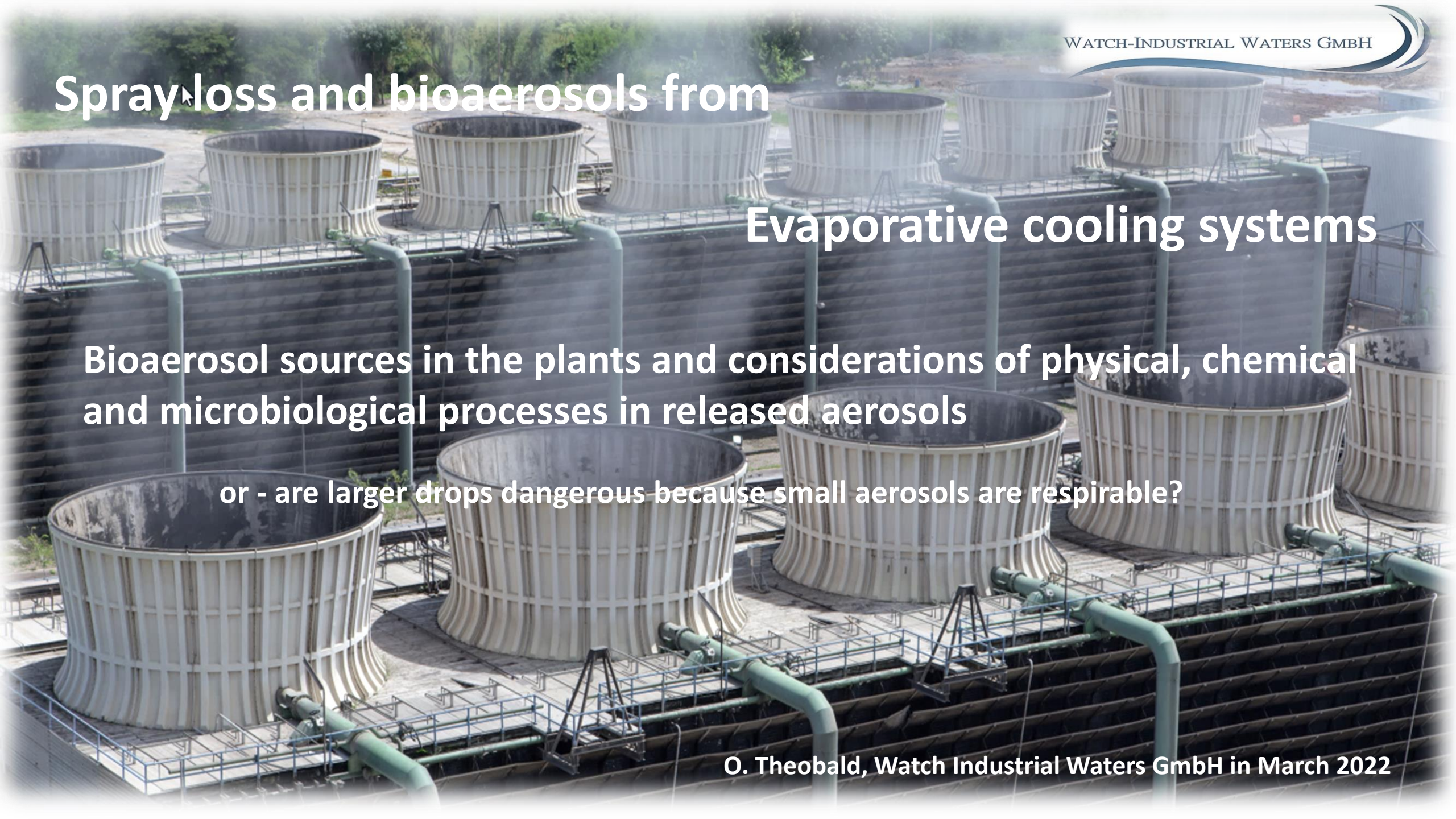
WATCH-INDUSTRIAL WATERS GMBH
Spray loss and bioaerosols from
Evaporative cooling systems
Bioaerosol sources in the plants and considerations of physical, chemical and microbiological processes in released aerosols
or - are larger drops dangerous because small aerosols are respirable?
O. Theobald, Watch Industrial Waters GmbH in March 2022

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Introduction - why considerations on released aerosols

In August 2017, the 42nd Federal Immission Control Ordinance came into force in Germany. This ordinance applies to the construction, condition and operation of facilities in which water is trickled or sprayed or can otherwise come into contact with the atmosphere. It applies in particular to evaporative cooling systems, cooling towers and wet separator systems (wet scrubbers).

All these systems have in common that the closest possible contact between the fluid (usually cooling water, washing water) and the gas (usually air) should be achieved in order to achieve a high degree of efficiency. According to VDI 2047-2 (*Ensuring hygienic operation of evaporative cooling systems; January 2019*), all technologies in which water is fed into an air stream have a tendency to form aerosols. Despite the use of drift eliminators, however, droplets can be carried along by the exhaust air in these systems and enter the environment.

In the plants, there are usually favourable development conditions for microorganisms (constant availability of water, heat, oxygen supply, nutrients, colonisable surfaces for biofilm formation). Since there is constant contact between biofilms and the water body at the water-wetted interfaces of these systems, the water droplets carried along by the exhaust air can also contain high numbers of microorganisms, whereby legionella in particular are to be considered very critical because they can cause very serious lung infections. According to the BioStoffV, **bioaerosols** are airborne liquid droplets and solid particles that consist of or are contaminated with biological agents or their metabolites. Due to their small size (typically 0.1 - 20 micrometres), they are suspended in the air and can be inhaled (*Baua definition).*

In an effort to implement the Ordinance, operators, accredited testing laboratories, water conditioning companies and authorities are paying a great deal of attention to the hygienic quality of the service water (cooling water, washing water), because the Ordinance defines test values and an action value for Legionella spp. for the service water. Less attention was paid to sessile bacteria on water-wetted surfaces, because they are of course not easily detectable analytically. Less attention was also paid to the actual hazard potential, namely the emission situation with regard to the aerosols released in terms of quantity and quality (droplet spectrum, microbiological load) and thus also the potential exposure, associated with the risk of Legionella infection, at possible places of immission. Practically no attention at all was paid to what might happen *in* released aerosols.

In the case of a legionella outbreak last year, it was then also reported that the responsible health department suspected that the evaporative cooling system they were looking for *emitted some kind of invisible aerosol cloud into which these people got caught*. (Source: https://www.swr.de/swraktuell/baden-wuerttemberg/heilbronn/legionellen-im-weisnsberger-tal-100.html). So the idea of releases from such plants is very diffuse.

- What is in such an invisible aerosol cloud? What is being emitted, how are the plumes to be assessed?
- What is the number of (bio)aerosols in an aerosol cloud how many legionella can be in such an aerosol cloud?
- Is it rather the number of aerosols released or their mass, i.e. the total aerosol ejection, e.g. in litres/hour, that is decisive for the risk?
- To what extent is the size of the aerosols (aerodynamic diameter) decisive for the hazard potential emanating from a plant?
- What actually happens in released aerosols, depending on physical, chemical and microbiological conditions?
- What are the "travel conditions" of aerosols?
- Why are only the releases from the water body of such installations considered? Aerosol releases from biofilms, in particular from the installations in the exhaust air area, are not considered?
- What role do protozoa play in this?

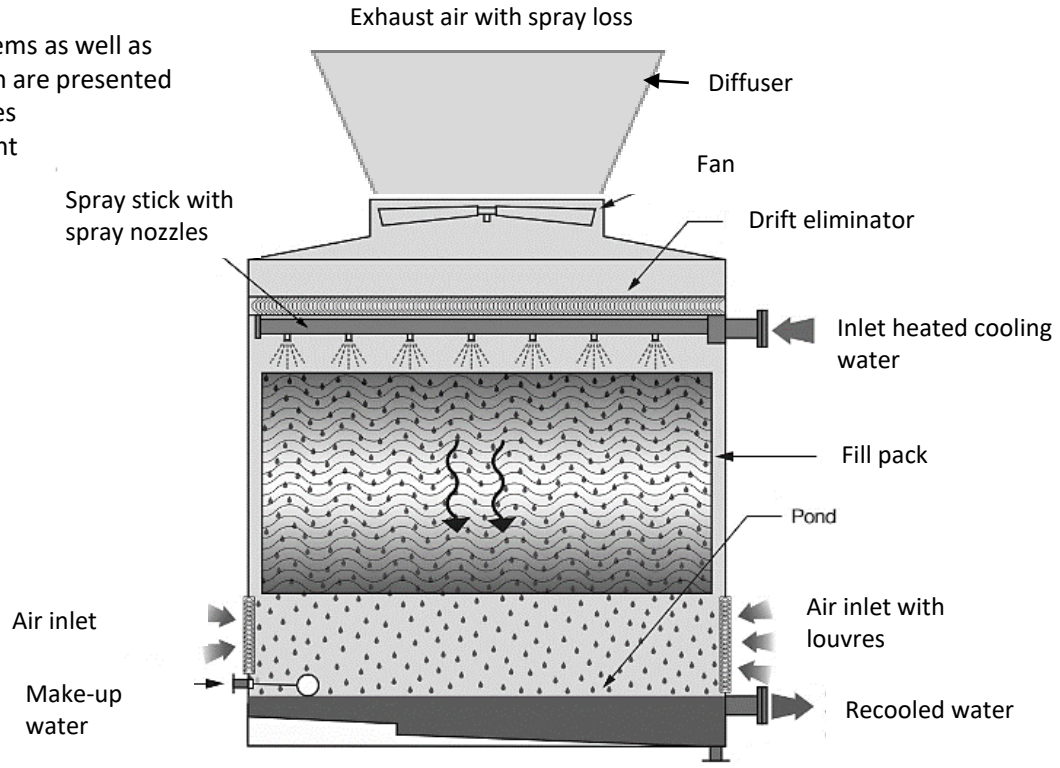
The following explanations are intended to show that, for the hygienic operation of these systems as well as for the infection incidence in the case of legionella outbreaks, the hygienic quality of the cooling water with regard to the concentration of *planktonic* legionella in the service water is not necessarily the decisive assessment criterion for the hazard potential of such a system, but that other factors can be much more decisive under certain circumstances, i.e. that the actual hazard potential does not necessarily result from the treated cooling water!

- what conditions must prevail at the *place of emission for the* aerosols to be respirable at the *place of immission*?
- To what extent does the hazard potential depend on the droplet size and how does the aerosol elimination performance relate to the droplet size?
- what are the bioaerosol sources in such plants and how are they to be assessed in terms of their pathogenic potential?
- what is the influence of meteorological conditions?

The following statements are based on many years of experience from the inspection of evaporative cooling systems as well as from bioaerosol measurements of the exhaust air from these plants. The deductions made and conclusions drawn are presented on the basis of of comprehensible examples. It would be in the interest of the hygienic operation of these facilities and it would therefore be gratifying in terms of infection control if this paper could be disseminated in the relevant professional circles would trigger a further discussion in the sense of optimising hygienic operation.
I have thought for a long time about whether I should put my thoughts, which I have put down on paper below, because to the round of professional colleagues. In the end, I decided to do so because many have certainly already thought about this and perhaps there are other exciting aspects. I am very much looking forward to your criticism.

Fischach, 07 March 2022 - O. Theobald

Notes:
The schematic representation of the refrigeration cell on the right may help to better understand the explanations.
The terms cooling water and process water are to be regarded as equivalent in the designs.
The considerations also apply in the broadest sense to wet separators, insofar as they are equipped with downstream equipment for droplet separation.



Source of sketch (without diffuser and labelling): Health and Safety Executive-Gov. UK

The difference between theory and practice is in the practice far higher than in theory. *Ernst Ferstl*

Known facts, which must be put first for consideration

First of all, a few facts that should be briefly recalled in order to understand the further explanations.

The actual hazard potential of these systems is hardly ever (e.g. apart from Pseudomonas aeruginosa) from direct contact with the process water, but from the release of inhalable aerosols, especially those containing legionella, via the exhaust air. Put simply, it is not what is *in* the cooling water that is decisive, but *what comes out through the air*, e.g. the release of legionella in water-containing aerosols. However, the decisive factor in the context of the obligation to ensure the safety of these systems is the legionella contamination in the cooling water. In the meantime, there is a procedure published by the Federal Environment Agency for the routine detection of legionella in air samples. However, such measurements are time-consuming and are rarely carried out. Ultimately, this is one of the reasons why the ordinance specifies the results of the service water samples as an assessment criterion, from which the emission situation is then indirectly concluded. However, VDI 2047-2 states (rightly) in Note 2: "There are currently no standardised procedures for testing for the presence of legionella in aerosols. At present, a correlation between legionella concentrations in the cooling water and in the exhaust air is not known". Why is this so?

The reasons for this can be found above all in the publications of Prof. Dr. Wurz, some of which have also found their way into VDI Guideline 3679-3. The emerging droplets are differentiated into primary, secondary and recondensation droplets depending on their origin. Due to typical interaction mechanisms with cooling tower internals (e.g. drift eliminators), these droplet types can have specific concentrations of microorganisms.

Planktonic and sessile bacteria - Biofilms

In the introduction it was already pointed out that in evaporative cooling systems there are usually quite favourable conditions for microorganisms to multiply because colonisable surfaces are available to a large extent for the formation of biofilms and, in addition, there is a fairly constant supply of heat, nutrients and moisture.

With regard to colonisation, a distinction must be made between *planktonic* and *sessile* microorganisms. Planktonic microorganisms (*plankton* Greek "the wandering", "the drifting") are "floating" in free (useful) water, with little or no movement of their own in free suspension. Sessile (sessile) microorganisms live at the *interfaces*, i.e. on water-wetted surfaces. They form EPS (Extracellular Polymeric Substances), the most essential component of biofilms, along with several other components. Bacterial densities in biofilms can be very high (up to 10^{11} per millilitre or gram wet weight), i.e. even 1 millilitre of biofilm can contain more bacteria than the entire cooling water volume of an evaporative cooling system. As a rule, the bacteria found in biofilms make up >95% of the total population, i.e. the planktonic bacteria play a subordinate role with regard to the total population. The accredited laboratories determine *only* plantonic bacteria in the examinations according to the 42nd BImSchV (as long as biofilm particles or sediments do not get into the sample due to incorrect sampling).

The biofilm protects the bacteria from biocides or harsh environmental conditions. For Legionella, association with other microorganisms is particularly important, as they are probably not able to produce all essential amino acids themselves. In biofilms, a predator-prey relationship usually develops between bacteria and protozoa. Incorrect or insufficient use of biocides can result in only the more biocide-sensitive protozoa (bacterial predators) with their long generation times and not the bacteria with their comparatively short generation times being damaged or eliminated.

