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Title: EXPERIMENTAL DETERMINATION OF DRIFT LOSS FROM A COOLING TOWER WITH DIFFERENT DRIFT ELIMINATORS USING THE CHEMICAL BALANCE METHOD

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Corresponding Author: Mr Manuel Lucas,

Corresponding Author's Institution: Universidad Miguel Hernández

First Author: Manuel Lucas

Order of Authors: Manuel Lucas; Pedro Juan Martínez; Antonio Viedma

Abstract: The existence of cooling towers arises from the need to evacuate power to the environment from engines, refrigeration equipment and industrial processes. Water drift emitted from cooling towers is objectionable for several reasons, mainly due to human health hazards. It is common practice to fit drift eliminators to cooling towers in order to minimise water loss from the system. The presence of the drift eliminator mainly affects two aspects of cooling towers: their thermal performance and the amount of water drift loss. This paper experimentally studies the drift loss emissions from a cooling tower without drift eliminator and fitted with six different drift eliminators. Chemical Balance is the selected method and Australian Standard methodology is taken as a reference. Some modifications are proposed to reduce uncertainty by increasing the duration of the test and the number of water samples. Installation of a drift eliminator, even in the worst case, reduces the water drift level to less than half of the situation without the eliminator. The water drift losses obtained with the different drift eliminators installed at the pilot plant, from 0.0118% to 0.161%, are within the range generally reflected in the literature. Finally, a criterion for designing drift eliminators in order to optimise both the collection efficiency and the cooling tower's thermal performance is proposed.

Suggested Reviewers: Syed M. Zubair
King Fahd University of Petroleum and Minerals
smzubair@kfupm.edu.sa

Robert Meroney
Colorado State University
Robert.Meroney@Colostate.Edu

I. L. Maclaine-cross
The University of New South Wales
i.maclaine-cross@unsw.edu.au



DEPARTAMENTO DE INGENIERÍA DE SISTEMAS INDUSTRIALES

Área de Máquinas y Motores Térmicos

Manuel Lucas Miralles
Departamento de Ingeniería de Sistemas Industriales
Universidad Miguel Hernández
Avenida de la Universidad, s/n
Edificio "Torreblanca", 03202, Elche. Spain
Tel: +34 96 6658887, Fax +34 96 6658979.
e-mail: mlucas@umh.es

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Prof. Dr.-Ing. Felix Ziegler
TU-Berlin
Fakultät III, Institut für Energietechnik, Sekr. KT 2
Marchstr. 18
10587 Berlin/ Germany
Tel.: +49 (0) 30 314 256 24
Fax: +49 (0) 30 314 222 53
E-Mail: Felix.Ziegler@tu-berlin.de

Dear Prof. Ziegler,

According to the instructions included in the web of the *International Journal of Refrigeration*, edited by Elsevier, we submit for publication the article

Titled: “EXPERIMENTAL DETERMINATION OF DRIFT LOSS FROM A COOLING TOWER WITH DIFFERENT DRIFT ELIMINATORS USING THE CHEMICAL BALANCE METHOD”

Authors: Lucas M., Martínez P.J. and Viedma A.

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According to IJR’s focus, research deals on condensation and air conditioning. Accent has been placed on experimental details. We hope the originals will fulfil all your requirements.

We look forward to your reply. Yours sincerely,

Manuel Lucas

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4 **EXPERIMENTAL DETERMINATION OF DRIFT LOSS FROM A COOLING**
5 **TOWER WITH DIFFERENT DRIFT ELIMINATORS USING THE CHEMICAL**
6 **BALANCE METHOD**
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11 **Lucas M., Martínez P. J.**

12
13 Departamento Ingeniería de Sistemas Industriales
14
15 Universidad Miguel Hernández
16
17 Avda. de la Universidad, s/n, 03202 Elche, España
18
19 Telephone: +34 966 65 88 87 Fax: +34 966 65 89 79
20
21 Email: mlucas@umh.es
22
23

