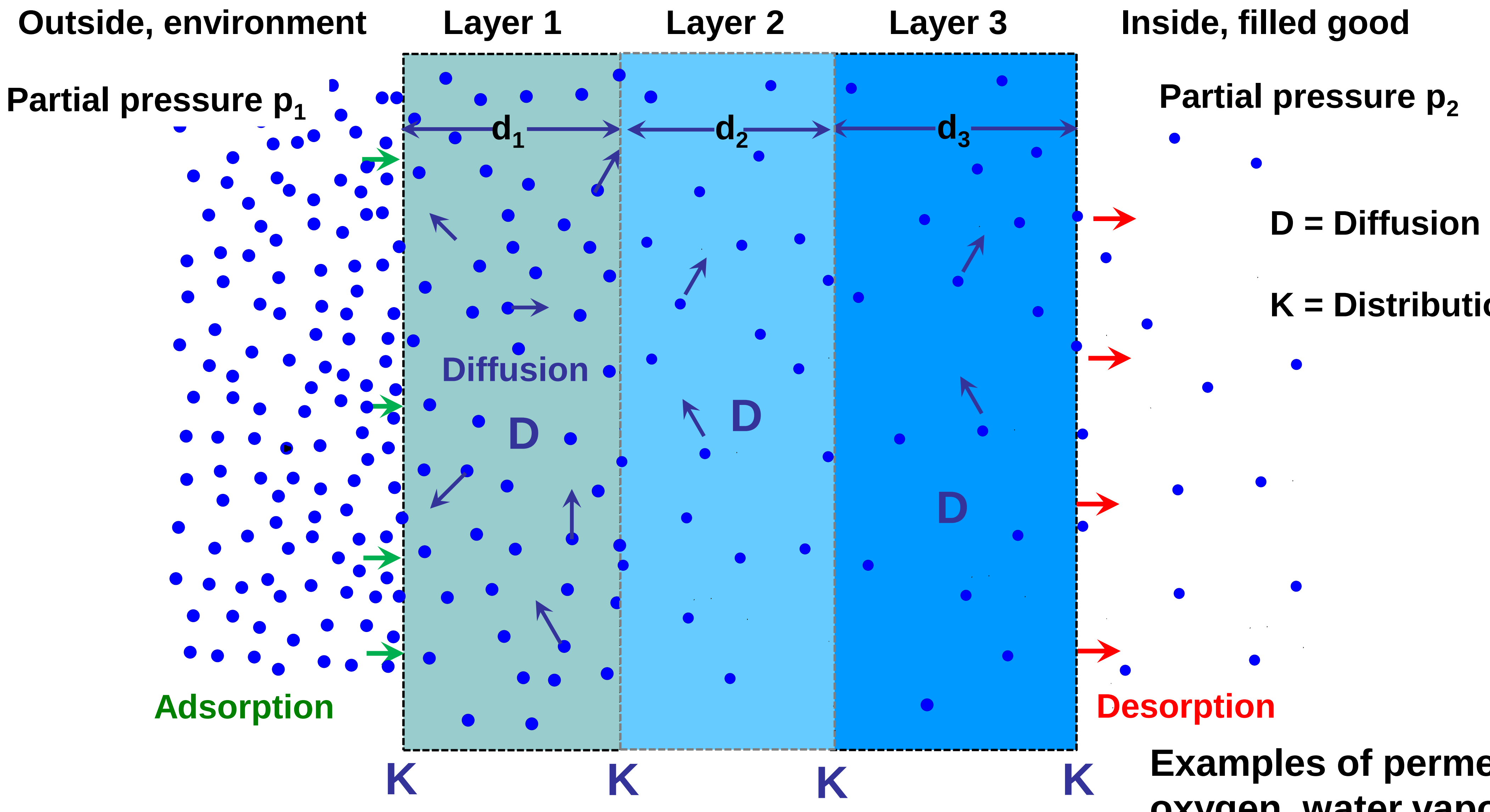
Barrier of polymer films at elevated temperature





In contrast to polymers the barrier of aluminium foil remains unaffected during thermal treatments in packaging