According to literature, the biofilm also provides contact with amoebae, which allegedly play an important role in the reproduction of legionella (legionella can reproduce inside the cells of free-living amoebae and are thus facultative **intracellular** parasites. (Source: RKI)**.** Under unfavourable growth conditions, amoebae can form so-called cysts which, with their thick cell wall, offer enormous protection against any biocide treatment. Amoebae can also secrete vesicles. If Legionella are in amoeba cysts, they benefit from this protection and can thus survive biocide-containing water or be transported in air over long distances. It cannot be ruled out that amoeba vesicles can also provide some temporary protection.

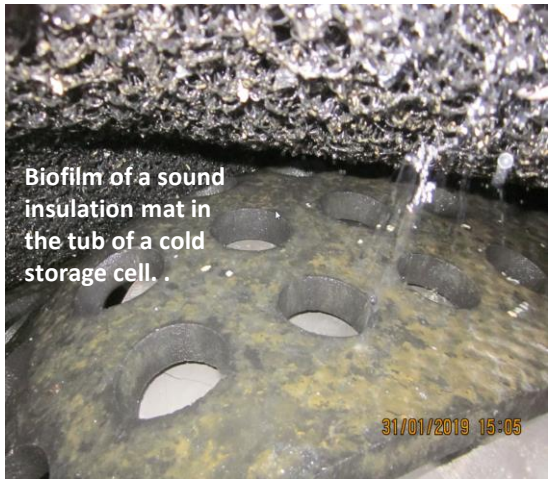
According to information from the RKI https://www.rki.de/DE/Content/Infekt/EpidBull/Merkblaetter/Ratgeber_Amoebenkeratitis.html, it is known that acanthamoebae can harbour a large variety of bacteria and viruses. This relationship is even essential for the spread of legionellosis.

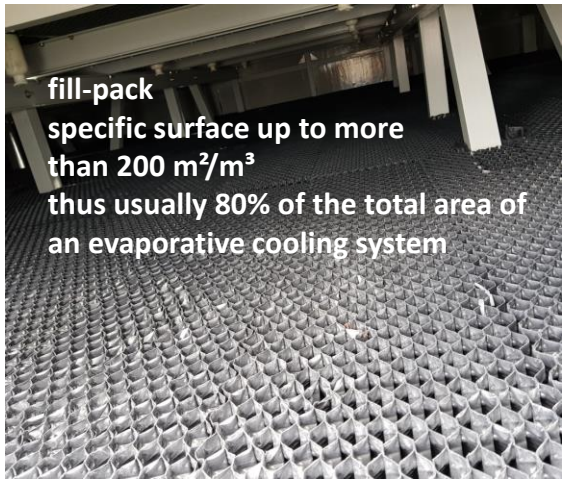
Due to the situation in biofilms and sediments, and above all as a fundamental prerequisite for Legionella to be able to multiply intracellularly in amoebae, amoebae must find favourable growth conditions in such systems, at least temporarily. However, there are hardly any studies on the number of amoebae in cooling water or in biofilms of evaporative cooling systems. At least for river water I was able to find quantitative data: Michel et. al. (1995) were able to detect 10,000 amoebae per litre in river water used for groundwater recharge (*Source: Biology Centre Linz/Austria; 17.09. 2004) Occurrence of free-living amoebae and infections with free-living amoebae in Austria; J. Walochnik*).

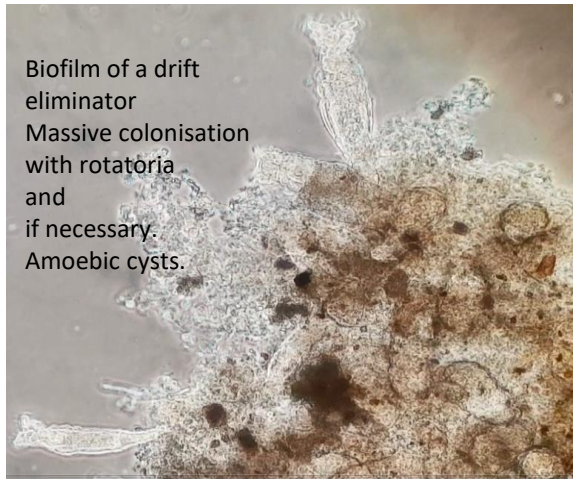
Since most microorganisms cannot be expected to multiply in the free water body, surfaces are required. In terms of colonisable boundary surfaces, the **fill pack** with an inner surface of >200 m²/m³ is usually by far the highest growth surface in these systems. In evaporative cooling cells with a capacity of e.g. about 1.5 MW, the packed surface can easily amount to 3000 m². Even if the biofilm thickness of 1/100 mm is assumed to be extremely thin (practically undetectable by sensory means), this results in a total mass of biofilm on the packing of 30 litres or approximately 30 kg, in which an enormous number of bacteria can be found with a colonisation density of up to 10^{11} CFU/ml!

If efficient use of biocides successfully prevents biofilm growth on the packing surface and thus also in heat exchangers, another component remains which, under certain circumstances (which will be described below), is excellently suited for bacterial colonisation - the **drift eliminator.** For a system of the aforementioned capacity, a potentially colonisable surface of about 200 m² can be assumed. In contrast to the packing, bacteria in the drift eliminator are hardly exposed to biocide. The danger of drying out is rather the limiting factor here.

Since the component „drift eliminator" plays a very decisive role in the hygienic operation of a system, it is examined in more detail below.







Drift eliminator- boundary droplet, primary and secondary separation

In evaporative cooling systems, the cooling water is sprayed as finely as possible and evenly over the surface of the fill packing or trickling bodys for optimum thermal efficiency. For hygienic reasons, however, the release of these spray droplets should be reduced to a technically possible minimum. For this reason, a drift eliminator is installed above the water distribution system to separate and return the water droplets carried along with the air flow. Apart from any silencers that may be present, the drift eliminator is thus the last instance before the exhaust air leaves the system. Whereas *in the past*, when legionella was still unknown in this country*, the focus was on* reducing the discharge of cooling water treatment chemicals that were harmful to vegetation (see Held, Kühlwasser, Vulkan-Verlag Essen, 1984 - page 518; chromates), today the focus is on reducing bioaerosol emissions. Very detailed explanations on the technology of droplet separation can be found in VDI Guideline 3679-3.

The performance of drift eliminator in terms of reducing droplet ejection is considerable. Without a drift eliminator, the ejection can amount to more than 0.1% of the circulating water volume (see Held page 518). With modern drift eliminators, a separation efficiency of 0.01 to 0.0005% of the circulating water volume can be achieved. Testing/certification of the separation efficiency according to the US American standard *CTI ATC-140 is* carried out in Europe by Eurovent. The performance data for drift eliminators are therefore based on the CTI ATC-140 test method (Isokinetic Drift Test Code) and are intended as guide values. The separation performance of the drift eliminator is understood to be the ratio of droplet ejection/water flow (in % of the circulating water volume). The measurements are carried out at a defined rain density of 20 m^3/m^2h and an approximate average air velocity of 3 m/s.

In order to achieve such separation efficiencies, the drift eliminator elements must be installed over the entire surface with absolutely no gaps. The droplet load point velocity must not be exceeded at any point of the drift eliminator and the flow profile must be as uniform as possible across the cross-section.
Baffle (lamella) drift eliminators which are most commonly used for evaporative cooling systems are inertial separators.

Primary separation:
Drift eliminators use the higher inertia of liquid droplets compared to the lower inertia of the gas (air) carrying them. In evaporative cooling systems, the aerosol-laden air is guided through installations in which the flow direction of the air is deflected several times. The liquid droplets cannot follow these changes in direction, which is why they collide with the internals and settle there. The drops are thus deposited on the baffles due to their mass. Therefore, a minimum velocity is required to make the inertia effect work. The separation performance initially improves as the flow velocity increases until the droplet rupture velocity (droplet load point velocity) is finally reached.

The separation and elimination efficiency depends on the droplet diameter. Those droplets which, under given conditions, just come into 100% contact with the profile wall and form a liquid film there are referred to as **limiting droplets** $d_{99,5}$, i.e. the droplet size for which the separation efficiency just becomes 99.5%. According to VDI 3679-3, the theoretical limiting droplet is thus defined as the droplet that just makes contact with the lamellae even in the most unfavourable starting position at the inlet, e.g. of a lamella (baffle) eliminator, and with an approach direction orthogonal to the inlet plane. Smaller droplets that start from a more favourable position than $d_{99,5}$, i.e. closer to the lamella, can naturally reach the wall, i.e. also be separated.

Droplets with a diameter smaller than the limiting droplet are no longer quantitatively primarily separated. Due to inertial separation, large droplets are therefore separated better than small droplets.

The limiting droplet diameter for vertical-flow lamella (baffle) eliminator is specified in VDI 3679-3 as 15 - 40 µm (see also table - page 17).

Diagramm 1: Abscheidegrad in Abhängigkeit von der Anströmgeschwindigkeit

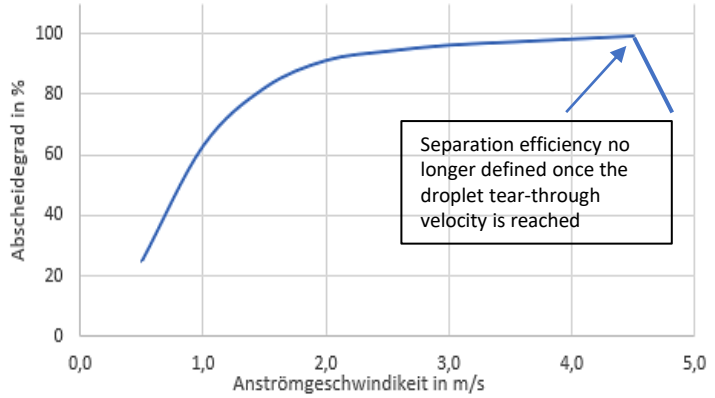


Diagramm 2: Fraktionsabscheidegrad bei einer günstigen Anströmgeschwindigkeit

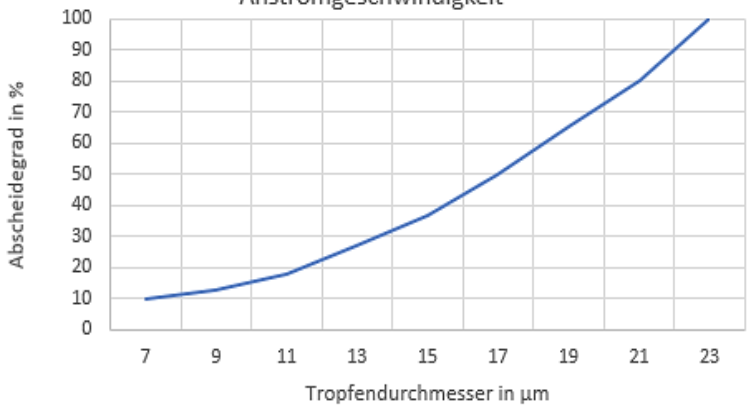
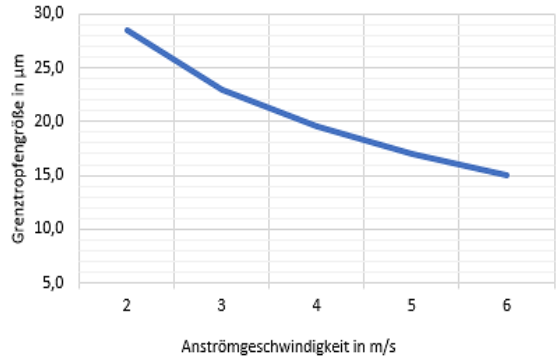


Diagramm 3: Grenztropfengröße in Abhängigkeit von der Anströmgeschwindigkeit des TA



The graphs show the dependence of the aerosol separation efficiency on various parameters (face velocity, droplet diameter, size of the boundary droplet). The numerical values given are only to be understood as "approximate" and orienting. They must be determined individually for a specific drift eliminator. As the following explanations will show, every operator should have the specific performance data of the installed drift eliminator available for his system and this should be checked within the framework of risk assessments according to §3(4) or expert inspections according to §14 of the 42nd BImSchV.

Restrictions on separation efficiency:

- Reduced surface tension (biodispersants) can have an influence on the separation efficiency.
- a hydrocarbon load of > 1 ppm in the cooling water can also impair the separation performance.
- in the case of completely new drift eliminators, the plastic surface is hydrophobic, which can also impair the separation performance.
- The elimination efficiency of old drift eliminators decreases. The hydrofiling of the surface, which also increases in the process of ageing, may change the drainage behaviour and possibly favour the possibility of colonisation by microorganisms.

With efficient drift eliminators, residual mist contents of < 75 mg/m³i$_{.N.f.}$ can be achieved in the exhaust air, as described in VDI 3679-3, which is usually equivalent to an ejection of about 0.01% of the circulating cooling water volume.

Legionella are to be expected in the droplet fraction with diameters > 1 µm (source: UBA-UFOPLAN "Entwicklung eines sensitiven Verfahrens zum routinemäßigen Nachweis von Legionellen in Aerosolen von Verdunstungskühlanlagen").

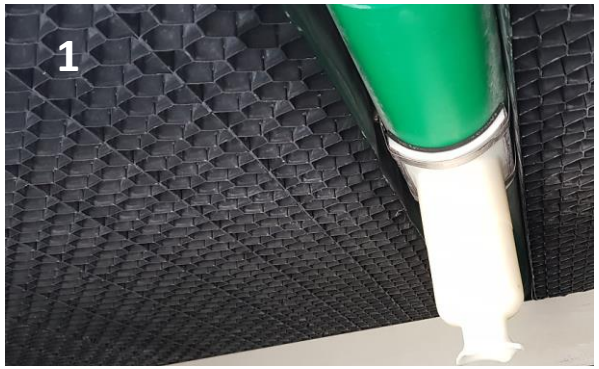
Secondary separation - dewatering of the drift eliminator

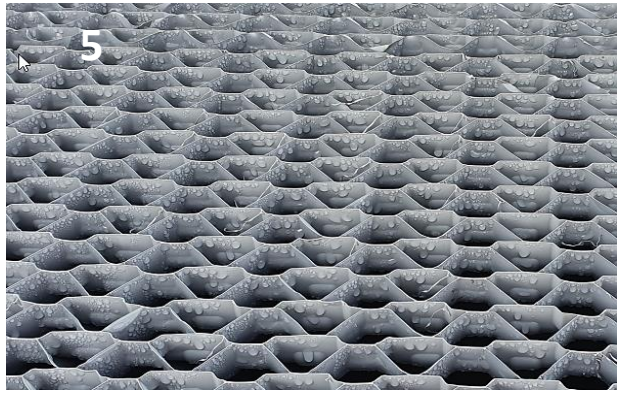
VDI 3679 states: "The design of the mist eliminator must be such that the liquid film that forms on the profile wall as a result of the primary separation is discharged from the air flow. In vertically flowing lamella (baffle) eliminators, the liquid film must be discharged downwards out of the eliminator system against the air flow When the tear-through velocity is exceeded, even smaller drops are primarily caught by the separator lamella, but the drainage of this liquid is no longer possible. As a result, the eliminator fills up more and more with liquid, which leads to secondary droplets being removed and carried to the clean gas side. The drift eliminator then acts as an agglomerator". The more perfectly the secondary separation succeeds, the better the overall separation efficiency of the drift eliminator".

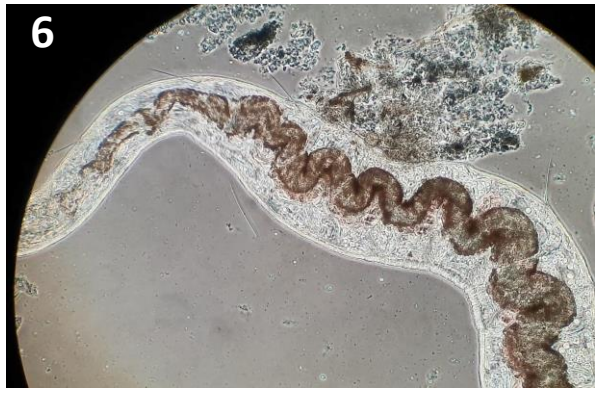
Since the drift eliminator is located above the trickling or rainfall area, the biocide in the cooling water does not reach it, or only insufficiently via the spray (drift) loss. The biocide concentration in the area of the drift eliminator surface is therefore usually below the MHK or MMK, while at the same time the depletion is high. The liquid film on the drift eliminator, which can also partly result from condensate, leads to the fact that e.g. pollen and other particles in the air are also separated according to inertial separation. As a result, permanently damp surfaces or surfaces covered by a liquid film are created with a high nutrient supply. Largely uninfluenced by biocides added to the cooling water, an unknown specific biocoenosis develops here, which in addition to bacteria can also include protozoa and amoebae.

Picture examples:

1) Absolutely hygienic drift eliminator;
2) Old, partially destroyed drift eliminator with dried biofilm;
3) Very heavily slimed drift eliminator, spray nozzles above, with very poor spray pattern;
4) Mineral deposits on the exhaust air side of the mist eliminator resulting from the minerals of the spray loss. If applicable, droplet rupture on the clean gas side;
5) New drift eliminator of an evaporative condenser. Still scrupulously clean, but a lot of condensate on the exhaust air side.
6) Nematode infestation with high density of free bacteria







Swath

The *vapours* that become visible in cooler weather result from the condensation of the escaping gaseous water vapour in the colder air (water-saturated air dew point undershot fog formation). Since it is condensate, these vapours are predominantly free of the minerals and bacteria of the cooling water. However, the plumes are interspersed with aerosols of spray loss, which contain the ingredients of the cooling water (minerals, organic ingredients and also bacteria).

According to literature data, light wetting fog to dense fog are aerosols with a droplet size of 10 to 40 µm.
According to VDI 3679-3, Table 1, this corresponds (coincidentally) quite exactly to the largest fraction of aerosols released with an intact drift eliminator from the cooling water!

The swath can serve as a *rough* estimate of the radius at which water-containing aerosols can occur under given meteorological conditions at the time of observation. From the distance where the plume dissolves, the aerosols of the primary droplets from the cooling water (see page 14) will also have largely evaporated (due to mineralisation, however, the process for the aerosols of the primary droplets will be somewhat different and somewhat delayed - see pages 20 and 21).

Swath of an evaporative cooling system
Source: Wikipedia

The droplet spectrum generated by spray nozzles in an evaporative cooling system

According to VDI 3679-3, "Drops above approx. 10 µm are usually called sprays, drops below that are usually called aerosol or mist drops. While spray is formed almost exclusively by mechanical atomisation of liquids, aerosols are very often also formed by condensation of gaseous components as a result of cooling of the gas phase".

The spray pattern by atomisation depends not only on the viscosity of the medium and the geometric shape of the spray nozzle, but above all on the opening diameter of the nozzle and the spray pressure. Basically, according to general life experience in garden watering: low pressure and large opening = large drops - and high pressure and small opening = small droplets. For example, for a droplet size of 18-25 µm, the technical documentation of a nozzle manufacturer states: Nozzle bore 0.15 mm; ideal pressure 20 to 100 bar; flow rate 3 l/h.
In conventional evaporative cooling systems, considerable amounts of water are sprayed over the packing. At a rain density of e.g. 15 m^3/m^2h, generated e.g. via 9 spray nozzles per m^2, 28 litres/min of cooling water must be sprayed via each nozzle. In order to be able to spray such a quantity at a typical upstream pressure of 0.6 bar at the nozzle block, the nozzle diameter must not be too small (apart from the fact that the susceptibility to clogging would become a problem if the nozzle diameter were too small).

Spray stick (somewhat corroded) with spray nozzles. Above drift eliminator below packing.

If the droplet diameter is too small, part of the spray mist would not reach the packing at all, but would be carried along by the air flowing upwards in countercurrent. The droplet sizes produced will therefore range from a minimum of "fine" to "medium" and "coarse", i.e. in the range of 100 to > 500 µm. It cannot be deduced how very fine drops (<50 µm) and finest drops (<20 µm) should be produced at the low spray pressure in the evaporative cooling system.

The droplet spectrum of primary droplets generated due to the spraying (see page 14) is actually intercepted quite well by the drift eliminator. (With regard to the droplet size produced, there is also a certain dependence on the surface tension of the service water (biodispergator!).

Note: The situation is somewhat different with hybrid and especially some adiabatic systems. In these systems, a spray pattern with very fine or very fine droplets is usually generated (high spray pressure required) in order to realise the complete evaporation of these droplets in a relatively short air passage and thus to generate the adiabatic cooling of the supply air.

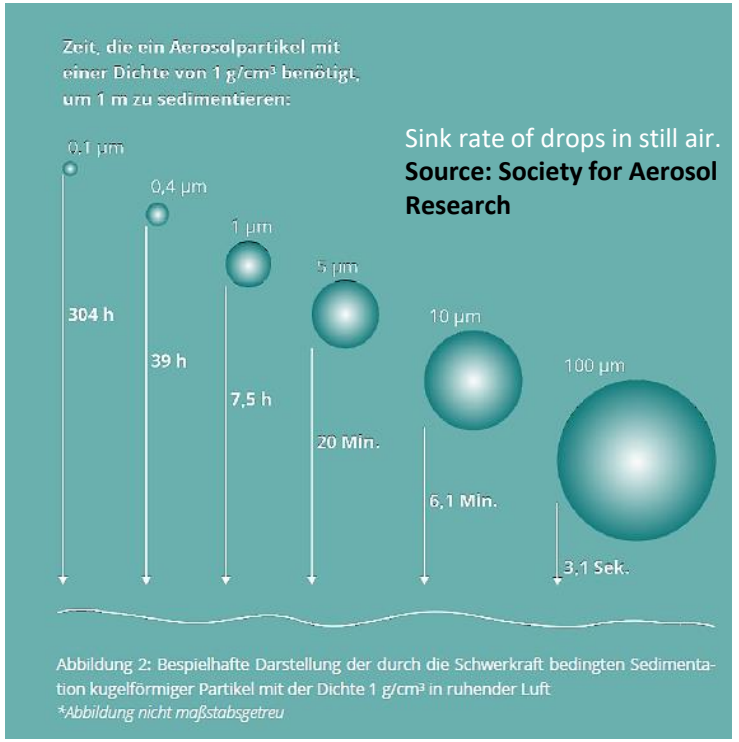
Considerations on physical, chemical and microbiological processes of released (bio)aerosols

For an exposure to bioaerosols containing legionella, associated with their inhalation and, possibly, an infection as a consequence, it is necessary to consider, in addition to the emission situation described above, which physical, chemical and microbiological processes can take place in aerosols from the place of release to the place of immission. Here again, a differentiation must be made between primary droplets and secondary droplets (see page 14). If aerosols containing legionella are released via the exhaust air of these plants, it depends on many factors whether there is a risk of exposure to respirable aerosols in the possible immission area. There are somewhat divergent statements in the literature on the respirable nature of the pathogens (is respirable in the thorax sufficient for infection or is respirable in the alveoli a mandatory prerequisite). Typical aerosol diameters characterised by their inhalability are therefore given from < 20 to < 5 µm.

It is shown that the possible immission range depends not only on meteorological conditions but also on which aerosols are emitted (aerodynamic diameter, microbiological composition, chemical composition, water content). Since air does not serve microorganisms as a habitat but only for locomotion and legionella are very sensitive to dehydration, the environmental conditions in the medium air play a major role for the transport of bacteria as well as for the risk of exposure. The main influencing factors are:

- the *aerodynamic* diameter of the aerosol released (is defined as the diameter of a sphere with the *normalised* density of 1 g/cm³). Depending on the mineralisation of the cooling water, the aerosol density increases in the course of evaporation. However, these density changes can be neglected for these considerations.
- the evaporation rate as well as the sink rate
- the concentration caused by evaporation (thickening)
- the increase in hygroscopicity and desiccation
- meteorological parameters (relative humidity, temperature, radiation power of the sun, wind speed)
- Not considered are electrostatic effects, coagulation and interception of particles as well as the
- Form factor with respect to the aerodynamic diameter. Aerosols are formed due to the initially high water content and thus the surface tension is assumed to be largely spherical. The deviating aerodynamic behaviour of non-spherical biofilm particles compared to the aerodynamic behaviour of spherical particles of the same mass cannot be recorded.

It will be shown that for the aerosols released from evaporative cooling systems, the **evaporation rate is** the most important factor. and the resulting **thickening** are the essential factors. If the gravitational force is the decisive variable and thus the
If the descent rate is the decisive factor for the elimination of the aerosol from the air by deposition, this mostly takes place in the in the immediate vicinity of the plant. For aerosols of this magnitude, see pages 22 and 23.



Sink rate of drops in still air.
Source: Society for Aerosol Research

Abbildung 2: Bespielhafte Darstellung der durch die Schwerkraft bedingten Sedimentation kugelförmiger Partikel mit der Dichte 1 g/cm³ in ruhender Luft
**Abbildung nicht maßstabsgetreu*

Table on the right:
Rate of descent of aerosols. Source: Aerosolfysik-I; VL-Dr. W. Hofmann; script compiled by P. Madl

Terminal settling velocity, uncorrected and slip corrected, Cunningham slip factors, and root-mean square Brownian displacement for various diameters of unit-density (1g/cm³) spherical particles. Adapted from tables for use in aerosol physics, BGI Inc. 1971

Particle diameter [µm]	Cunningham slip correction factor	Sedimentation velocity [cm/sec]	Corrected sedimentation velocity [cm/sec]	rms Brownian displacement [cm/sec]
0.01	22.2	$3.01 \cdot E^{-7}$	$6.69 \cdot E^{-6}$	$2.23 \cdot E^{-2}$
0.05	4.97	$7.53 \cdot E^{-6}$	$3.74 \cdot E^{-5}$	$6.84 \cdot E^{-3}$
0.10	2.87	$3.01 \cdot E^{-5}$	$8.63 \cdot E^{-5}$	$3.67 \cdot E^{-4}$
0.50	1.33	$7.53 \cdot E^{-4}$	$1.00 \cdot E^{-4}$	$1.11 \cdot E^{-4}$
1.00	1.16	$3.01 \cdot E^{-2}$	$3.50 \cdot E^{-4}$	$7.40 \cdot E^{-4}$
5.00	1.03	$7.53 \cdot E^{-2}$	$7.77 \cdot E^{-2}$	$3.12 \cdot E^{-4}$
10.00	1.02	$3.01 \cdot E^{-1}$	$3.06 \cdot E^{-1}$	$2.19 \cdot E^{-4}$
50.00	1.00	7.29	7.31	$9.72 \cdot E^{-5}$
100.00	1.00	$2.48 \cdot E^{1}$	$2.48 \cdot E^{1}$	$6.87 \cdot E^{-5}$

On the rate of descent of aerosols

the sink rate is not a constant, but very often decreases because of the decrease in mass due to evaporation. The Cunningham slip factor and Brownian molecular motion do not play a significant role in the size of the hygiene-relevant aerosols emitted by evaporative cooling systems (> 1 µm). Up to a certain droplet size, the possible elimination of the droplets by sedimentation and deposition also plays a very minor role. Primary droplets from plants with faultless droplet separation technology will have evaporated to a certain *residual size* (see page 22) before they are eliminated from the environment by sedimentation at some point with a very low rate of descent, as an anhydrous residual aerosol.

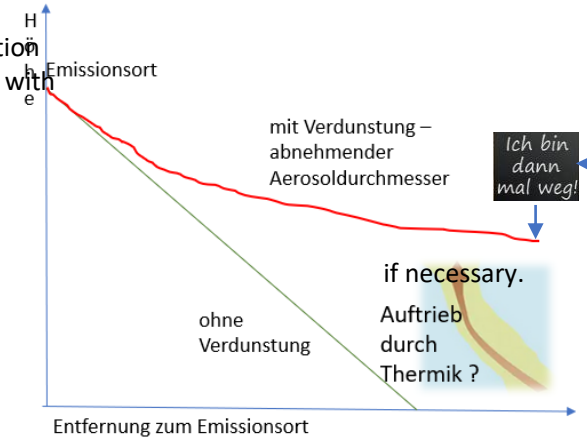
In certain weather conditions (morning fog, November fog, inversion, frost, freezing of aerosols or freeze-drying of aerosols), the conditions may be different as described below. According to the LANUV and the University Hospital Bonn (outbreak management of the Legionella outbreak in Warstein 2013), most of the documented outbreaks occurred during the warmer months of spring, summer and autumn, so that inversion, freezing or freeze-drying cannot have played a role.

Due to morning fog and associated very high humidity (but mainly near the ground), the emitted aerosols can act as condensation nuclei, with corresponding effects = decrease in evaporation rate, increase in sedimentation rate.