Permeation through packages

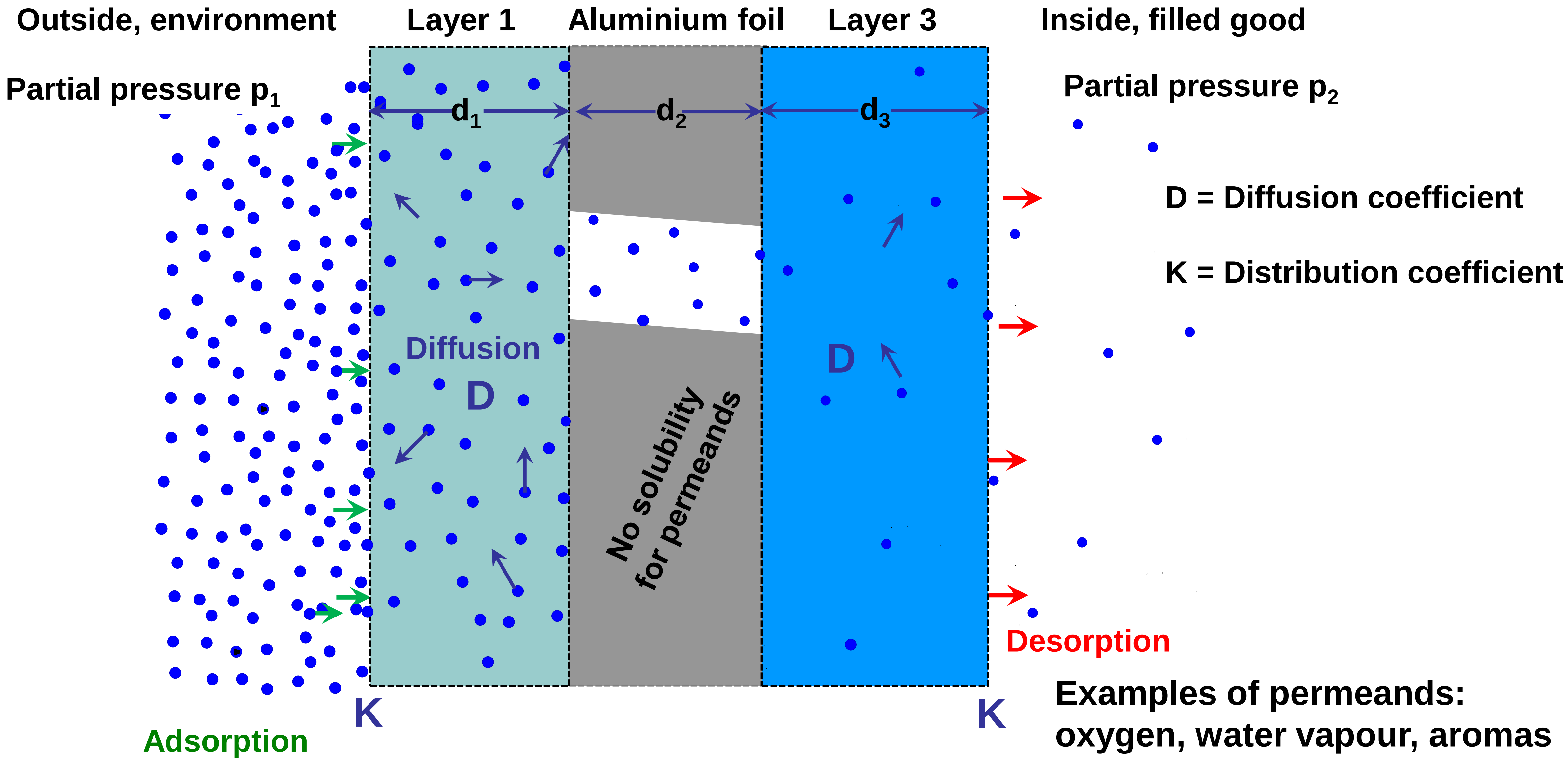


D = Diffusion coefficient

K = Distribution coefficient

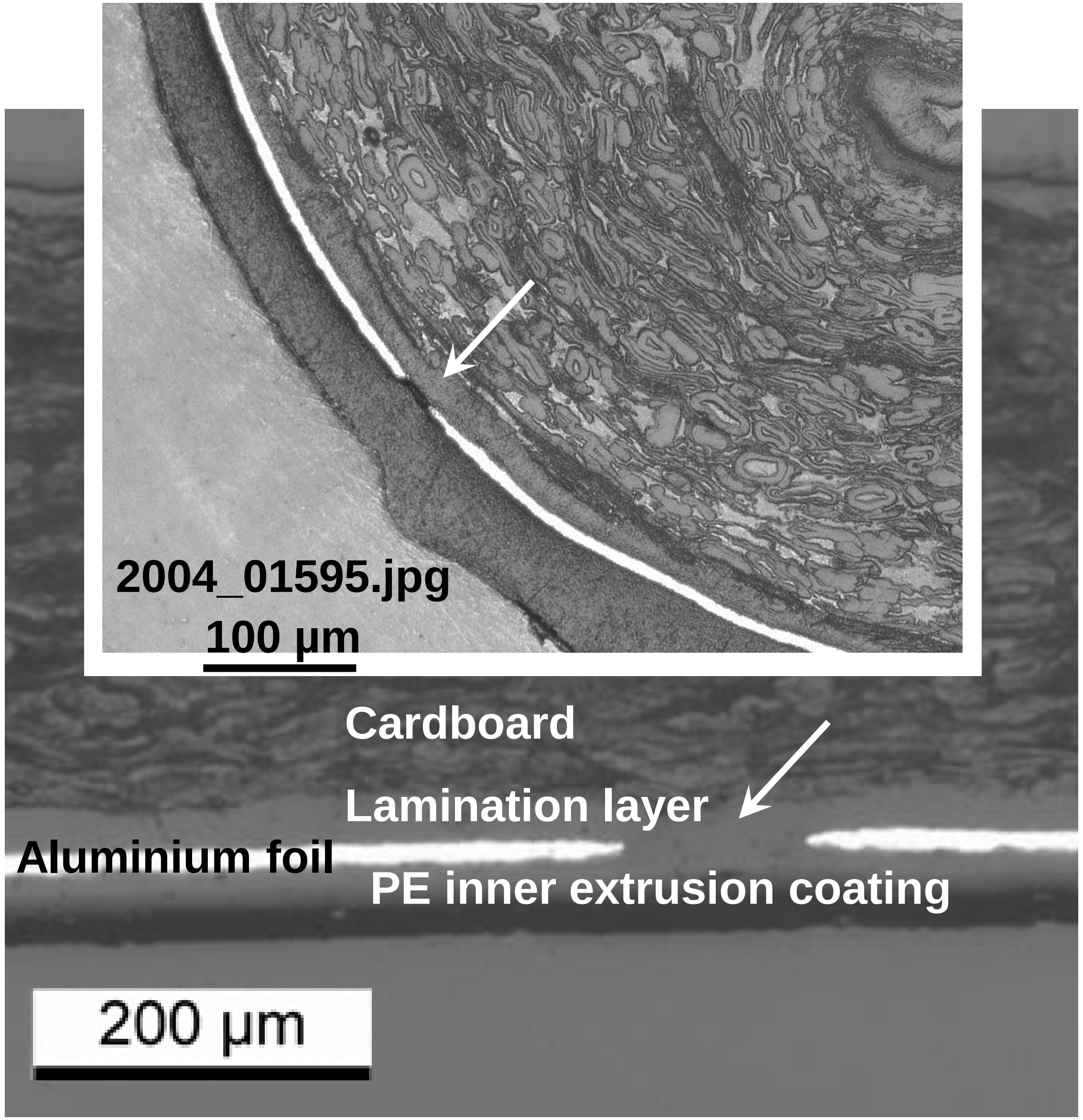
Examples of permeands:
oxygen, water vapour, aromas

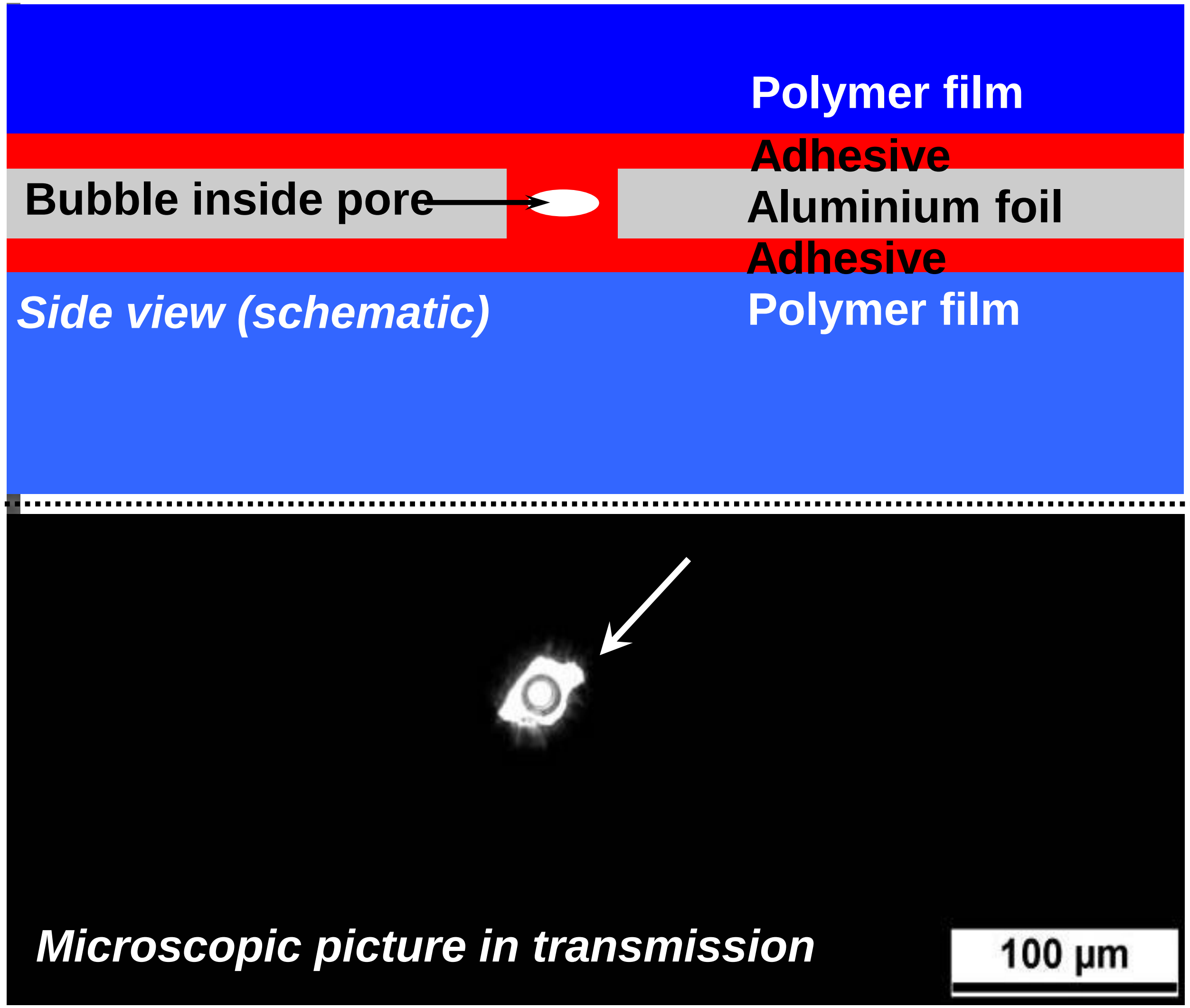
Permeation through aluminium foil package