Aerosol elimination through evaporation

Vertical sedimentation velocity decreasing with mass loss

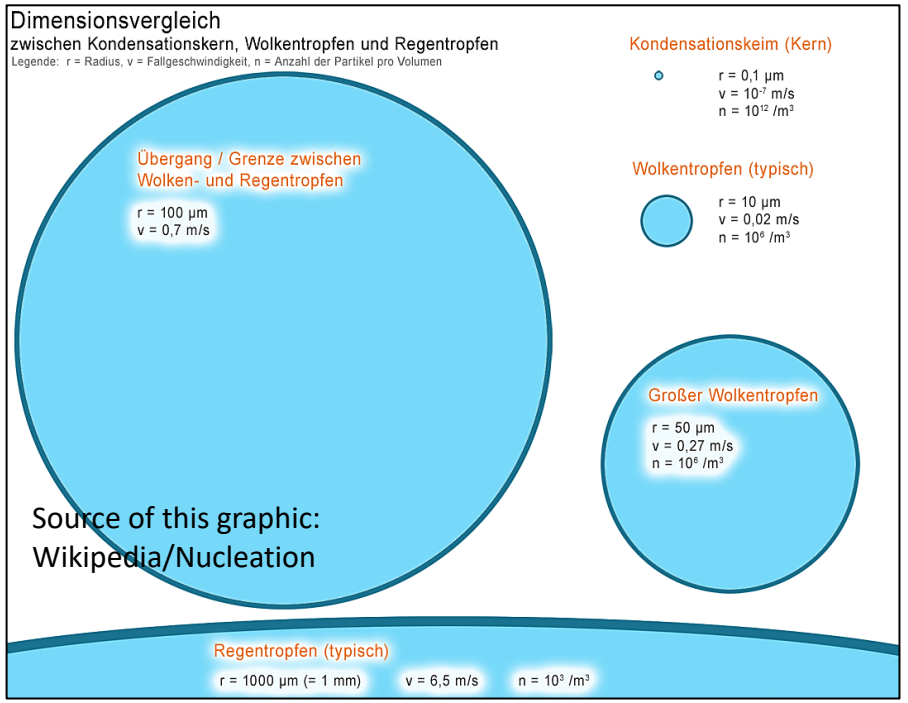
If necessary, lift through thermals



Horizontal speed = wind-dependent

important: of course, this only applies to aerosols made of water <u>without</u> any ingredients.

With ingredients, the situation is clearly different - see pages 21 to 22.



On the evaporation rate of aerosols

According to the Society for Aerosol Research, the evaporation process of aerosols was already described by Wells in 1934 *(source: Society for Aerosol Research; position paper on understanding the role of aerosol particles in the SARS-CoV-2 infection process and Wikipedia - Wells curve).* The aerosols thereby dry and shrink at a rate that depends on the particle surface as well as the air temperature and especially the relative humidity. For particles of the same composition, smaller particles evaporate faster due to the larger surface-to-volume ratio. **For the droplet fraction, below the boundary droplet, i.e. for very small droplets (< 40 µm), there are usually very short existence times of a few seconds, i.e. the smaller the droplets, the more difficult they are to separate, but the faster they usually evaporate.**

Especially with larger droplets, the evaporation rate may be reduced because the droplets are not stationary and are circulated by the air, but travel largely isokinetically in the air flow. This means that the water vapour saturation in the immediate vicinity of the droplets will be somewhat higher and therefore the evaporation rate will decrease. With increasing thickening, the increasing hygroscopicity then also plays a limiting role for further evaporation (see page 21 for this). For aerosol diameters up to the size of the limiting drop, these effects should not play a significant role. Larger droplets (from about > 100 µm) are usually not considered for other reasons (see page 22), so that the reduced evaporation rate does not play a role anyway.

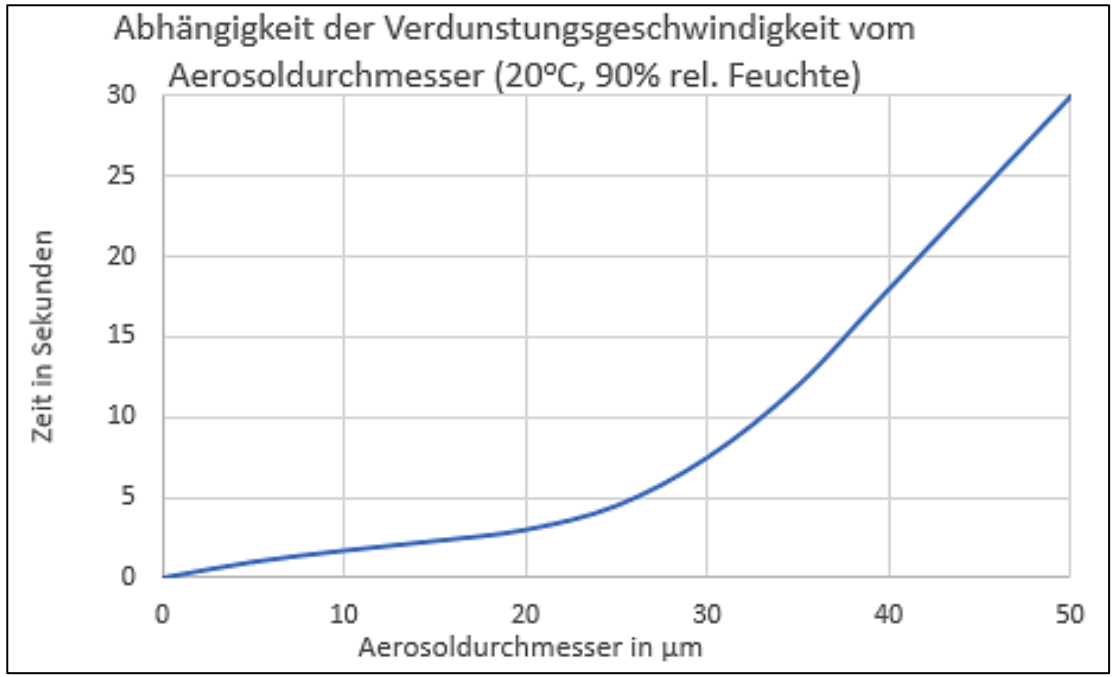


Figure above: ratio of evaporation rate to aerosol diameter derived from various literature sources.

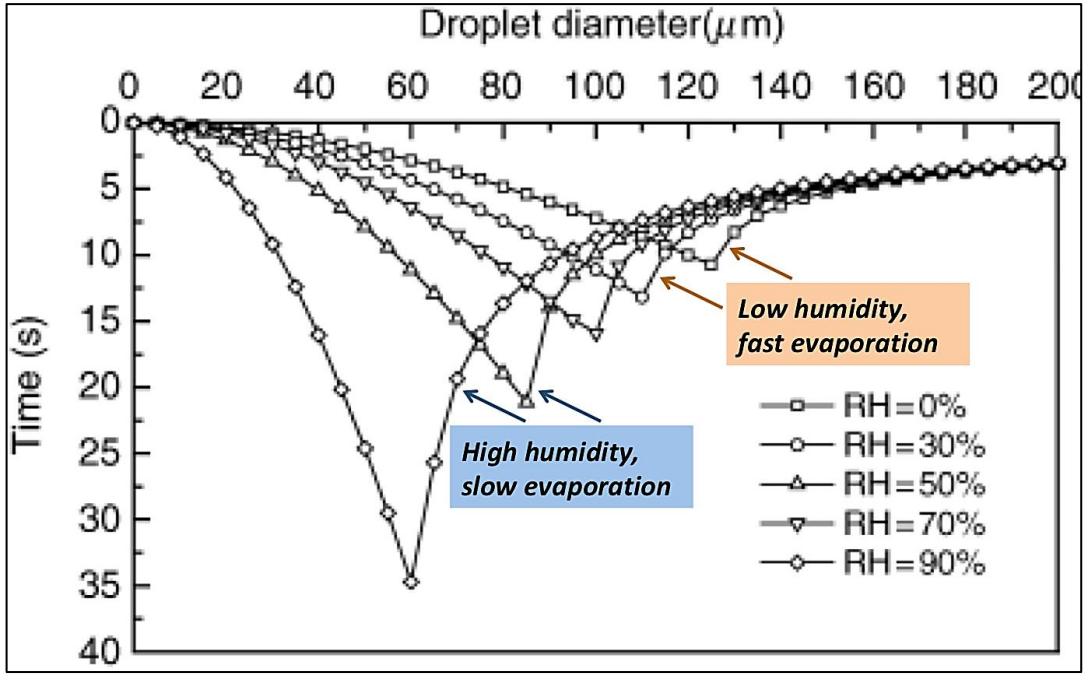


Image above: Evaporation rate Wells diagram (source Wikipedia)

Bioaerosol emission sources

Before turning to the processes in released aerosols, one must consider the possible aerosol sources in such water-bearing systems, i.e. which release possibilities can occur at all from such systems and what this can mean in terms of germ load but also the fate of the respective bioaerosols.

With regard to the emission sources, a distinction must be made between **primary droplets and secondary droplets.** VDI 3679-3 also refers to this. However, the original definition with extensive considerations comes from **Prof. Dr. Wurz.** According to his explanations "Drops, emissions from microorganisms, wet cooling towers - VDMA lecture 16.06.2016, a differentiation is made between primary and secondary drops as follows:

Primary drop
"Primary droplets originate from the sprayed cooling water, which were able to pass through the cooling tower internals and the drift eliminator *without* coming into contact with the wall. As an aliquot of the cooling water, the microbial load (species) of the entrained cooling water droplets is identical to that of the cooling water". VDI 3679-3 states: The main source of emissions of germs (e.g. Legionella) are not the droplets from the circulating water, which can be well controlled by conditioning, but those germs that multiply dramatically during long dwell times in a liquid recirculation zone in the area of the fan and diffuser".

Emitted *primary droplets* thus originate directly from the service water and have left the system without further wall contact with system parts. Since the process water is usually treated in the sense of hygienic operation and in accordance with the specifications of the VDI guideline and the 42nd BImSchV, it is often of perfect to acceptable hygienic quality, which then also applies to the emitted primary droplets.

Secondary drop
Prof. Dr. Wurz refers to secondary droplets as those "resulting from **impact interaction of** the cooling water droplets (primary droplets) with surfaces in the cooling tower that are covered with biofilm (partly highly viscous liquid films with very high microbial load due to a long residence time). The microbial load of the secondary droplets can be 10^4 - 10^6 CFU/ml greater than that of the cooling tower circuit water. 1% mass fraction of the secondary droplets in the total droplet emission can be decisive for the germ emission!" To illustrate this with a more drastic example: if you clean the walls of a slaughterhouse with a high-pressure cleaner powered by drinking water, you have less to fear from the primary droplets from your device than from secondary droplets that are reflected back from the walls.

In evaporative cooling systems, the surfaces from which secondary droplets can be released are the installations in the exhaust air area (fan(s), exhaust air silencer, diffuser), but in **terms of area**, **the drift eliminator are the most important.** In the areas where light penetrates and where mosses/lichens still persist despite partly high air flow velocities, we could mostly find a high density of (small) protozoa in microscopic examinations, but (perhaps because of the protozoa) only a low bacterial density. This also applies to the growth on exhaust air silencers. In laboratory tests of eluates (sterile water adjusted to 2000 µS/cm with NaCl + 0.05% Tween 80) no legionella were detectable. The author of the report interpreted this to mean that the habitat is obviously not suitable for Legionella, especially since Legionella, with their long generation times, do not recover from the feeding of protozoa as quickly as other bacteria.

Deposits in the fan area
Diffuser

Other sources of (bio)aerosols: In principle, germs can be emitted from all surfaces that are in the air flow and that are permanently covered with a water film and can thus be afflicted with biofilms, if the forces of the air flowing past are greater than the adhesion forces of the bacteria on whose structures they live. In evaporative cooling systems with speed-controlled fans, for example, changes in the air flow rate or changes in the thermal load can lead to changes in the relative humidity of the exhaust air and thus to (partial) drying of the EPS of the biofilm, especially in the area of the drift eliminator. In the process of drying out, the biofilm loses its (mechanical) stability and the following occurs.

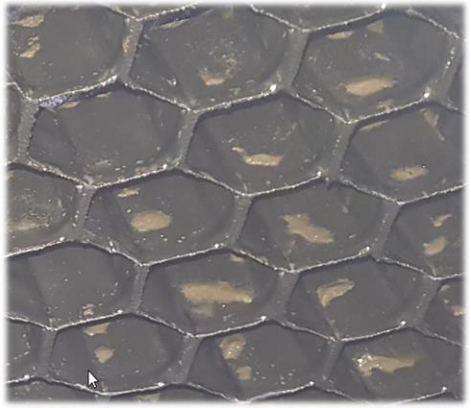
Discharge of biofilm particles, which are not yet completely dry in this phase. Even if evaporative cooling cells are temporarily taken out of operation, depending on the air flow conditions, releases can occur from the area of the drying packing surface and the surface of the drift eliminator. Even without these processes, biofilm mass can be released due to the dynamics in biofilms (build-up, degradation).

Poorly draining drift eliminator with floating droplets

As also stated in VDI 3679-3, liquid droplets that touch the surface of the drift eliminator lamellas on their way through the eliminator ideally form a liquid film there and are then considered to be primarily separated. However, this primary separation is not the end of the separation process. Secondary separation is still required to drain the drift eliminator. The more perfect this succeeds, the better the overall separation efficiency of the drift eliminator. However, dewatering the drift eliminator can be difficult,

especially in evaporative cooling systems with adjustable fans, i.e. variable air output. The phenomenon of floating droplets may form (see picture on the right, centre). Extremely high germ densities can occur in these water films and drops. If the fan power is increased, the water film may break off, so that droplets with a very high bacterial load are discharged via the exhaust air. Since primary droplets are predominantly deposited in this area by impaction, these impact interactions with this water film lead to the formation of the secondary droplets described by Prof. Dr. Wurz.

Biofilm in the drift eliminator with extreme bacterial load. If this load is flushed into the cooling water during heavy rain, this can, at least temporarily, significantly increase the bacterial cooling water load and lead to surprising laboratory results.



Poorly draining drift eliminator - floating droplets and thus highly contaminated water - biofilm in the drift eliminator. Extremely high density of bacteria visible under the phase contrast microscope.

Prof. Dr. Wurz: "The germ load of *secondary droplets* can be orders of magnitude higher than the germ load of *primary droplets from the* cooling water after shock interaction of primary droplets with biofilms, e.g. in the drift eliminator".
But even if the forces of the air flowing past exceed the adhesive forces when the fan power is increased, aliquots can be entrained from these droplets.

Packing

Packing areas that are not flowed around by the cooling water due to a poor spray pattern (e.**g. clogged nozzles)** (see picture on the right) reduce the cooling capacity on the one hand and also pose a risk for the formation of highly contaminated secondary droplets because these areas are mostly saturated with water vapour and moist but are not reached by the biocide.

Especially if the drift eliminator is not intact, there is a risk of biofilm particles being released from areas that are not reached by the cooling water. The exhaust air can be contaminated even if the biocide dosage and biocide effect are flawless and the process water is hygienically flawless according to laboratory reports.

Poorly flowing packing

Removed packing. Dried biofilm with lime. After the water of the EPS has evaporated, little remains in terms of mass. End of an unknown biocoenosis, which was perhaps even hostile to legionella due to numerous protozoa. However, the presence of (legionella-containing) amoebic cysts is just as unlikely.