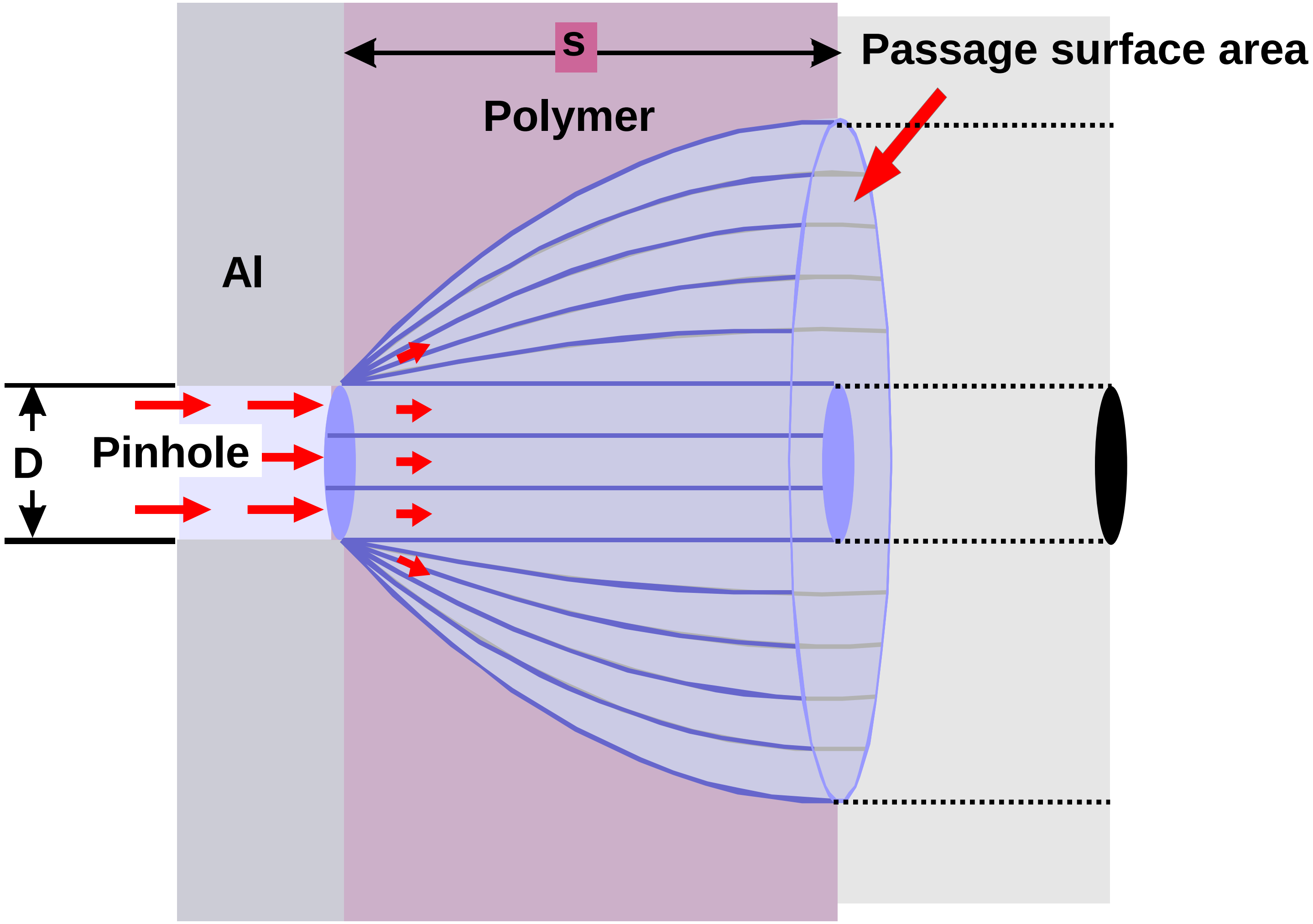
Examples of permeands: oxygen, water vapour, aromas

Break-throughs in foil in extrusion coating and adhesive lamination



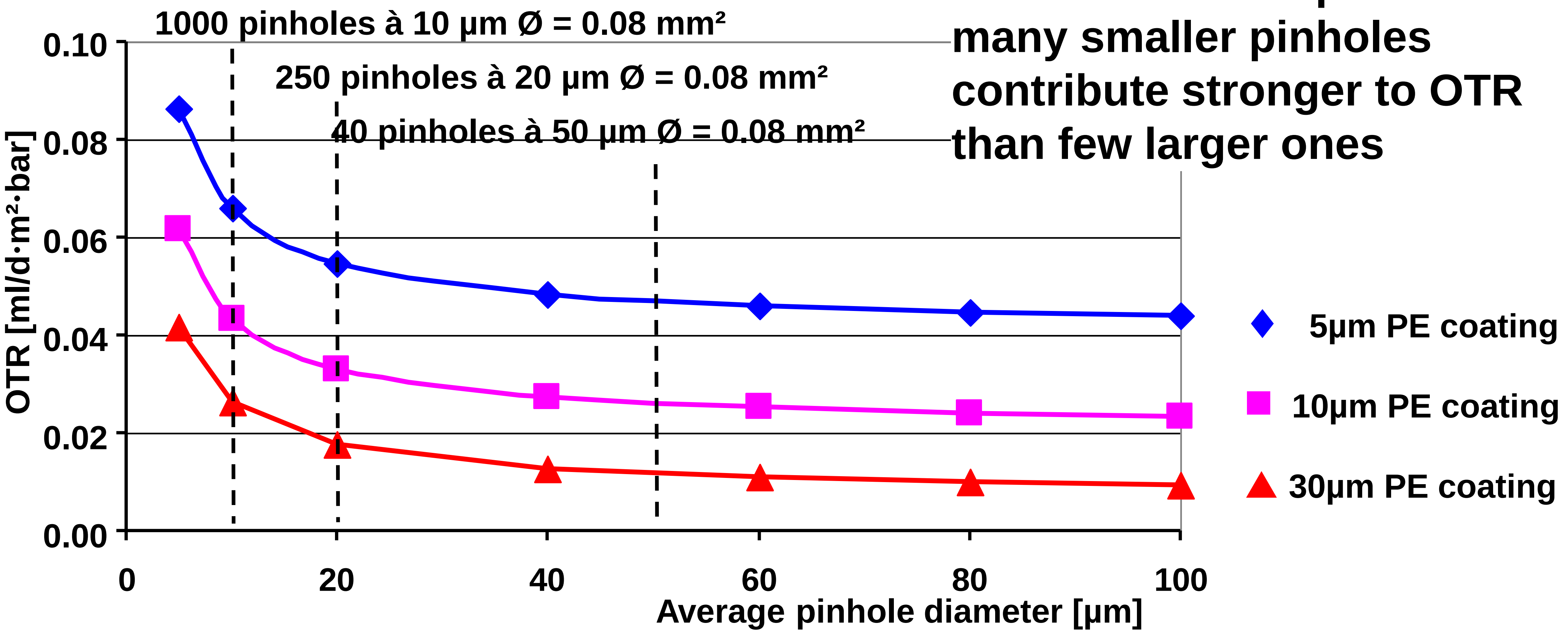


Transport model for laminates carrying pinholes in their aluminium foil



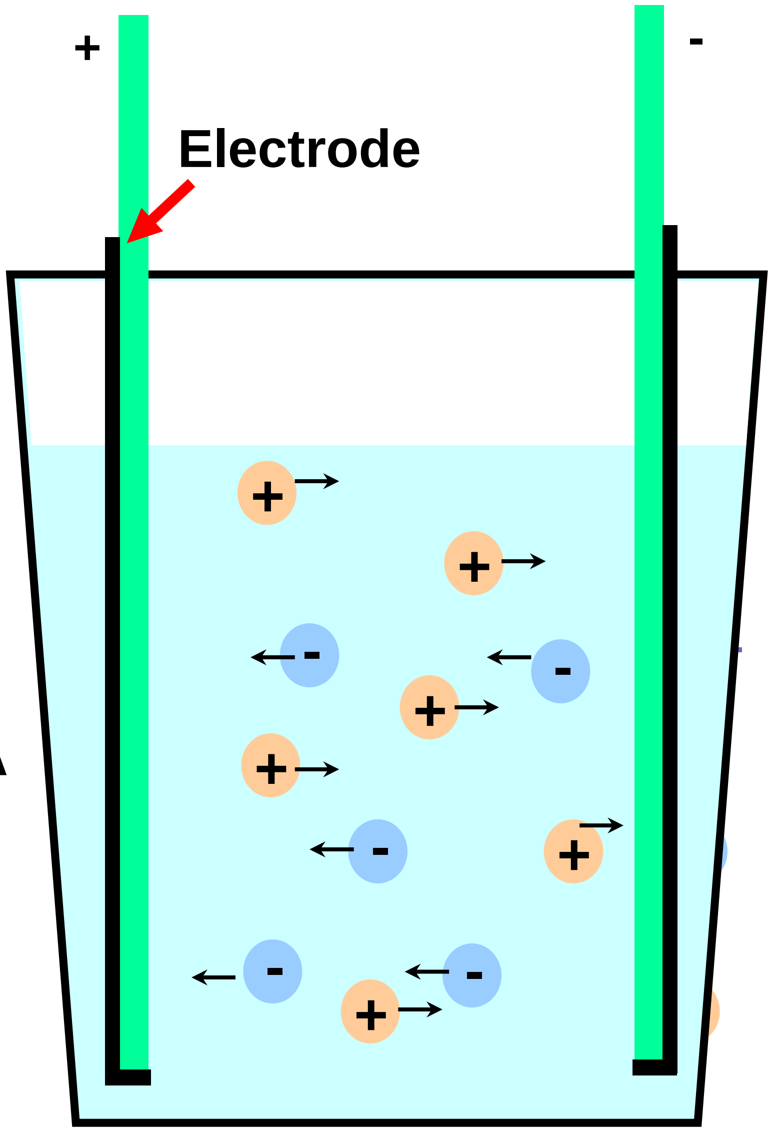
Oxygen permeation rate vs. pinhole size at constant total pinhole surface area (Al/PE_{ex})*

At constant total pinhole area, many smaller pinholes contribute stronger to OTR than few larger ones



*** Aluminium foil is here in this examples only single-side coated, total pinhole area assumed as 0.08 mm²/m² for all values**