The bacterial load of secondary droplets as well as those from other sources is therefore hardly reduced by biocides in the cooling water, because these areas are either not washed by the cooling water or, in the case of the drift eliminator, are only reached via spray loss. In this respect, biocenoses can form in these areas, which are fundamentally different from those in the cooling water-wetted area. **In this respect, laboratory analysis of the cooling water does not usually provide any information, e.g. on the condition of the drift eliminator, except in the case of certain events.**

(Heavy) rain events

During heavy rain (especially early summer - thundershowers, hail), the bacterial load of the drift eliminator can be washed into the cooling water.

However, even areas of the tower packing which, as in the picture on the right, are not completely flown through by the cooling water due to clogged nozzles or basically too low upstream pressure for spraying, are then flown through by the rainwater.

Depending on the condition of the drift eliminator and the packing, the bacterial load flushed into the cooling water as a result can be enormous (see example on page 24). Such events often give rise to discussions with the laboratory service providers due to supposedly implausible laboratory results (sudden load without a change in driving style or biocide use).

The problem is that it is not possible to conclude from the knowledge of the legionella contamination in the service water alone that the aerosols discharged with the exhaust air are contaminated with legionella. This means that the assessment of the hygienic risk posed by these systems is also only possible to a limited extent.

In order to assess the actual hazard potential emanating from evaporative cooling systems, it would ultimately be helpful to have a suitable collection and detection method for determining the aerosol discharge as well as for determining Legionella that can be cultivated or detected via PCR (molecular biological live/dead distinction?) in the exhaust air from these systems - see the sections on "*Consequences, measures, need for research and own experience from bioaerosol measurements*" *(page 34).*

The possible scenarios for *primary droplets* released

Case 1: with intact, state of the art, clean, fully laid drift eliminator and *proper* face velocities
i.e. consideration of the fraction from 1 to 40 µm

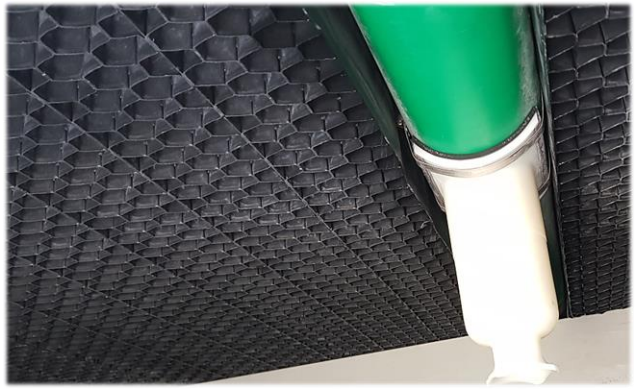
According to VDI 3679-3, Table 1 and Column Primer (Manfred Nietsche, Springer Verlag), a state-of-the-art drift eliminator with vertical inflow can completely separate practically all droplets up to the limiting droplet diameter, so that the drift rate specified for the eliminator refers in particular to the fraction below the limiting droplet size.

Table on the right: Excerpt from VDI 3679-3 "Limiting drop size for slat down divider".

Tabelle 1. Tropfenabscheidertypen und Anhaltswerte für den Einsatzbereich (System Wasser/Luft bei 20 °C und 1013 hPa)

Tropfenabscheidertyp	Anström-geschwindigkeit $v_{A,h}$ in m/s	Grenz-tropfen $d_{99,5}$ in µm	Druck-verlust Δp in hPa	Anwendungsgebiet
Absetzbehälter	0,5–1	> 500		Prozesstechnik, Verdampfer
Lamellen-Tropfenabscheider:				
• für vertikale Anströmung	1–6	15–40	0,5–3	Wäscher, Absauganlagen
• für horizontale Anströmung	1–12	15–30	1–10	Wäscher, Absauganlagen

Picture right: A drift eliminator which fully meets the requirements of case 1.



Droplets smaller than the limiting droplet are also separated, but not quantitatively. This results in a drift or a spray loss for drift eliminator (see explanations on page 8). For state-of-the-art drift eliminators, this value is 0.0005% (manufacturer's specifications) to 0.01% (Eurovent certificates) of the circulating water volume. **Thus, in case 1, the ejection of the fraction from 1 to 40 µm is considered.**

What this means for the aerosol discharge (mass and number of aerosols) and for a possible discharge of legionella is illustrated in the following example:
Evaporative cooling system - 160 m³/h circulation capacity; 150,000 m³/h air capacity. The spray loss is thus between 0.8 litres and 16 litres.
According to the last test report, test value 2 was reached for Legionella spp. in the cooling water (1000 CFU/100 ml).

Consideration for the emission point - directly at the exhaust air outlet
The legionella ejection caused by primary droplets is between 8000 and 160,000 individuals/hour in relation to **time.** The ejection in relation to the **volume is** thus a maximum of 1 legionella per m³ of exhaust air. With a respiratory rest volume of 10 litres per minute, the statistical probability of inhaling a legionella **directly at the exhaust air outlet,** i.e. with inhalation of 100% exhaust air, is thus reached after 100 minutes (with 0.0005% spray loss correspondingly only after 312 hours). The infectious dose of legionella during transmission by aerosols is not known. For *the speculative infectious dose,* data of 1000 legionella can be found in the literature. This seems very high, but at least individual bacteria are obviously not sufficient for an infection.

Estimating the number of aerosols released in the example is very difficult because the droplet spectrum is not known. The small droplets have hardly any mass and the large droplets have a disproportionate effect. Assuming that aerosols with an aerodynamic diameter of 10 µm would be released, then with 0.8 to 16 litres ejected and a single aerosol volume of 5.2E+02 µm³ at 16 litres, corresponding to 1.6×10^{16} µm³, this results in an ejection of about 10^{13} to 10^{14} aerosols per hour. This means that only about 1 in 1 billion aerosol droplets would contain legionella! However, why this is mostly of little relevance is explained below.

Case 1: **Primary droplet** - with intact, state-of-the-art, clean, fully laid drift eliminator and *proper* face velocities.
i.e. consideration of the fraction from 1 to 40 µm

Consideration of the probability of exposure to virulent legionella **for potential places of immission**

According to explanations on page 10, the sedimentation velocity for the potentially largest released primary droplets with an aerodynamic diameter of 40 µm is about 5 cm per second. However, the rate of descent is not a constant. Depending on the meteorological situation at the emission site, the aerosol will experience changes in diameter. Updrafts and relative humidity have a corresponding influence on the rate of descent during the aerosol's journey. Very often, the rate of descent will decrease very rapidly because evaporation reduces the aerosol diameter.

For aerosols < 40 µm, it can be stated that the sink rate will usually be too low to eliminate the water-containing aerosol from the environment by *deposition.* **The evaporation rate is likely to be much more decisive for aerosols of this size.** According to the explanations on page 13, it can be assumed that an aerosol with a diameter of 40 µm evaporates within about 20 seconds at relative humidities of < 90%, and within 5 seconds at a relative humidity of < 50%.

If the water of the aerosol available for typical wet germs, such as Legionella, has evaporated and if Legionella are *no longer growable (virulent) within 30 seconds after drying out* according to *Annals of Clinical and Laboratory Science, Vol. 17, No. 3; Copyright 1987 "The Effect of Drying, Heat and pH on the Survival of Legionella pneumophila;* within 30 seconds after drying out, the possible exposure radius with virulent Legionella is limited to only 68 to 150 metres, i.e. to the immediate vicinity of the plant!

The probability of exposure in case 1 with virulent Legionella from *primary droplets* is thus to be considered extremely low to practically impossible even at some distance from an evaporative cooling system, especially since in addition to an extremely low Legionella density in the aerosols and the removal of water from the aerosols, there are other considerable stress factors for bacteria, especially due to thickening - see page 22. At a further distance, i.e. taking into account the ever higher dilution and the prerequisite that several virulent, *free* Legionella from ***primary droplets*** must be inhaled for an infection, exposure, especially still of several persons, appears to be practically impossible.

In Warstein, wind speeds of 2-3 m/s prevailed during the infection period; relative humidity only in the early morning hours sometimes > 90%, otherwise mostly < 50%. Aerosols < and << 40 µm evaporated within 12 seconds, i.e. typical wet germs such as legionella lacked the protective hydrate envelope from a distance of about 40 metres from the emission site. In addition, they were exposed to the UV radiation of the sun during the day. The infections must therefore have taken place in the early morning hours, when the vast majority of people are sleeping indoors. However, this is also unlikely - see example on page 28 above.

At the distances of several kilometres from the emission site documented in outbreak cases, even assuming very unfavourable conditions (legionella concentration in the cooling water very high; 1 legionella already sufficient as an infectious dose; very special weather conditions such as morning fog, November fog or a freeze-up of the aerosols (also freeze-drying in freezing weather conditions)), exposure is still extremely unlikely, but perhaps not entirely impossible. According to LANUV, however, most outbreaks occurred during the warmer months of the year (see page 12).

Case 1: **Primary droplets** with intact, state of the art, clean, fully laid drift eliminator and *proper* face velocities
i.e. consideration of the fraction from 1 to 40 µm

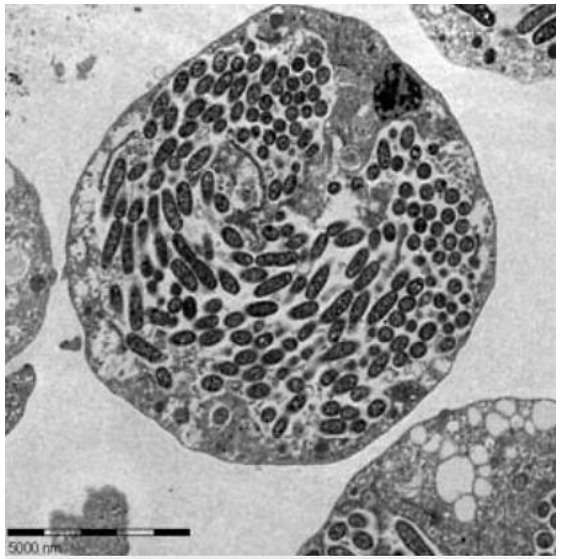
Legionella in amoebae from primary droplets (probability of the presence of amoebae, amoebic cysts or amoebic vesicles in the free cooling water).

According to the numerous publications available, there is no doubt about the possible occurrence of amoebae in evaporative cooling systems. However, the statements are mostly of a qualitative nature, in the sense of "detectable". However, there are no reliable findings on their *numbers, e.g. in the* free cooling water or in biofilms. The fact that the number of *planktonic* amoebae, amoebic cysts or amoebic vesicles is similar to the number of Legionella is certainly not impossible, but seems unlikely. In systems with partial flow sand filtration, amoebae or biofilm particles containing amoebae should be eliminated from the cooling water to a certain degree. In numerous own investigations of cooling water concentrates (1 : 500 via membrane filtration) as well as of biofilms and sediments, at least no trophozoites of amoebae could be observed.

The extent to which amoebae from primary droplets, or their cysts or vesicles, can be released from an intact drift eliminator due to free flight through the exhaust air can only be estimated from the size data (see e.g. picture on the right - diameter approx. 12 - 14 µm). Due to their size and adhering water, they are detected during primary separation in the drift eliminator, but probably not quantitatively. **Perhaps, however, the separation of amoebic cysts on the lamellae of the drift eliminator poses a problem - see page 25!**

If the number of amoebae, amoebic cysts and amoebic vesicles is low in the free cooling water (< or << 100/100 ml) and partial removal from the exhaust air flow via the drift eliminator occurs, then a possible exposure to amoebic vesicles from *primary droplets is* even less likely.
than exposure to free Legionella, especially since one probably also has to inhale several amoebic vesicles for an infection (see below).

What if this assumption just made, that the number of amoebae and their cysts or vesicles in the cooling water must be low, is wrong?
It would be urgent to examine the cooling water for amoebae after concentration via membrane filtration, because in each cyst or vesicle could potentially contain a high number (probably up to several hundred) of legionella.
According to literature data, it must also be assumed that Legionella present in amoebae exhibit increased virulence.
and legionella in amoebae mostly elude detection by analysis according to DIN-EN-ISO 11731. Added to this is the risk of contamination by environmental influences and atmospheric transport of legionella in these cysts and vesicles, protected from desiccation. This would reduce the primary hazard potential.
are clearly more likely to come from amoebae than from *free* Legionella. In addition, the biocide applications into the cooling water would mostly be of little benefit if thereby only the free legionella (detectable by the laboratory) but not the legionella protected in the amoebic cysts and possibly vesicles are eliminated. could. This means, however, that in order to protect against infection, completely different approaches would be needed (further reduction of the limiting droplets size, effective filtration, much more powerful biocide impacts).



Hartmannella vermiformis amoeba filled with Legionella pneumophila

Image source: Robert Koch Institute

This is what the LGL states on its homepage
https://www.lgl.bayern.de/gesundheit/arbeitsplatz_umwelt/biologische_umweltfaktoren/bioaerosole/legionellen.htm

"An infection can already be caused by a few inhaled legionella-containing amoeba vesicles. It is currently not possible to detect the legionella contained in amoebae, in vesicles or in the resistant permanent forms, the amoebic cysts, with the available standard analytical methods. Due to the routine cultivation method, there is a further problem in estimating an infectious dose (concentration). When detecting colony-forming units (CFU - detection), both a single bacterium and a large number of bacteria released from an amoeba/vesicle form only one "colony unit".

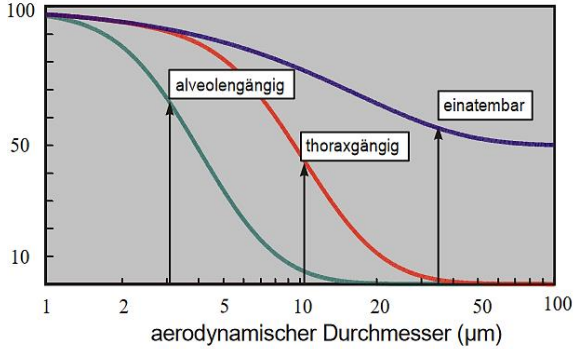
The possible scenarios for released *primary droplets*

Case 2: Primary droplets in the absence of a drift eliminator, one that is not intact, does not comply with the state of the art or is not installed over the entire surface, or if the droplet tear-through velocity is exceeded, i.e. consideration of the fraction from 1 to > 40 µm, i.e. up to X µm - and how large can X be?

The droplet spectrum to be expected in an evaporative cooling cell was described on page 10. Even though the formation processes of very small droplets in an evaporative cooling system cannot be explained so easily, a wide spectrum, i.e. from very small aerosols to droplets of 400 µm, is assumed for safety reasons. If the drift eliminator is missing or not intact, droplets up to an aerodynamic diameter will be able to escape, at which the gravitationally induced sinking speed roughly corresponds to the speed of the escaping exhaust air. As a rule, the outgoing air velocity in evaporative cooling systems does not exceed a value of 5 m/s. Thus it can be calculated that droplets up to 300 µm or, in extreme cases, up to 400 µm can initially escape, but due to the then immediately decreasing vertical air velocities, they usually immediately fall back onto the drift eliminator (which is still present in parts, for example) and thicken further there or even float and dance in the air above the non-existent drift eliminator (which can certainly be observed) or are removed from the air directly next to the system by deposition. The aerosol deposition practically competes with the evaporation rate, which is not linearly dependent on the diameter, as the mass increases with the power of 3.

Depending on the situation (e.g. strong thermals in the area of the building on which the exhaust air outlet of the evaporative cooling system is located), it can be assumed that droplets up to a size of about 300 µm can make the journey. As far as the **number of droplets is concerned, in** the absence of a drift eliminator, this can be 100 or 1000 times higher than in case 1. However, the **mass of** what is released by such a system is not in the number of small aerosols that are released, but in droplets that are (significantly) larger than e.g. the limiting droplet (which, however, now exists),
no longer exists due to the non-intact or missing eliminator) - because again the mass increases with the 3rd power of the diameter (spherical volume).

1 droplet of 100 µm has 1000 times the volume of a droplet of 10 µm and a droplet of 300 µm diameter has 1000 times the volume of a limiting droplet in intact drift eliminators (case 1), i.e. this droplet can also carry 1000 times the bacterial load!
If the drift eliminator is not intact or missing, the emitted aerosol mass in particular will increase considerably!



Directly at the point of emission, it is precisely the drops that are of a size that can be inhaled that are dangerous. At more distant locations from the point of emission, however, it is precisely those drops that were significantly larger at the point of emission and have shrunk on their journey to the point of immission due to evaporation that are dangerous. However, these droplets still contain their original bacterial load, but now concentrated accordingly - i.e. in terms of the infectious dose, such aerosols are much more dangerous!

If exposure to thoracic or alveolar aerosols is to be possible at the place of immission, this aerosol must now shrink to an inhalable size, i.e. to < 20 µm or < 5 µm!

But what happens when a drop of, say, 200 µm diameter, induced by thermals, starts its journey? It must first become rapidly smaller by evaporation in the updraft so that it does not succumb to gravity and is very quickly removed from the air by deposition in the immediate vicinity of the plant.

While the evaporation begins, there is now some time to think about the constituents of this aerosol. Let's assume the drop resulted from triple-thickened cooling water with a conductivity of 2000 µS/cm, mainly resulting from the cations calcium and sodium and the anions hydrogen carbonate, chloride, sulphate and nitrate. The organic matter resulting from the cooling water conditioning causes a COD of e.g. 90 mg/l together with other substances introduced via the air and production. In addition, this droplet is said to contain a bacterial load, which in terms of mass, however, plays no role whatsoever with halfway normal bacterial counts. As far as the emission of droplet fractions is concerned, the number of large droplets will (have to) be many orders of magnitude lower than that of small droplets, because otherwise the large droplets would contribute considerably to flushing. Without a drift eliminator, however, the released droplets are large enough to carry protozoa, amoebae or amoebic vesicles, which in turn can carry a considerable Legionella load.

Example: What happens in released droplets during weather conditions that have often prevailed in the documented legionella outbreaks?

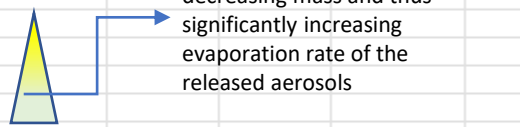
- The building on which the evaporative cooling system was built is clearly warmed up by the sun. The drop rises slightly due to the velocity of the exhaust air and then supported by the thermals. The horizontal speed due to the wind is e.g. 3 m/s.
- depending on the relative humidity, evaporation will start and the droplet will begin to shrink.
- the evaporation rate will be lower than the theoretical assumptions because the droplet travels isokinetically with the air and creates its own higher humidity in its immediate vicinity because the vapour produced is not immediately removed. The larger the droplet the more this effect will play a role in *terms of time,* the smaller the less.
- there is a rapid and significant increase in the electrical conductivity in the droplet.
- depending on the weather conditions, the droplet will be exposed to a certain amount of UV radiation during the day.
- As far as (organic) biocides were present, an enormous increase in biocide concentration occurs due to thickening.
- Increase in pH value.
- Solubility products are exceeded (failure of calcium carbonate, then calcium sulphate).
- The evaporation rate depends on the salinity of the water because the partial pressure depends on the salinity, so it will decrease due to thickening.
- the chloride concentration increases considerably, e.g. from 150 mg/l to ultimately 150,000 mg/l.
- the COD concentration rises to 90,000 mg/l.
- Increase in hygroscopicity = further decrease in evaporation rate.
- Increase in density.
- (Significant) increase in osmotic pressure (depending on the type of cations and anions in the aerosol, or at what number of dissolved particles solubility products are exceeded).
- Hyperosmotic stress for bacteria. This creates a pressure inside the cell, the turgor. The hyperosmotic stress leads to rapid water loss from the cell and thus possibly to plasmolysis.
- Within a short time, the original droplet has shrunk to what is probably a somewhat sticky, hygroscopic residual particle.
- Legionella that were not protected in amoebic vesicles or cysts (if any were present at all) will hardly have survived the process. If they do, and if a legionella in this dried-out residual aerosol has reached a supposedly rescuing, moist lung, this process takes place again in a similar way in the reverse direction when the aerosol particle takes up water in the lung!

Dramatic change in environmental conditions per unit of time

This scenario is of course relevant for droplets that can shrink to an inhalable size. But: Can a droplet of e.g. 200 µm at the point of emission shrink at all to an inhalable size, i.e. by a factor of 1000 in terms of mass = 1000-fold thickening? Are there places of immission where the resulting residual droplet could be present in an inhalable fraction?

Berechnung notweniger Eindickungen für lungengängige Aerosolpartikel am Immissionsort für Kühlwasser mit einer LF von 2000 µS/cm = 1400 mg/l Salinität + 100 mg/l Organik
gültig für PRIMÄRTROPFEN bei Anlagen mit drückendem Ventilator oder bei Betrachtung nach saugendem axialem Ventilator - bei angenommener Lungengängigkeit ab < 20 µm

Durchmesser Aerosol am Emissionsort in µm	Aerosolradius in µm	Volumen Aerosol am Emissionsort in µm³	für Inhalierbarkeit notwendiger Aerosol-Durchmesser am Immissionsort in µm	maximales Volumen lungengängiger Aerosole in µm³	Volumen-Aliquot des ursprünglichen Aerosols am Emissionort in Vol-%	notwendige Eindickung für Lungen-gängigkeit	resultierende Salinität nach Eindickung in Gramm/Liter
20	10	4,2E+03	20	4,2E+03	100,0	1	1,5
25	12,5	8,2E+03	20	4,2E+03	51,2	2	2,9
30	15	1,4E+04	20	4,2E+03	29,6	3	5,1
40 ← Boundary droplet - from here with intact drift eliminator complete separation	20	3,3E+04	20	4,2E+03	12,5	8	12,0
50	25	6,5E+04	20	4,2E+03	6,4	16	23,4
60	30	1,1E+05	20	4,2E+03	3,7	27	40,5
70	35	1,8E+05	20	4,2E+03	2,3	43	64,3
80	40	2,7E+05	20	4,2E+03	1,6	64	96,0
90	45	3,8E+05	20	4,2E+03	1,1	91	136,7
100	50	5,2E+05	20	4,2E+03	0,8	125	187,5
120	60	9,0E+05	20	4,2E+03	0,46	216	324,0
140	70	1,4E+06	20	4,2E+03	0,3	343	514,5
160	80	2,1E+06	20	4,2E+03	0,2	512	768,0
180	90	3,1E+06	20	4,2E+03	0,14	729	1093,5
200	100	4,2E+06	20	4,2E+03	0,10	1000	1500,0
250	125	8,2E+06	20	4,2E+03	0,05	1953	2929,7
300	150	1,4E+07	20	4,2E+03	0,03	3375	5062,5



Decreasing separation efficiency of the drift eliminator, but massively decreasing mass and thus significantly increasing evaporation rate of the released aerosols

Difference in performance (hazardous droplet spectrum) of a system without (intact) drift eliminator in terms of droplet size (not the number of emitted droplets)

from here on hardly any further thickening possible, i.e. droplets > 140 µm can never shrink to an inhalable size!

increasing density, but largely irrelevant for these considerations

Droplets from about 140 µm will thus never be able to shrink to an inhalable limit in a cooling water of this mineralisation, unless suction axial fans are present to beat some of them small! For inhalability, 20 µm was assumed in the example. There are reports that the risk of Legionella infection is only given for aerosols < 5 µm (see link https://www.pharmazeutische-zeitung.de/inhalt-24-2002/medizin1-24-2002/ and text excerpt on the right, as well as the note in VDI 2047-2 on page 6).

If this is true, then aerosols resulting from primary droplets of service water of the above quality could no longer shrink to an inhalable size at the point of emission from a diameter of about 40 µm! See also from page 28 - Questions and need for research.

Infektion über Aerosole

Im Trinkwasser, das als solches genutzt wird, sind Legionellen keine Gefahr für den Menschen. Die Erreger müssen direkt in die Lunge gelangen. Dies ist nur möglich über Aerosole, deren Tröpfchen im Durchmesser kleiner als 5 µm sind.

Conclusion of case 2:

Knowledge of the salinity and organic load of a cooling water is of considerable importance. Cooling waters with *lower* salinity and/or organic load are to be regarded as more risky with regard to the transmission of bacteria by aerosols, because larger droplets, which can carry a correspondingly higher microbiological load, are more likely to evaporate down to an inhalable level.

Bioaerosols: evaporated, cured, sedimented - and when dangerous

Depending on the inorganic and organic constituents of the cooling water, it can be calculated from which droplet size the emitted droplets no longer pose a danger either at the emission point or at any immission points because they can no longer be reduced to an inhalable size by evaporation.

Regardless of whether bacteria would survive the described processes during this thickening process at all, if mineralisation is known and the organic constituents are known, it can be determined from which size droplets emitted due to a non-intact or missing drift eliminator are irrelevant. However, if the eliminator is missing, not intact or not installed over the entire surface, it can be assumed that the number of emitted aerosols *with a critical size, i.*e. those that mostly do not already evaporate in the immediate vicinity and, on the other hand, can shrink to a size that can be inhaled (> 40 µm to about 200 µm with quite low mineralisation), is considerably higher.

Systems with missing or not intact drift eliminator are therefore to be considered dangerous. This applies in particular to cooling cells with suction axial fans, because drops which could never shrink to a respirable size are broken up and the resulting smaller drops can then already be respirable or can evaporate to a respirable size.

Other reasons that would cause aerosols to break apart on their journey through the atmosphere are actually inconceivable - what forces in the atmosphere would these be that are stronger than the intermolecular forces (Van der Waals, dipole moment, hydrogen bonding, surface tension) in the aerosol?

For the assessment of plants (especially in the event of an outbreak), it is therefore very important to know which process technology is used and what the condition of the drift eliminator and the flow through the packing is like. Other parameters, such as mineralisation and the organic load of the cooling water, are also important in order to be able to deduce from which droplet size no more inhalable droplets can result, because for more distant immission sites (several kilometres) only these are usually considered, because the small aerosols (depending on the relative humidity) have usually long since evaporated in the vicinity of the emission site.

Based on the described processes in the course of evaporation-induced thickening, it can also be assumed for case 2 that Legionella can only remain infectious if they are protected in amoebae or other protozoa from the enormous milieu changes described on page 21! This means that the examination for amoebae should actually have the same status as the examination for legionella!

This also has considerable consequences for bioaerosol measurements! At the point of emission, a droplet of 300 µm is completely harmless because it cannot be inhaled. However, such large droplets deliver a possibly high, but irrelevant bacterial load for the bioaerosol sample! Isokinetic sampling of bioaerosols and subsequent examination of the collected liquids for Legionella without prior determination and thus knowledge of the droplet fractions (impactor measurement) and consideration of the aerosol diameter (fractionating sampling) make no sense against this background, or do not allow any interpretation of the results!

Considerations for released **secondary droplets** (e.g. resulting from wet drift eliminator covered with biofilm)

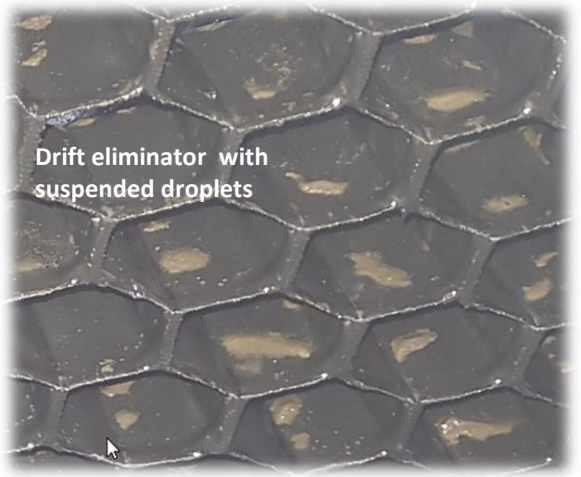
The preceding considerations have shown that exposure and inhalation of bioaerosols with virulent Legionella from the **primary droplets of the cooling water are** extremely unlikely with a state of the art, clean drift eliminator even from a fairly short distance from the emission point and are practically impossible with mostly prevailing meteorological conditions. If a drift eliminator is missing or not intact, a significantly increased aerosol emission can be assumed. However, depending on the mineralisation and organic load of the cooling water, there is a limit above which the droplets cannot shrink to a size that can be inhaled at any time at any place of immission. This calculable threshold size may be as low as < 60 µm at the point of emission! Smaller droplets usually evaporate quickly. If, according to medical findings, individual Legionella bacteria are not sufficient for an infection, then primary droplets are only possible, if at all, in the case of extremely high germ contamination of the cooling water or through the protection of protozoa/amoebae.

But what about the **secondary droplets that** form in the exhaust air area, e.g. from areas like the one in the picture on the right?

What are the main differences to primary drops?

- Microbiological load usually higher by orders of magnitude
- possibly rich in protozoa and possibly also amoebae
- The electrical conductivity (mineralisation) of the water film on the drift eliminator can be low, because the water film not only consists of the droplets of the spray loss but mainly of a condensate component results = advantage for the bacteria, as the hyperosmotic stress does not become so high with thickening
- UV radiation can only penetrate poorly due to colouration and turbidity
- Largely biocide-free
- Release conditions dependent on operating condition (fan power; partial drying of the Water film on the drift eliminator and detachment of fragments of the biofilm with residual water and virulent bacteria).

The drift eliminator- a component that is absolutely underestimated in terms of its hazard potential from a hygienic point of view.