Electrode model



Electrode surface A

Distance between electrodes s

Resistance R

Voltage drop V

Specific conductivity K = s / R·A

Flux F = V / R·A

Electrode model

Electrode surface A

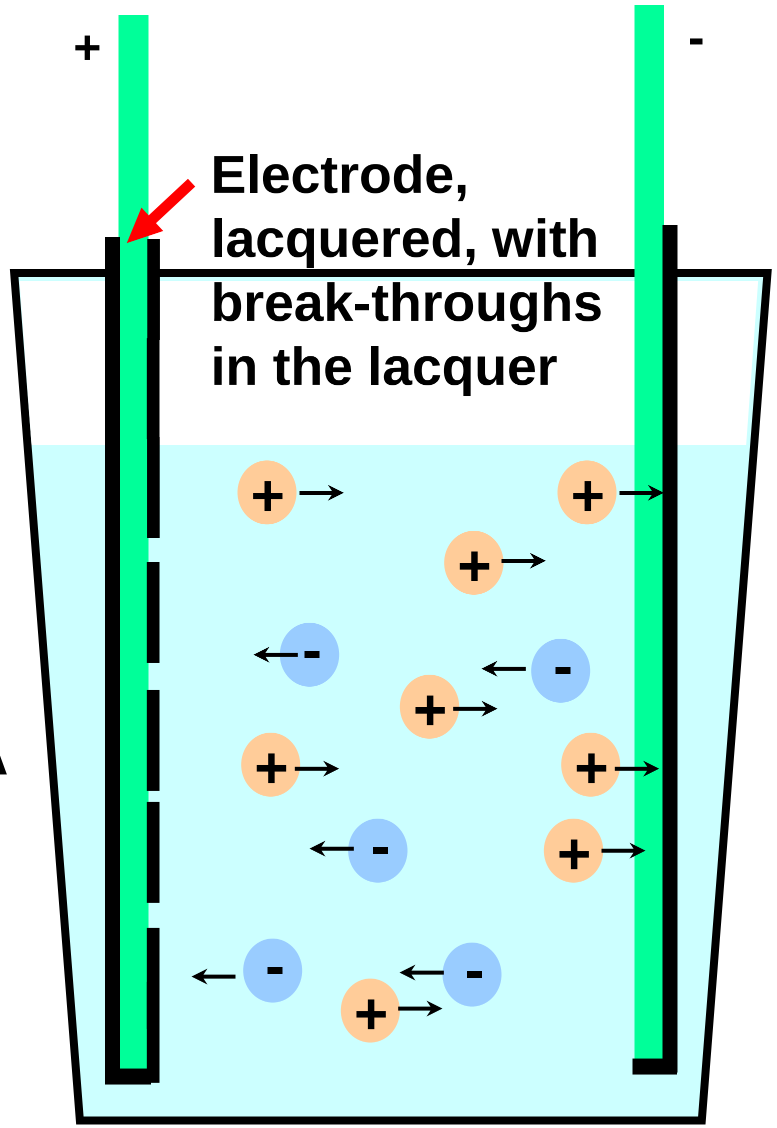
Distance between electrodes s

Resistance R

Voltage drop V

Specific conductivity $K = s / R \cdot A$

Flux $F = V / R \cdot A$



Empirical “electrode equation“ to calculate permeation rates through single-side coated aluminium foil carrying pinholes

$$Q = 4\pi\, 10^{-12} \cdot D^2 \cdot N \cdot Q_{100} \cdot \frac{100}{s} \ \{1 + 1{,}149 \cdot (\frac{s}{D})^{0{,}8456}\}$$

Example for LDPE

Q_{100} = Permeation rate for 100µm film, e.g. for LDPE 1610

N = Number of pinholes [1/m²]

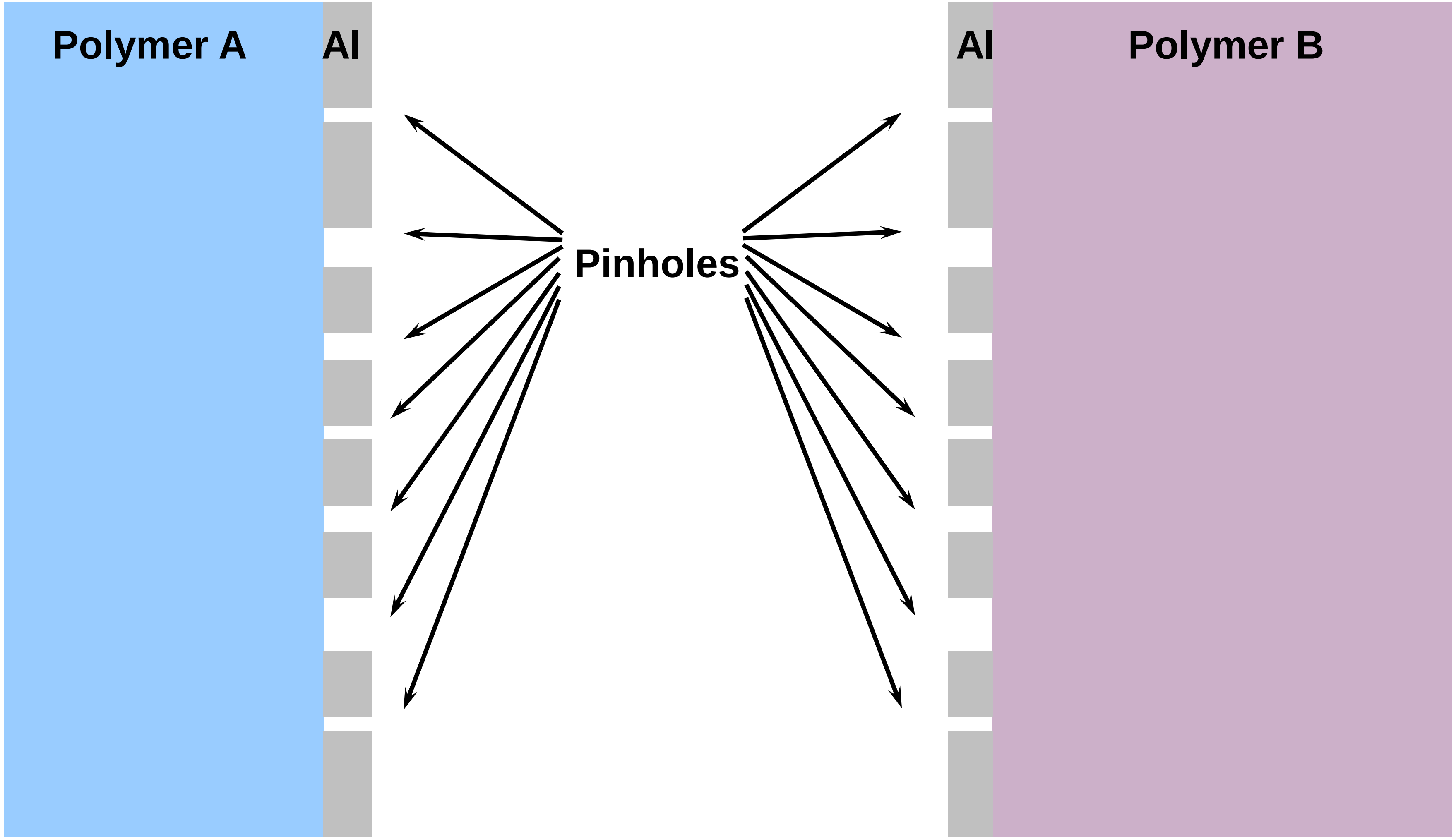
D = Average diameter of the pinholes [µm]

Q = Flux (permeation rate) [ml/d · bar · m²]