The potential mass of secondary droplets in the drift eliminator should not be underestimated. Looking at the picture on the right, one can assume at least about 5 drops per chamber, which may well remain in suspension for a longer period of time under certain operating conditions. The inlet area per chamber is about 6 cm² and the total surface area is about 120 cm^2 . If the total surface area of the drift eliminator for an evaporative cooling cell is 14 m² = 140,000 cm², the following calculation results: 20 droplets correspond to about 1 ml. This results in a total of about 16,000 chambers, á 0.25 ml = 4 litres. With bacterial densities of 10^9 to 10^{10} /ml occurring in these areas, this results in a total load of about 10^{12} to 4 x 10^{13} bacteria. For comparison, the cooling water with a general colony count of e.g. 10,000 CFU/ml: assuming 10 m³ cooling water volume = 10^4 CFU/ml x 10^7 ml = 10^{11} , i.e. there are up to 400 times more bacteria in the drift eliminator than in the entire cooling water and all largely unaffected by the biocide and there is no further barrier to the outside!

In such a condition, the drift eliminator is very likely to be many times more dangerous than anything else! So a regular, very precise inspection of the eliminator is very important.

If the bacterial load from the drift eliminator is flushed into the cooling water, e.g. during thundershowers, the primary droplets can also become dangerous in such events due to this cooling water contamination if the bacterial load is not promptly pushed back by biocide application.

Increased bioaerosol emission is therefore more likely after heavy rain events or hail. As heavy rain events often occur at times of the year when pollen is on the move and thus sufficient protein is deposited on the drift eliminator (the protein content of pollen is stated in the literature to be between 10 and 40 wt.%), the situation is further worsened due to the supply of nutrients.

Again, the role of the amoebae:

If there is a risk of Legionella in amoebic cysts or amoebic vesicles, one would think that conditions must be provided so that any amoebae in the primary droplets cannot pass through the drift eliminator as a barrier, which is already the case, at least in part, with a state-of-the-art drift eliminator. However, this risks the amoebae accumulating and multiplying in the drift eliminator! They are then emitted from the drift eliminator when, for example, the biofilm half dries, loses its mechanical stability but is still moist enough or the fan power is increased! Thus, nothing would be gained by the successful separation.

A lot of condensate can collect in the drift eliminator. Therefore, a higher aerosol thickening is possible with released aerosols than with primary droplets, i.e. these aerosols can shrink to a respirable size sooner. With an initial bacterial count of e.g. 10^6 CFU/ml in the secondary droplet, the bacterial concentration in the inhalable fraction can then be 10^8 CFU/ml with e.g. 100-fold thickening by aerosol evaporation, so that the necessary infection dose is much more likely to be reached than with the primary droplets!

However, the concentration can also take place on the drift eliminator surface itself. According to the observations, the dewatering of the drift eliminator does not only take place when the separated droplets run together and finally form such a large droplet, which then drips into the cooling water or onto the packing due to gravity. The dewatering also takes place by evaporation of the secondary droplets on the drift eliminator surface, in particular when operating conditions (reduced thermal load or higher fan speed) prevail in which the exhaust air is not completely (temporarily) saturated with water vapour.

<u>Primary droplet</u> from cooling water - 2000 µS/cm
Influences/changes during the "journey".
in air

- Clear UV influence on clear, colourless droplets
- High hyperosmotic stress
- sharp increase in biocide concentration due to thickening
- *Critical* salinity for particles already reached from approx. 80 µm at the point of emission. No thickening to alveolar fraction possible.

<u>Secondary drop</u> 100 µS/cm
Influences/ changes during the "journey
in air

- little UV influence on cloudy, coloured droplets
- little hyperosmotic stress
- no or hardly any biocide influence
- no critical salinity for particles up to 300 µm at the point of emission. Thickening up to 20 µm possible !
- inhalable aerosols up to > 1000-fold bacterial load of the initial aerosols - so that the infectious dose is reached!

This would also make it easier to explain such apparent phenomena.

Offensichtlich reichen einzelne Bakterien für eine Infektion oft nicht aus. Eine besondere Rolle scheinen infizierte Amöbenpartikel zu spielen, da Legionellen ihre Virulenzgene erst innerhalb von Zellen aktivieren. Dies würde auch das häufig beobachtete Dosis-Wirkungs-Paradox erklären. Denn einerseits treten trotz stark kontaminierter Wassersysteme oft keine Infektionen auf, andererseits wurden Erkrankungen beobachtet, obwohl nur sehr wenige Legionellen im Wasser nachweisbar waren. So zeigt eine Studie aus Singapur, dass zwischen 1991 und 1995 144 Menschen an der Legionellose erkrankten. Bei sechs Patienten ließ sich die Legionellen-Infektion eindeutig nachweisen. Gleichzeitig waren in der Millionen-Metropole etwa jeder dritte Kühlturm und eine beträchtliche Zahl an Brunnen inner- und außerhalb von Gebäuden mit Legionellen infiziert.

from https://www.pharmazeutische-zeitung.de/inhalt-24-2002/medizin1-24-2002/

Process and operational boundary conditions

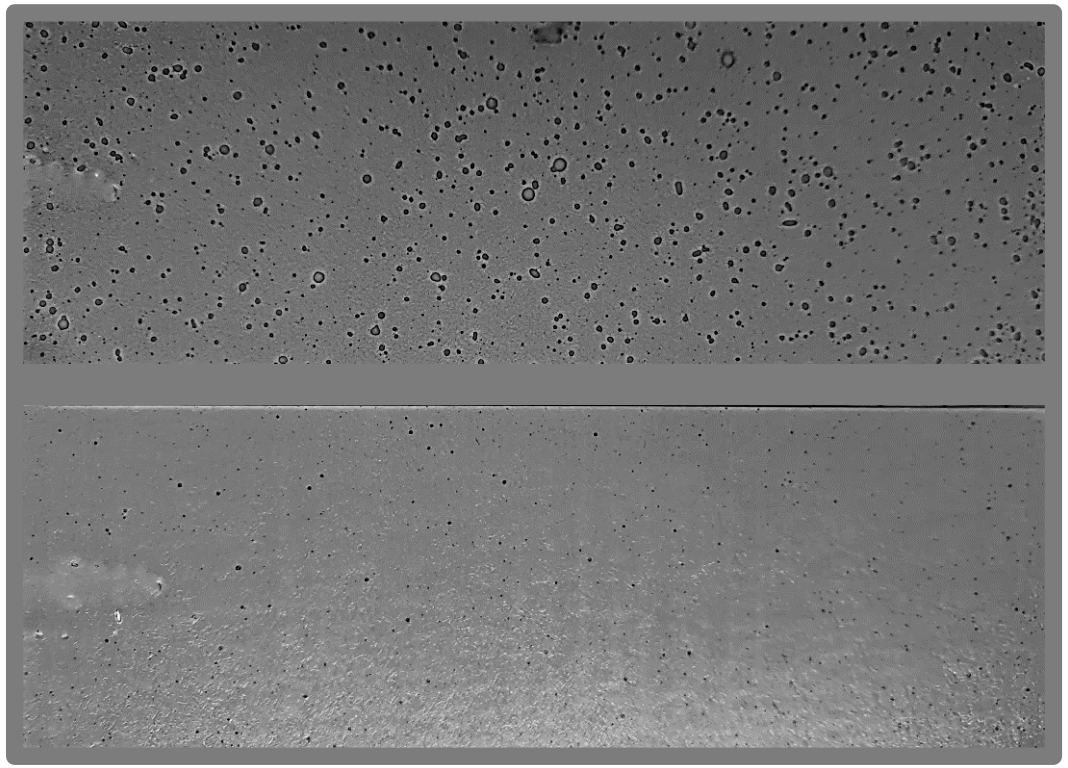
Conditions which, under certain circumstances, can have an influence on the emission of microorganisms (independent of other dominating factors such as nutrient ratio, temperature) - **but can only become effective if water conditioning is inadequate and hygienic operation is not mapped according to VDI 2047-2 (in particular hygiene inspections according to Table 1)**

		Justification
Horizontal inflow drift eliminator	**Vertical inflow drift eliminator**	*slightly smaller limiting droplet size and slightly better dewatering behaviour (secondary separation) = rather slightly drier eliminator = lower tendency to biofilm formation.*
Fan rigid power	**Fan adjustable (FU)**	*If necessary, temporary release of biofilm particles and droplet break-off when the air flow rate is increased.*
Pressurised centrifugal fan	**Fan axial suction**	*breaks up large drops, which could never evaporate to inhalable size, into smaller ones*
Pumps rigid power	**Pumps FU regulated**	*In the case of structures adapted to low shear forces, adhesion forces at interfaces may be temporarily exceeded - biofilm detachment*
Additional water softened	**Make-up water not softened**	*Important calcium for biofilm build-up present as well as some loss of lime possible = amorphous growth surfaces*
Low technical residence time	**High technical residence time**	*Advantage for bacteria with a long generation time*
Always high hydraulic dynamics	**Low or changing hydraulic dynamics**	*increased biofilm formation or biofilm detachment*
Regular (daily) drying of the cold room	**Only occasional drying through of the cell**	*Detachment and release of biofilm particles containing legionella, if applicable.*
Stainless steel and/or plastic surfaces only	**Black steel installation**	*amorphous iron oxide hydrates ideal for legionella, which are essentially dependent on iron*
Well maintained cooling water filtration	**No cooling water filtration**	*no elimination of biofilm particles and possibly amoebae from the cooling water*
No or <u>permanent</u> dosing Biodispergator	**<u>occasional</u> dosage of biodispergator**	*possibly reduction of aerosol separation efficiency and biofilm detachment as well as biofilm particle release; influence on the limiting droplet size (surface tension)*
correct face velocity of the drift eliminator (TA)	**Drip irrigation without a fan or with greatly reduced performance or, in relation to the area of the TA, strong differences in the incident flow.**	*Incoming flow velocity to the drift eliminator undershot - poor separation performance. Poor drainage behaviour. Biofilms only partially present and, unfortunately, not in the area of the inspection opening where they are checked.*
Exhaust air not completely saturated with water vapour	**Exhaust air always absolutely saturated with water vapour**	*Instead of a rather dry drift eliminator, the drift eliminator may be constantly wet - biofilm formation is actually an inevitable consequence.*
Largely constant exhaust air humidity	**constant change of the exhaust air humidity**	*Temporary drying and release of biofilm particles (amoebae)*
Flawless pre-pressure at the nozzle block and flawless spray pattern	**Spray pattern and flow through packed bed poor**	*In the packing, areas can arise which are saturated with water vapour, through which air flows but which are not reached by the biocide.*

Impactor measurements

The explanations have shown that knowledge of the diameter of the released droplets is of considerable importance. Therefore, here is a brief insight into impactor measurements.
VDI 3679-3 provides information on impactor measurements:
"*Sampling droplet measurement methods (impactor methods) are methods in which the droplets are deposited on an impactor surface by inertial forces. This is covered with a water-sensitive, colour-reactive membrane or with a fine dust layer (MgO, soot), so that the drops are imaged as colour spots or impact craters. The link between the spot or crater diameter and the drop diameter causing it must be determined in calibration tests. The impactors are evaluated microscopically by classifying the droplet tracks and providing both the droplet size distribution and - by integrating them - the area-related droplet mass flow density. The lower diameter limit of the droplets that can still be detected with these methods is 5 µm". (Own note: with reflected light microscopic evaluation).* Since it is of course not possible to carry out such impactor measurements in rain or fog, i.e. when the relative humidity of the outside air is very high, there are no water-containing aerosols < 5 µm anyway, because they evaporate the second they are released.

In addition to the integral sampling methods (described on page 33), the impactor method provides good, semi-quantitative information on aerosol mass per area and time unit and, above all, an overview of droplet sizes. At extremely low aerosol concentrations in the air to be investigated, the method is even clearly superior to the integral methods with regard to the lower limit of determination.



Impactor measurement of the exhaust air of an evaporative cooling system.

- Same system, same measurement location. Only changed air performance.
- Exposure time 10 seconds each

Largely the same number of drops but enormous increase in mass (sphere volume 3rd power) in the upper measuring strip.

For exposure, the situation shown on the lower strip may be more dangerous than the one shown above, because many of the droplets above will not have an inhalable size at any exposure site.

However, with the integral sampling method (impinger, cyclone) as described e.g. in the UBA report *"Development of a sensitive method for routine detection of legionella in aerosols from evaporative cooling systems",* a completely different picture emerges.

If these aerosols enter the sample according to the upper measuring strip, the **collected aerosol volume** is a **thousand times higher** than in the case below. In this respect, the test result will possibly also show a much higher legionella load and thus a higher hazard potential. But this conclusion would be wrong, because from a certain mineralisation of the cooling water, these large droplets never result in a hazard potential. They will never reach a respirable diameter.

Apart from this, the statistical probability that one of these (larger) aerosol impacts detectable in the upper impactor contains a legionella from primary droplets is < 1/10,000, even if the measure value in the cooling water is reached. Bioaerosol measurements with sufficient precision and accuracy therefore require very high air sample volumes - see page 34.

Conclusion

Due to the described emission conditions of an evaporative cooling system as well as the influence of atmospheric transport, it is very unlikely that an intact, clean drift eliminator according to the state of the art would pose an exposure risk of planktonic legionella from **primary droplets** that could fly freely through the drift eliminator.

The following is a very unfavourable case for illustration:

Legionella concentration in cooling water 100,000 CFU/100 ml, morning fog, rel. humidity very high, no aerosol evaporation. The probability that a respirable aerosol of 5 µm, with a volume of 6.5E+01 µm³, contains a legionella is then 1 : 15,000,000. If several legionella must be inhaled for an infection, either a lot of aerosol must be inhaled or several legionella must be present in a single aerosol, for which the probability is much lower.
If the morning fog has disappeared and the relative humidity has dropped to e.g. 60%, then aerosols of the diameter of the limiting droplet, i.e. about 40 µm (at the point of emission) could still shrink to the inhalable size of 5 µm. The probability of a Legionella being present in this initial aerosol at the above load is then about 1 : 30,000. For infection, however, this Legionella would then have to survive the process of aerosol thickening described on pages 21 and 22, in this case about 500-fold, and should not be sensitive to desiccation.

Objections:

- ***Cell agglomerates of*** *legionella could be released from the cooling water.* How likely is it that cell agglomerates are not dissolved during the pump runs? I have never been able to detect cell agglomerates of bacteria in cooling water concentrates obtained via membrane filtration. They would also have to pass through the barrier of the drift eliminator and, if cell agglomerates were the cause, the legionella analysis would have hardly any significance because only one colony would grow out of each cell agglomerate. The danger would therefore remain analytically invisible.
- *There could be very high concentrations of* ***amoebic cysts or amoebic vesicles*** *in the service water.* See page 19 and page 25.
- *Other, small and thus respirable* ***protozoa*** *could possibly also have incorporated virulent Legionella.* Among the small protozoa, Aspidisca cicada is indeed very often found in biofilms and sediments. However, as typical grazers, they are not found in free cooling water. Moreover, at 25 µm or more, they are hardly respirable and are at least partially intercepted by the drift eliminator.

What would then remain as an explanatory model for infections further away from the point of emission? Actually, only one *legionella is sufficient for an infection and legionella are not sensitive to the process of aerosol thickening and to desiccation.* But this is not exactly current doctrine. The other explanation would be: *the hazard does not result from the primary droplets from the cooling water but from exposure to Legionella from secondary droplets and/or released biofilm particles.*

- Amoeba trophozoites, amoeba cysts and amoeba vesicles should be retained by state-of-the-art drift eliminators. However, if the drift eliminator is wet and covered with biofilm, this can be very dangerous because amoebae can multiply in the mist eliminator. It is much more likely that amoebae are in biofilms than that amoebae (protozoa) are in the free water body.

- Various protozoa (ciliates rotatoria, flagellates) can very often be observed in biofilms of drift eliminators. These protozoa can be advantageous for the reduction of the legionella load, because the legionella do not recover from the feeding of the protozoa as quickly as other bacteria due to their long generation times. However, it may also be that this causes an accumulation of legionella not only in amoebae but also in other protozoa, if these should not be digested.

- Operating a system with a drift eliminator that is not intact or missing is undoubtedly dangerous, but operating a system with a drift eliminator that is covered with biofilm may be even more dangerous.

- It is not legitimate to deduce the emission situation from the hygienic cooling water quality alone. If *and only if the* drift eliminator is clean and completely free of biofilm, then one can deduce that the source of any bioaerosols containing legionella is the primary droplets from the cooling water. Thus, if the hygienic quality of the cooling water is known and the spray loss is known, the emission can also be estimated approximately.
- If there is no drift eliminator or if it is not state of the art, not intact or not installed over the entire surface, then the number of aerosols and, above all, the mass of aerosols can increase considerably. However, the danger lies not in the absolute mass of aerosols released but in the number of aerosols of critical size. The critical size depends on several factors. The most important are the relative humidity at the time of emission and the inorganic and organic constituents of the droplet. At a rel. humidity of < 90%, aerosols with a diameter of < 40 µm dry out within 30 seconds, i.e. still in the immediate vicinity of the emission point.
- Depending on the mineralisation and organic content of the water from which they originate, droplets above a certain size can no longer thicken to an inhalable size by evaporation. The emission of larger droplets, which can thicken higher due to *lower* mineralisation, is more dangerous than the emission of droplets of the same fraction with higher mineralisation.

- In the LANUV report, legionella outbreaks are documented in the *first warm days of* the year (Pamplona outbreak = report page 99). The following possible explanations result from the observations:
  - A thundershower washed the sessile bacterial load from the drift eliminator into the cooling water. The sessile bacteria became planktonic bacteria, which were released due to a non-intact drift eliminator.
  - The fans were regulated upwards due to increasing thermal load. The air velocity increased accordingly. In the biofilm adapted to lower air velocities, the adhesion forces of the bacteria on the structures they live on were no longer sufficient to withstand the shear forces of the now higher air velocities. They were released.

  This could have been the case - but **such derivations are only possible in the event of an outbreak if the operating conditions of these plants** are **recorded and documented.**

- Secondary droplets are largely or completely unaffected by the biocide added to the cooling water.

- There are plants which, due to their process technology and mode of operation, with insufficient cooling water conditioning and insufficient hygiene inspection, probably have a somewhat higher risk for the emission of bioaerosols than others - see page 26. Suction axial fans in particular can increase the ejection of droplets with a dangerous aerodynamic diameter because larger droplets, which could not become respirable in themselves due to their mineralisation or which would immediately sediment, are broken up into smaller droplets which can then become respirable in this way.

- The indications that the danger comes less from primary droplets and more from secondary droplets are obvious. There is evidence that the problem can emanate significantly from the area of the drift eliminator. Effort and costs to check and, if necessary, remedy this are rather low. Therefore, there is actually nothing to be said against including this in the considerations and the monitoring requirements.

- According to the LANUV report (source), the majority of outbreaks occurred during the warm season, i.e. between April and October. For the reasons described above, this also speaks more against primary droplets from the cooling water of plants with an intact drift eliminator but more for secondary droplets.

- Varying thermal loads and/or controllable fans can cause the water vapour saturation of the exhaust air to decrease and biofilms on drift eliminator to dry on or completely dry off and thus lose their EPS-supported mechanical stability. In this phase, massive releases of microorganisms may occur (possibly also a source of amoebae).

- **In the event of an outbreak,** inspections of potential plants should not only include microbiological examinations of the cooling water (the primary droplets), but also the parameters listed on page 26 for the process technology and mode of operation of the plant, because it would be important to know these boundary conditions for assessing the hazard potential. The area of droplet separation must be inspected in detail. The inorganic contents (determination via electrical conductivity is usually sufficient) and the organic load of the cooling water, as TOC or COD, should be recorded. An impactor measurement (*after the* suction axial fan in plants equipped with it) of the exhaust air should be carried out without fail. If the meteorological conditions (relative humidity, wind speed) are known, this information allows a much more detailed assessment of the possible immission situation.

Consequences and measures

- In the literature, values for inhalability or respirable permeability can be found, whereby a distinction is made between thoracic and alveolar permeability. If an aerosol with infectious Legionella must be alveolar in order to cause an infection, i.e. it must have a diameter of < 5 µm, then there is almost no possibility of infection even at a short distance from the point of emission, because the cooling water droplets undergo the changes described on page 21 when thickened to this size, or cannot thicken to this fraction at all due to their contents.

- It is well known **that qualified bioaerosol measurements of the** exhaust air would provide more insights than determining the situation in the cooling water. Prof. Dr. Wurz already referred to this in 2016. However, the sampling would have to be fractionated. **Droplets that can never shrink to an inhalable size due to their size and constituents, but which make an enormously disproportionate contribution to the collected aerosol volume, must be left out!** In this respect, however, a much simpler technique for aerosol collection (sampling) would also be needed - see page 34.

- Aerosol analyses, supported by the addition of tracers (fluorescein) to the cooling water, can provide information on the total discharge of water-containing aerosols and their bacterial load after isokinetic or fractionating sampling (see description on page 34). The sampling must be accompanied by impactor measurements.

- Check the drift eliminator. Does it comply with the state of the art (evidence of corresponding performance data (Eurovent). Is it installed absolutely full-surface. Suspended drops in the drift eliminator must be prevented at any air flow rate, thermal load and relative humidity.

- Regular hygiene checks of the drift eliminator surface (biofilm, floating droplets) are very important. A microscopic examination and, if necessary, a swab for laboratory testing for legionella should be requested if the drift eliminator has a biofilm. A superficial check is not sufficient here, as the biofilms often form deep inside in the separation zone.

- Regular impactor measurements of the exhaust air should be carried out to determine the drop spectrum. They also provide information on whether the drift eliminator is in order, because it is often not visible everywhere.

- the minimum face velocity must not be fallen short of. This should be checked and ensured especially for fans with frequency converter control.

- The drop tearing speed must not be exceeded (measurement v_{min} and v_{max} by experts if necessary).

- all the above points should be taken into account in risk assessments.

- Raising the operators' awareness of these issues, e.g. as part of the VDI training courses, would contribute a great deal to more hygienic operation.

- During inspections, drift eliminator are often found to be clean and even largely dry. In many cases, however, the picture is completely different. Here, regular disinfection of the drift eliminator would be of considerable advantage from a hygienic point of view. Manual disinfection can be carried out via the inspection openings. However, since disinfection should be carried out as weekly as possible, **automatic disinfection that covers not only the drift eliminator but also the packing would be** advantageous. For this, the biocide dosing technology would have to be modified, see e.g. https://register.dpma.de/DPMAregister/pat/PatSchrifteneinsicht?docId=DE102019103299A1&page=1&dpi=300&lang=de&full=true.

- **Amoeba-dense drift eliminator.** It would be desirable to increase the performance of the drift eliminator with regard to the reduction of the limiting droplet size and the separation performance of small aerosols in order to further retain amoebic cysts and amoebic vesicles. This would be possible, for example, by combining baffle mist eliminators and knitted wire-mesh pads - as far as the pressure loss permits). Ideally, no more aerosols > 15 µm should occur at the exhaust air outlet (verification via impactor measurement). If amoebae are retained, regular disinfection of the drift eliminator should be carried out in any case, so that nothing gets into the clean gas side.

- and last but not least: a clean drift eliminator saves energy because the pressure loss is lower.

Questions and need for research

- Legionella are supposedly very sensitive to dehydration. Unfortunately, there are hardly any *current* studies on how long they can survive without a protective hydration shell. Is a change to a VBNC state even possible if the described thickening processes in the aerosol take place within seconds? The study from 1987 shown on page 18 is all I have found on this. If there are no more, there is actually a need for research to determine this in appropriate experiments (according to the experiences I used to have with colleagues in the microbiology laboratory, but better with robust wild flora instead of laboratory strains). The extent to which legionella can survive the described hyperosmotic stress in the process of thickening the aerosols also needs to be clarified.

- If no amoebae are present, it seems extremely unlikely, due to the effects described on page 21 as well as desiccation, that infectious Legionella can still be present at more distant sites, unless the Legionella can also multiply unmolested intracellularly in *other protozoa by being* incorporated by other protozoa but not eliminated by digestion. **So is intracellular proliferation of Legionella very host-specific focused on amoebae?** Answering the question of whether Legionella can multiply in other protozoa or are rather decimated by them would be an important finding for assessing the presence of protozoa in biofilms (rather good or rather bad for hygienic operation).

- If amoebae are essential for intracellular proliferation of Legionella, why was the author of this report never able to detect amoeba trophozoites in hundreds of phase-contrast microscopic examinations of highly constricted cooling water samples as well as in bacterially highly contaminated sediments and biofilms, although they should actually be easily detectable microscopically due to their size? If the RKI writes "facultatively intracellular", can it *not be that* Legionella cannot multiply intracellularly under favourable biofilm conditions? This also works in laboratory analysis for legionella.

- Since amoebae would play an essential role for the undamaged transport of legionella in thickening aerosol droplets, shouldn't the examination for amoebae be given corresponding importance? In my opinion, one can legitimately discuss whether an amoeba examination of biofilm-contaminated drift eliminator might not be more important than the laboratory examination of the cooling water for planktonic Legionella.

Taking care of the quality of the cooling water and thus of the primary droplets is undoubtedly decisive for the hygienic operation of an evaporative cooling system - but not forgetting the secondary droplets is just as essential, because there's no use having good on the bottom and bad on the top. Especially in outbreak management, it is crucial that the process technology and mode of operation, the chemical water quality and, in particular, the exhaust air area are examined in detail and parameters such as air velocities, droplet spectrum and relative humidity are recorded.

With good cooling water treatment and regular inspection/disinfection of the installations in the exhaust air area, an evaporative cooling system is then more of a germ sink than a germ slinger, based on the ratio of the number of bacteria in the supply air/exhaust air area. Note 2 under 9.3.2.1 in VDI 2047-2 could then read: A correlation between the legionella concentration in the service water and in the exhaust air only exists with a clean and biofilm-free exhaust air area (drift eliminator, diffuser, silencer) and with clean and biofilm-free filling or trickling filters through which the service water flows over the entire surface or volume.

Final comment:
I hope that these reflections have aroused the interest of the readers and will give rise to further discussion of all these connections, which in my opinion are quite exciting.

Apart from my considerations of what can happen during the atmospheric transport of cooling water aerosols, Prof. Dr. Wurz has already presented in his lectures in 2016 and 2019 in one sentence what took me so many pages to explain how I understood it:

"Widespread misconception: emission of microorganisms mainly caused by the emission of droplets from the cooling tower circuit water, which could pass the drift eliminator in free flight. Caution: Independent biotope in the outlet area!"

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WATCH-ED WATER NEVER FAILS

Appendix: Own experience from bioaerosol measurements

Bioaerosol collection with the emission impinger according to VDI 4257-2: The main disadvantages are the small volume of the sampled air (only approx. 1 m³) and the small volume of the collected solution in the impinger for the analytical investigations. In addition, there are sometimes considerable losses of the collection solution. The achievable lower limit of determination (e.g. ejection of cultivable legionella from the system per hour) in impingement is so modest that operators then ask what they should do with the result of e.g. "ejection < 150,000 cultivable legionella per hour".

Bioaerosol collection with cyclones: With small cyclones, as with commercially offered collection systems, the disadvantages are also the small volume of the sampled air (only approx. 3 m³) as well as the small volume of the collected solution in the cyclone. In addition, considerable losses of the collection solution must be compensated for in the course of sampling (see also, for example, UBA report "Development of a sensitive method for routine detection of legionella in aerosols from evaporative cooling systems, section "Need for research"). The losses are partly caused by evaporation when the relative humidity of the exhaust air to be sampled is < 90%, but mainly, as can be seen from the numerous publications by *E. Muschelknautz, by* instabilities of the vortex core in the cyclone. As a result, collection liquid can also be aerosolised and discharged from the cyclone (minor findings!). In addition, there is the problem of the *secondary flow,* i.e. the part of the volumetric flow that leaves the separator directly from the cyclone inlet without entering the main flow (short-circuit flow, reduced results!). In practice, cyclones cannot be left unattended for a second for the reasons mentioned, which is not very pleasant in such relatively inhospitable places as exhaust air outlets. In our opinion, however, the most decisive disadvantage is that a cyclone is a **mass-force separator, i.e.** the particle mass is decisive for the degree of separation. Here one runs the risk that, in contrast to larger droplets, which are separated correspondingly well, light **biofilm particles in the air stream, which** can have a considerable bacterial load, are captured much more poorly. The collection stress of the bacteria in the cyclone (high kinetic energy) is added to this with longer collection times.

We have tried to set it up as follows:

a) All equipment is made of glass by experienced glassblowers in order to better observe and interpret the processes in the cyclone.
b) Dimensioning of the complete collection system for sufficiently high air capacities and sufficient sample volume
c) Continuously adjustable volume flow and thus adjustable circumferential speed over a wide range (centrifugal acceleration)
d) High physical collection efficiency by minimising secondary flow as well as aerosolisation of collection liquid
- *Variable immersion tube diameter*
- *Variable immersion tube length (immersion tube depth)*
- *Series connection of several separation systems for high collection efficiency*
- *Liquid management in ongoing collection operation for sufficient running time - downstream drip catcher according to Stutzer*

e) 360° rotatable suction nozzles for easy change from isoaxial horizontal suction to isoaxial vertical suction as well as for possible rinsing of the suction area during measurement

The disadvantage of the rather small air collection volume nevertheless remains.

Alternative collection technology: The prototype of a specially constructed collector is based on a completely different aerosol collection technology and achieves air flow rates of up to 500 m³/h. Comparative measurements with the emission impinger (zirconium chloride and fluorescein as tracers in the generated test aerosol) showed a similar physical collection efficiency. The collection time can extend to many hours, so that a very high air volume can be sampled.