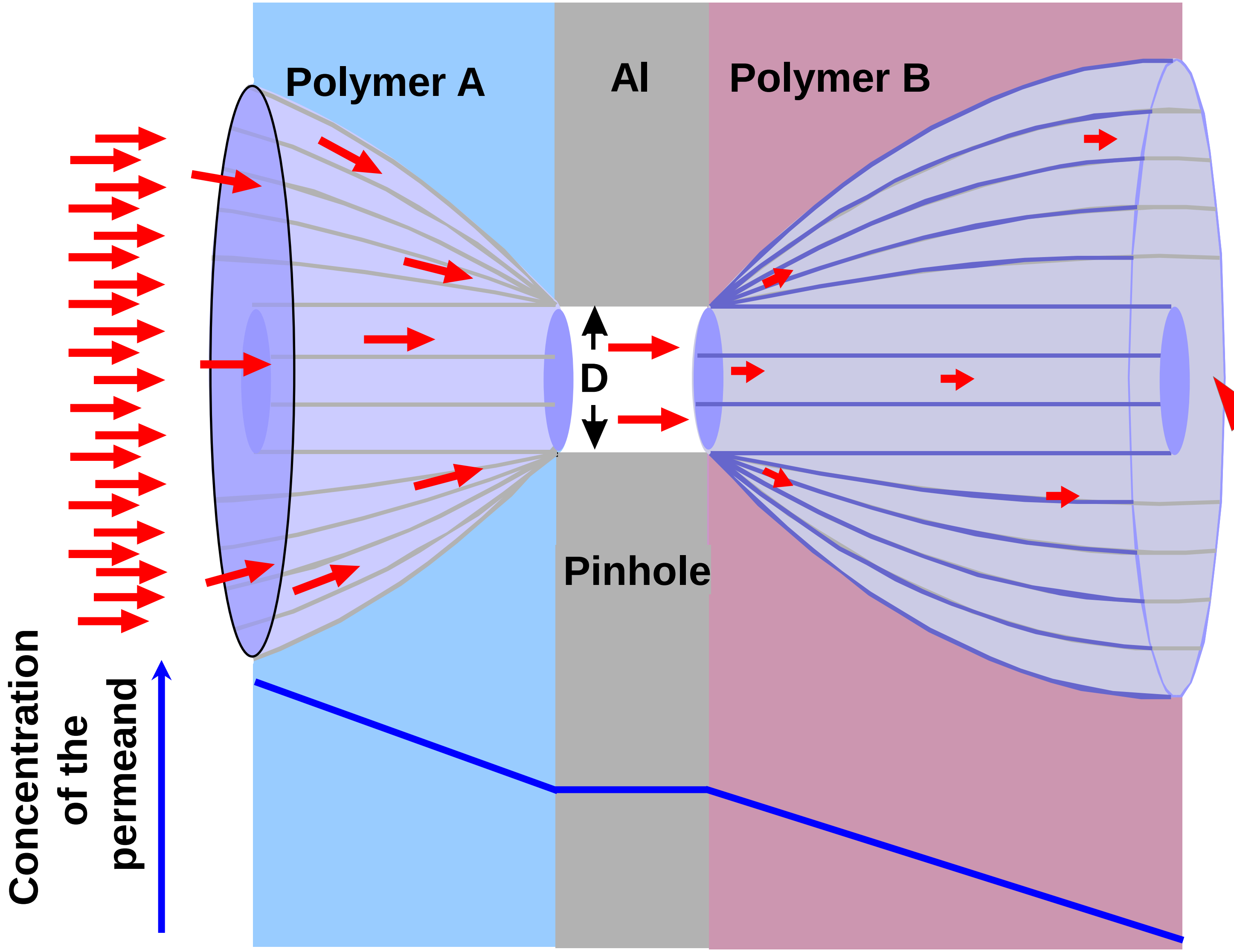
s = Film thickness [µm]

* Electrode equation according to: W. Prins , J. J. Hermans, “Theory of Permeation through Metal Coated Polymer Films“, J. Phys. Chem., 1959, 63 (5), pp 716–720

Merging model of two one-side coated aluminium foil laminates



Transport through a single pinhole in aluminium foil coated on both sides



Calculation of the oxygen permeation rate of a laminate PE/tie/aluminium foil/tie/PE-LD + PE-LLD

	Thickness	OTR	1/OTR
	[µm]	$cm^3/d \cdot m^2 \cdot bar$	
PE	14	11430	8,74891E-05
PE-tie	6	30000	3,33333E-05
Aluminium	7	0,0005	2000
PE-tie	6	30000	3,33333E-05
LLDPE+ LDPE	30	5333	0,000187512
Total		*0,0005*	2000,000342

**** An oxygen permeation rate of 0.0005 ml/d · m² · bar is the minimum threshold level of detection for state-of-the-art measuring equipment***

Calculation of the oxygen permeation rate of a laminate PE/tie/ pinhole /tie/PE-LD + PE-LLD at pinhole position (locally no aluminium foil)

	Thickness	OTR	1/OTR
	[µm]	$cm^3/d \cdot m^2 \cdot bar$	
PE	14	11430	8,74891E-05
PE-tie	6	30000	3,33333E-05
Pinhole			0
PE-tie	6	30000	3,33333E-05
LLDPE+ LDPE	30	5333	0,000187512
Total		*2926,82*	0,000341667

Oxygen permeation rate at position of no foil is rather high

Calculation of the oxygen permeation rate of a laminate PE/tie/EVOH/tie/PE-LD + PE-LLD (no aluminium foil inside)

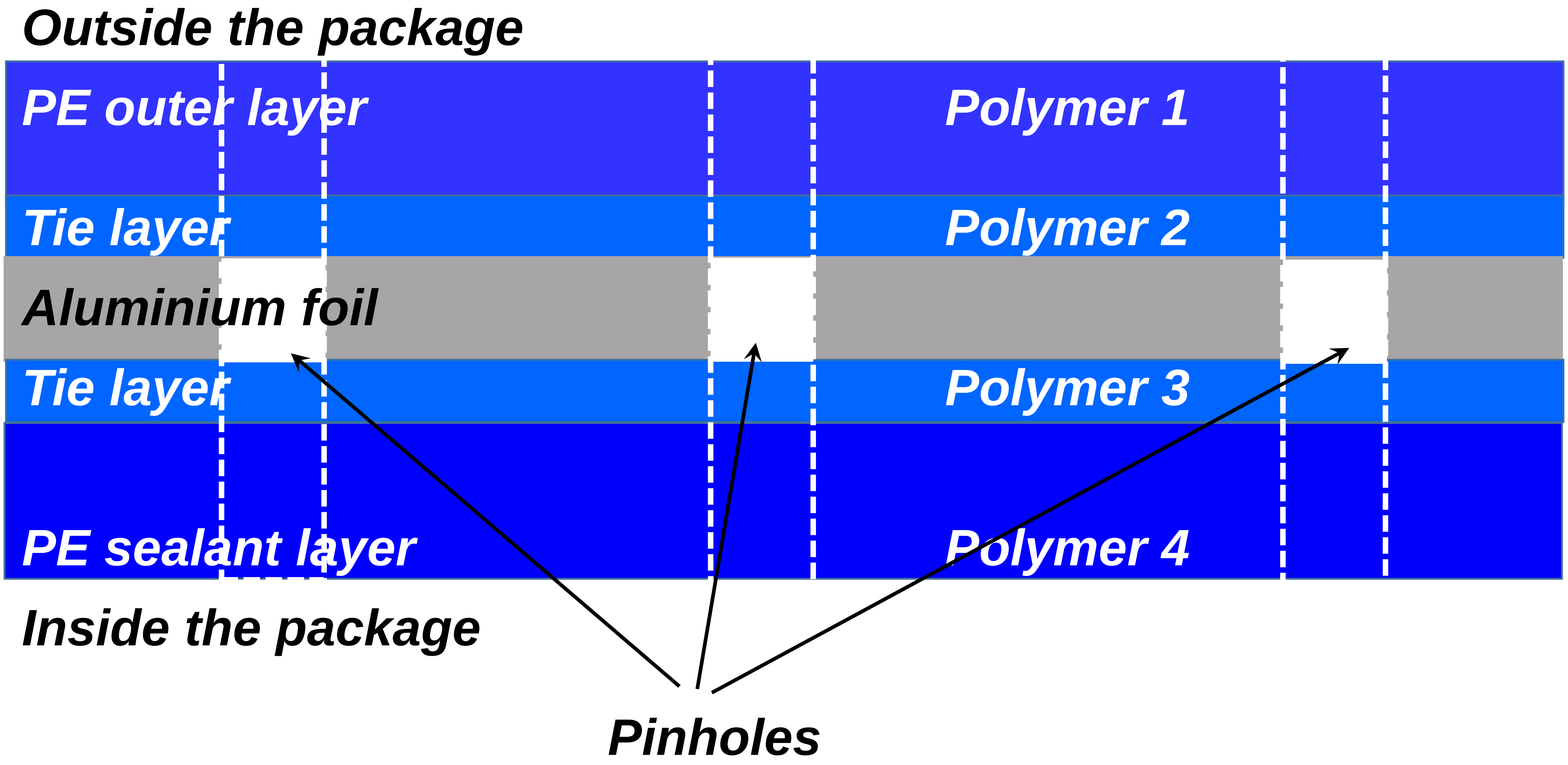
	Thickness	OTR	1/OTR
	[µm]	$cm^3/d \cdot m^2 \cdot bar$	
PE	14	8900	0,00011236
PE-tie	6	30000	3,33333E-05
EVOH (32%)	4	0,5	2
PE-tie	6	30000	3,33333E-05
LLDPE	30	5333	0,000187512
Total		*0,4999*	2,000366538

Oxygen permeation rate is at a good level

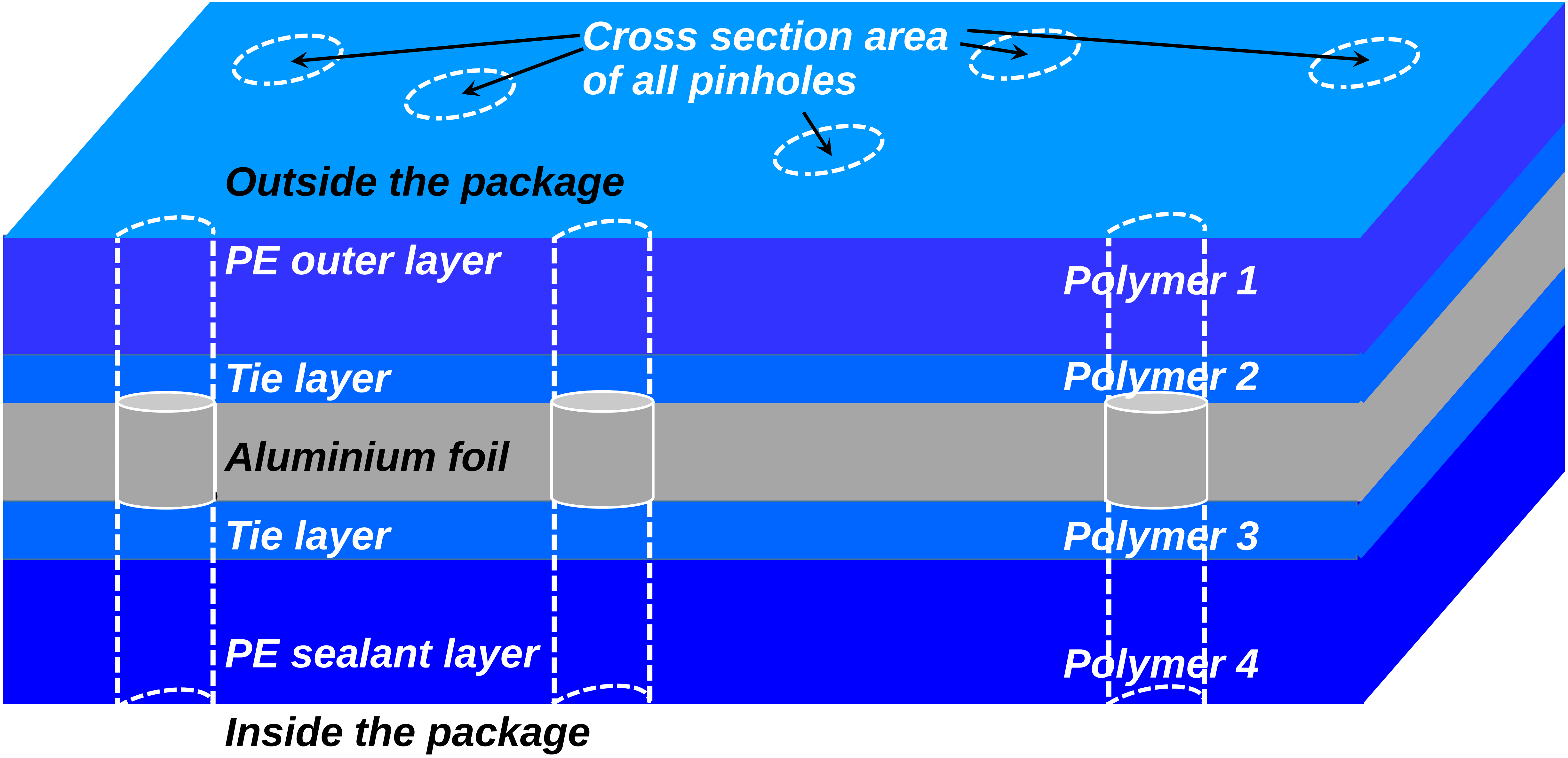
Calculation of the oxygen permeation rate of a laminate PE/tie/aluminium foil/tie/PE-LD + PE-LLD at pinhole position (locally aluminium foil missing)

How many pinholes can you afford, still being as good as an EVOH barrier laminate?

Area portion method



Area portion method



Calculation of the oxygen permeation rate of a laminate PE/tie/aluminium foil/tie/PE-LD + PE-LLD carrying pinholes in the foil – Area portion method

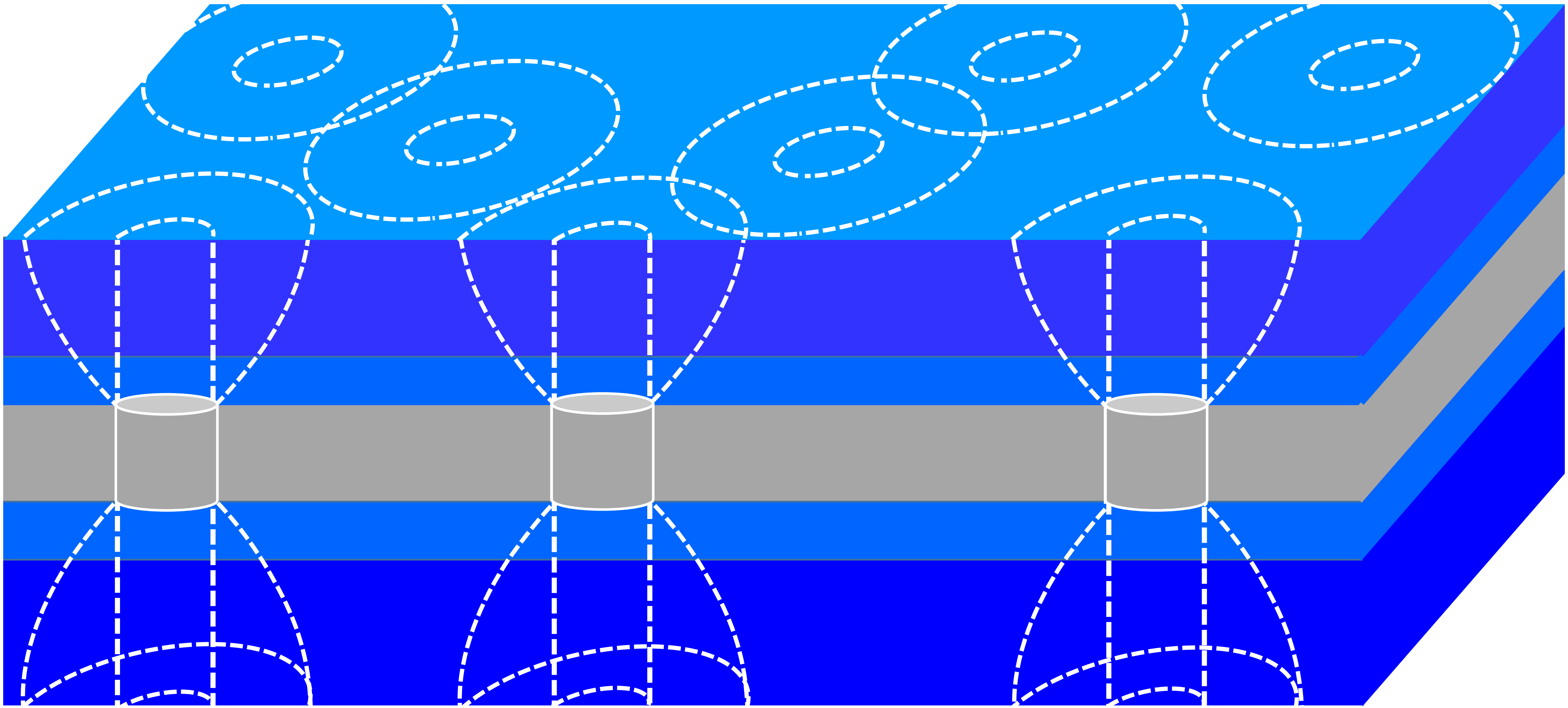
$$OTR_{total} = Portion_{\text{pinhole area}} \cdot OTR_{\text{pinhole area}} + Portion_{\text{alu laminate area}} \cdot OTR_{\text{alu laminate area}}$$

OTR = Oxygen transmission rate in cm³/m² · d · bar

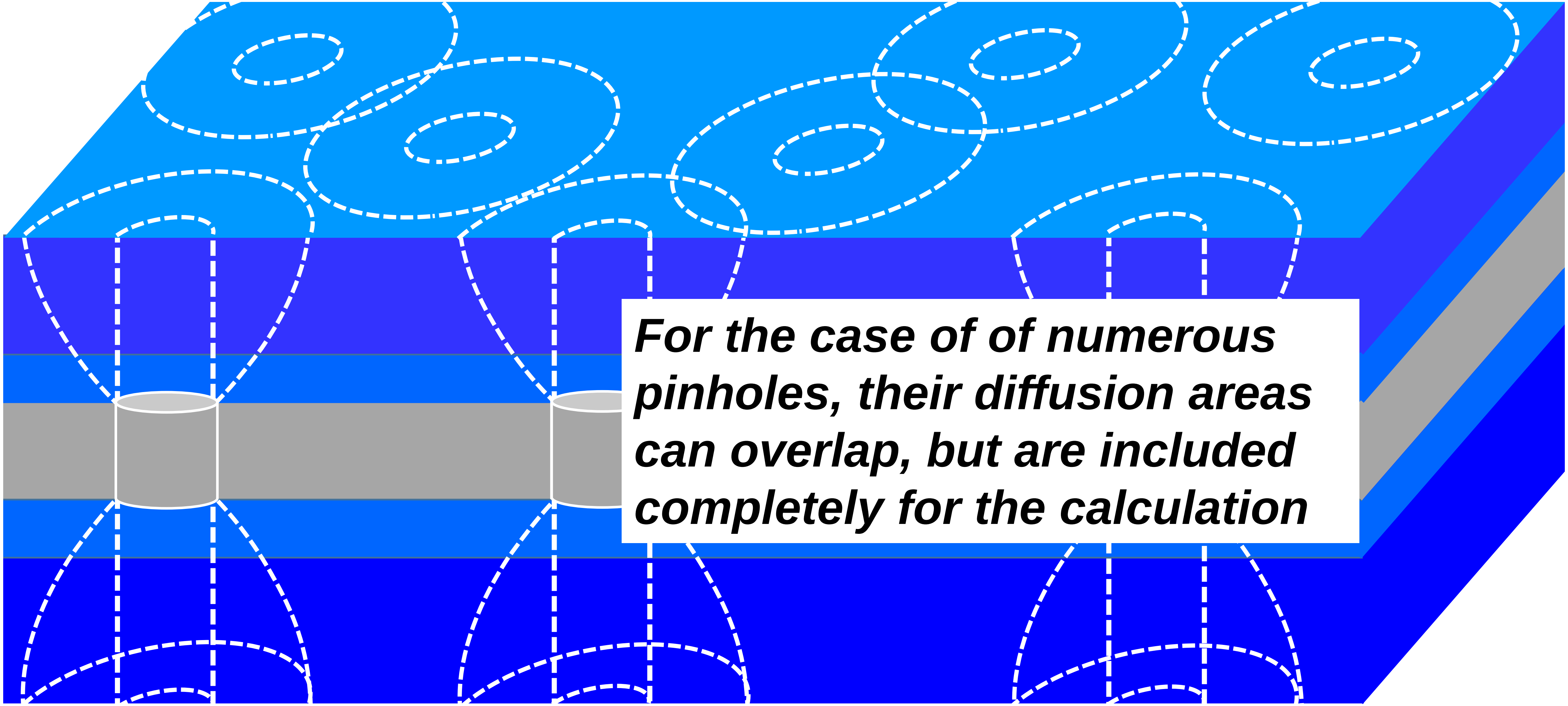
Calculation of the oxygen permeation rate of a laminate PE/tie/aluminium foil/tie/PE-LD + PE-LLD carrying pinholes in the foil – Area portion method

	Portion of pinhole area	OTR pinhole ar	OTR pinholes	Portion of aluminium	OTR aluminium a	OTR aluminium	OTR Total (Area portion model)
1 ppm pinholes (3183 pinholes of 20 µm diameter)	0,000001	2927	0,002927	0,999999	0,0005	0,0005	0,0034
13000 pinholes of 20 µm diameter	0,000004	2927	0,0120	0,999996	0,0005	0,0005	0,0140
100 ppm pinholes (318300 pinholes of 20 µm diameter)	0,0001	2927	0,2927	0,9999	0,0005	0,000500	0,2932
170 ppm pinholes (541100 pinholes of 20 µm diameter)	0,00017	2927	0,49759	0,99983	0,0005	0,000500	0,4981

Permeator method (worst case calculation)



Permeator method (worst case calculation)



For the case of of numerous pinholes, their diffusion areas can overlap, but are included completely for the calculation

Calculation of the oxygen permeation rate of a laminate PE/tie/aluminium foil/tie/PE-LD + PE-LLD carrying pinholes in the foil – Permeator method

Barrier calculator for aluminium foil laminates, both sides coated		
Number of pinholes in the aluminium foil per m²	1000	*[1/m²]*
Average pinhole diameter	20	*[µm]*
Q_{100} (polymer 1+2)	1655	*[cm³/(d·m²·bar)]*
Thickness of polymers 1+2	20	*[µm]*
Q_{100} (polymer 3+4)	1630	*[cm³/(d·m²·bar)]*
Thickness of polymers 3+4	36	*[µm]*
Permeation rate foil + polymer layers 1+2 (Q1)	8,94E-02	*[cm³/(d·m²·bar)]*
Permeation rate foil + polymer layers 3+4 (Q2)	6,57E-02	*[cm³/(d·m²·bar)]*
Permeation rate complete laminate Q	3,79E-02	*[cm³/(d·m²·bar)]*

1000 pinholes/m² typical population for thin foil;
20 µm diameter is a rather large average value

Calculation of the oxygen permeation rate of a laminate PE/tie/aluminium foil/tie/PE-LD + PE-LLD carrying pinholes in the foil – Permeator method

Barrier calculator for aluminium foil laminates, both sides coated		
Number of pinholes in the aluminium foil per m²	13000	[1/m²]
Average pinhole diameter	20	[µm]
Q_{100} (polymer 1+2)	1655	[cm³/(d*m²*bar)]
Thickness of polymers 1+2	20	[µm]
Q_{100} (polymer 3+4)	1630	[cm³/(d*m²*bar)]
Thickness of polymers 3+4	36	[µm]
Permeation rate foil + polymer layers 1+2 (Q1)	1,16E+00	[cm³/(d*m²*bar)]
Permeation rate foil + polymer layers 3+4 (Q2)	8,55E-01	[cm³/(d*m²*bar)]
Permeation rate complete laminate Q	4,92E-01	[cm³/(d*m²*bar)]

With 13.000 pinholes/m² of 20 µm diameter OTR is still equivalent to an EVOH-laminate (under worst case conditions)

Calculation of the oxygen permeation rate of a laminate PE/tie/aluminium foil/tie/PE-LD + PE-LLD carrying pinholes in the foil – Both methods

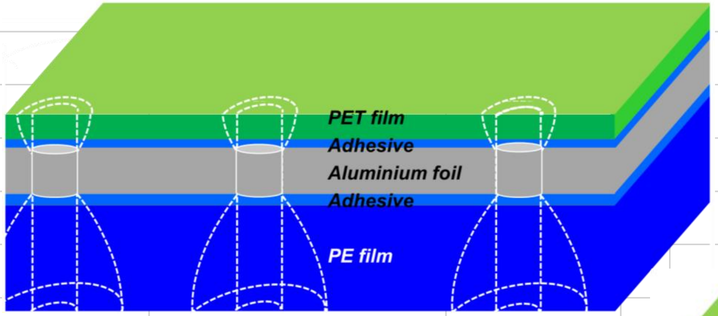
	Portion of pinhole area	OTR pinhole ar	OTR pinholes	Portion of aluminium	OTR aluminium a	OTR aluminium	OTR Total (Area portion model)	OTR Total (Permeator model)
1 ppm pinholes (3183 pinholes of 20 µm diameter)	0,000001	2927	0,002927	0,999999	0,0005	0,0005	0,0034	0,121
13000 pinholes of 20 µm diameter	0,000004	2927	0,0120	0,999996	0,0005	0,0005	0,0140	0,492
100 ppm pinholes (318300 pinholes of 20 µm diameter)	0,0001	2927	0,2927	0,9999	0,0005	0,000500	0,2932	12,1
170 ppm pinholes (541100 pinholes of 20 µm diameter)	0,00017	2927	0,49759	0,99983	0,0005	0,000500	0,4981	20,5

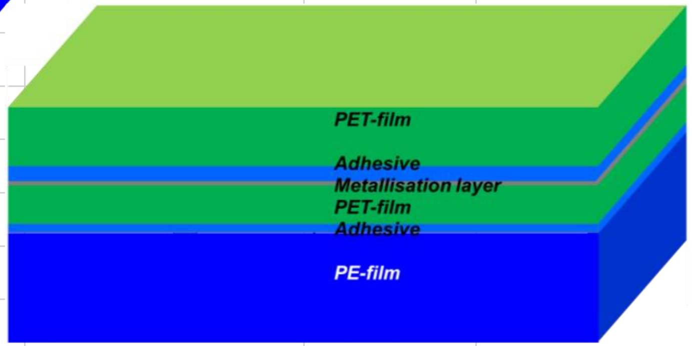
Area portion model calculation – better values than reality

Barrier in reality even better than permeator calculated values

Comparison of oxygen permeation rate of laminates with aluminium foil or metallised PET-film

		OTR	1/OTR
	µm	cm³/d·m²·bar	
PET	12	65	0,0154
Adhesive	3	314,2	0,0032
Aluminium foil	6	0,0005	2000,0000
Adhesive	3	314,2	0,0032
LLDPE	75	1600	0,0006
Area without pinholes in the foil		0,0005	2000,0224

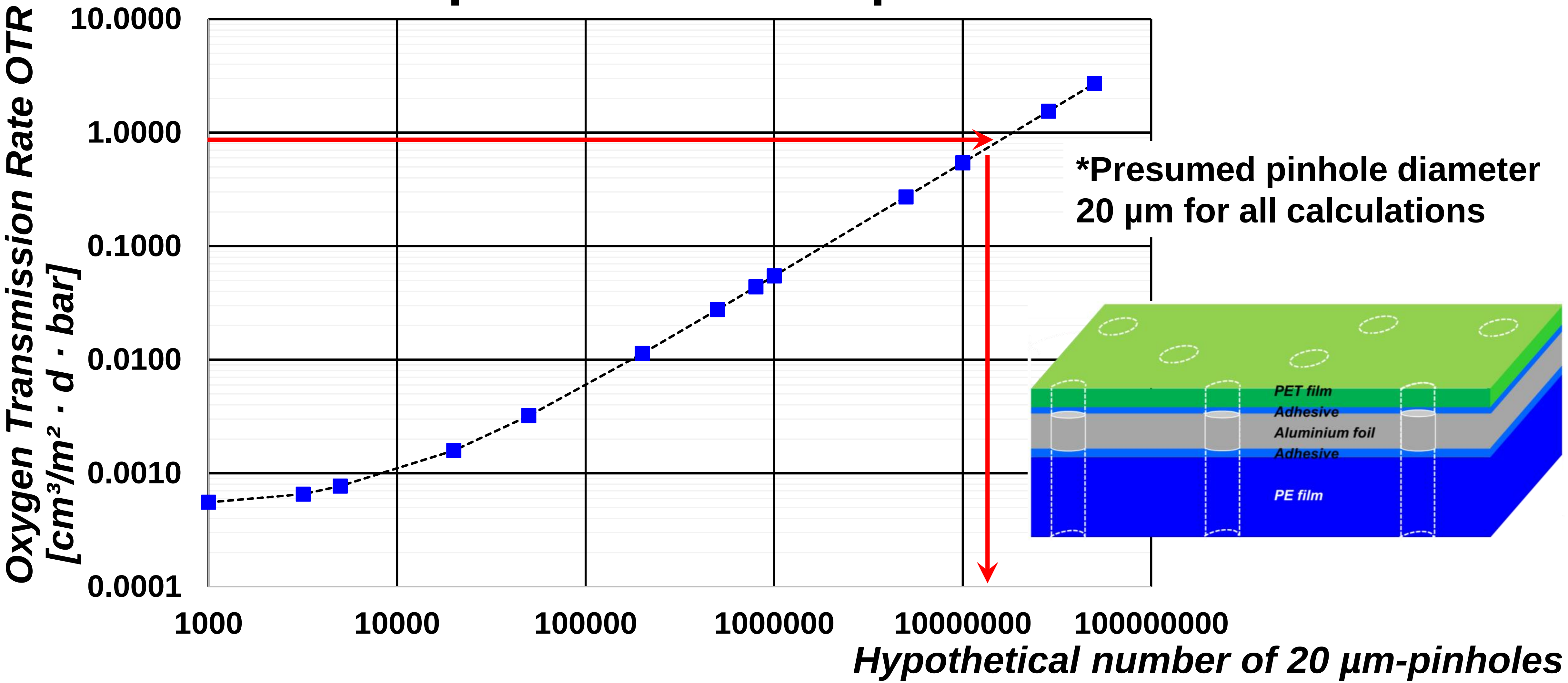




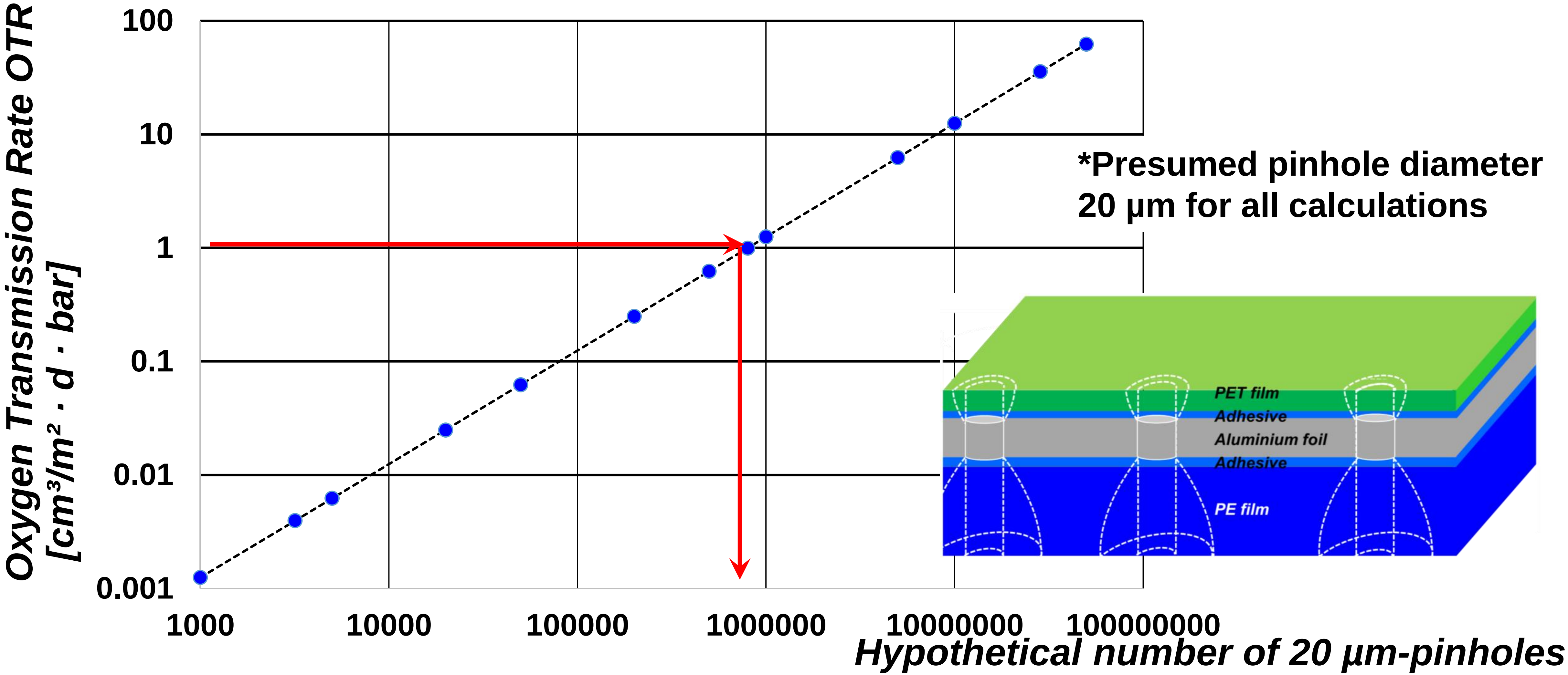
		OTR	1/OTR
	µm	cm³/d·m²·bar	
PET	12	65	0,0154
Adhesive	3	314,2	0,0032
Pinhole			0
Adhesive	3	314,2	0,0032
LLDPE	75	1600	0,0006
Area of pinholes in the foil		44,6928	0,022375

		OTR	1/OTR
	µm	cm³/d·m²·bar	
PET	12	65,4	0,0153
Adhesive	3	314,2	0,0032
PET_{met}	12	1	1
Adhesive	3	314,2	0,0032
LLDPE	75	1600	0,0006
Laminate with PET + metallised PET		0,9782	1,0223

Calculation of the oxygen transmission rate through a laminate PET/adh/aluminium foil/adh/LDPE depending on the number of pinholes – Area portion method



Calculation of the oxygen transmission rate through a laminate PET/adh/aluminium foil/adh/LDPE depending on the number of pinholes – Permeator method



Summary

Aluminium foil in flexible packaging laminates has competitors regarding barrier like metallised films, AlO_x- or SiO_x-coated films, barrier polymers or so-called nano-barriers

Aluminium foil provides many advantages over these competitors

- **Best and most complete barrier (true high-performance) at low area (package) cost, even at the presence of numerous pinholes/break-throughs**
- **No barrier loss or retort shock of barrier during retorting**
- **Barrier not affected by sealing**
- **High stiffness even at high temperatures, no softening like plastics**
- **Dead-fold**
- **Excellent heat conductivity for sealing, can be heated by induction to seal**
- **Unsurpassable barrier for light**

Alternative barrier materials will continue to challenge aluminium foil, but foil's combination of beneficial attributes, when needed, will make the use of aluminium even more compelling

Thank you for your attention

Burning questions?

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