24
25 **Viedma A.**

26
27 Departamento de Ingeniería Térmica y de Fluidos
28
29 Universidad Politécnica de Cartagena (Campus Muralla del Mar)
30
31 Dr. Fleming, s/n, 30202 Cartagena, España
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6 **Abstract**
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10 The existence of cooling towers arises from the need to evacuate power to the
11 environment from engines, refrigeration equipment and industrial processes. Water drift
12 emitted from cooling towers is objectionable for several reasons, mainly due to human
13 health hazards. It is common practice to fit drift eliminators to cooling towers in order
14 to minimise water loss from the system. The presence of the drift eliminator mainly
15 affects two aspects of cooling towers: their thermal performance and the amount of
16 water drift loss. This paper experimentally studies the drift loss emissions from a
17 cooling tower without drift eliminator and fitted with six different drift eliminators.
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25 Chemical Balance is the selected method and Australian Standard methodology is taken
26 as a reference. Some modifications are proposed to reduce uncertainty by increasing the
27 duration of the test and the number of water samples. Installation of a drift eliminator,
28 even in the worst case, reduces the water drift level to less than half of the situation
29 without the eliminator. The water drift losses obtained with the different drift
30 eliminators installed at the pilot plant, from 0.0118% to 0.161%, are within the range
31 generally reflected in the literature. Finally, a criterion for designing drift eliminators in
32 order to optimise both the collection efficiency and the cooling tower's thermal
33 performance is proposed.
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48 *Keywords:* cooling tower; drift eliminator, chemical balance
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6 **1. Introduction**
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10 The existence of cooling towers arises from the need to evacuate heat to the
11 environment. The second law of thermodynamics requires the presence of a heat sink
12 for the operation of both heat engines and refrigeration equipment. In addition,
13 industrial processes evacuate heat to the environment to maintain operating conditions
14 within the design limits. Cooling towers' operation principle is based on heat and mass
15 transfer using direct contact between ambient air and hot water. Cooling towers require
16 distributing or spraying water over a heat transfer surface across or through which a
17 stream of air passes. As a result, water droplets are incorporated in the air stream and,
18 depending on the velocity of the air, will be carried out of the unit. This is known as
19 drift and it is independent of water lost by evaporation.
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31 Cooling tower drift is objectionable for several reasons, Lewis (1974). Mainly, it
32 represents an emission of chemicals or microorganisms to the atmosphere. In addition,
33 corrosion problems can result on equipment, piping and structural steel, and can be the
34 source of electrical systems' failure. Atmospheric emissions from cooling towers are
35 becoming an increasingly important factor in the design and operation of industrial and
36 commercial cooling systems. Micheletti (2006) examines the environmental regulations
37 related to cooling tower emission.
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48 In the case of cooling towers, undoubtedly, the most well known pathogens are the
49 multiple species of bacteria collectively known as legionella. These bacteria tend to
50 thrive at the range of water temperatures frequently found in these cooling systems.
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4 Hence, workers or other persons near a cooling tower may be exposed to drift, may
5 inhale aerosols containing the legionella bacteria, and may become infected with the
6 illness. Several legionella outbreaks have been linked to cooling towers (Bentham and
7 Broadbent (1993); Brown et al. (1999) and Isozumi et al. (2005)).
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12 It is common practice to fit drift eliminators to cooling towers in order to minimise the
13 water loss from the system. Drift eliminators work by changing the direction of the
14 airflow as it passes through the eliminator section so that most of the entrained droplets
15 are separated from the air stream and fall back into the unit. The presence of the drift
16 eliminator mainly affects two aspects of cooling towers: their thermal performance and
17 the amount of water drift loss.
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27 Cooling tower thermal performance is mainly conditioned by the packing geometry.
28 Many studies that show this aspect can be found in the literature, Goshayshi and
29 Missenden (2000), Gharagheizi et al. (2007) or Elsarrag (2006). However, the presence
30 of a drift eliminator will reduce the air mass flow rate within the cooling tower thus
31 decreasing the tower's cooling capacity. This particular effect can be very detrimental in
32 natural draft cooling towers since only the air flow rate induced by the air density
33 difference between the entrance and exit of the cooling tower pass through them. In
34 mechanical draft cooling towers, the cooling capacity reduction caused by the pressure
35 drop introduced by the drift eliminator can be overcome with an increase in the fans'
36 power consumption. Therefore, for an inexpensive cooling tower performance, the
37 pressure drop across the eliminator should be as low as possible. Although pressure
38 drop is a primary variable, to evaluate a drift eliminator it will be necessary to assess its
39 influence on the cooling tower's thermal performance. Lucas et al. (2009) have
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4 demonstrated, by the experimental calculation of the tower characteristic, that the
5 physical configuration of the drift eliminator influences the thermal performance of the
6 cooling tower for the same water to air mass flow ratio. This result was explained in
7 terms of the drift eliminator getting wet and therefore becoming an additional packing
8 volume and contributes to the heat and mass transfer exchange.
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15 The literature describes numerous techniques and devices to measure cooling tower drift
16 emissions, diverse in terms of sophistication, basic principles of operation and
17 measurement capabilities. The most detailed comparison of methods can be found in the
18 work of Golay et al. (1986). The results indicated that no single device is superior to the
19 alternatives over the entire range of cases tested. Devices performing best under low
20 water loading conditions utilise sensitive surface techniques. Devices performing best
21 under high water loading conditions include the isokinetic mass sampling and chemical
22 balance techniques. Whittermore et al. (1993) compared two isokinetic methods
23 HGBIK and EPA 13A, which differ only in the collection train. They found nearly
24 identical results in the series of tests. Missimer et al. (1998) studied the relationship
25 between Sensitive Paper and HGBIK drift measurements. They concluded that the drift
26 rate computed for the Sensitive Paper test method was approximately 12% higher than
27 the average drift rate produced by the HGBIK method. However, they pointed out the
28 need for a second look. Missimer and Wheeler (1997) present a revision paper of the
29 available drift measurement. They concluded that the rate of drift loss in industrial
30 cooling towers had been reduced from 0.05% to 0.004% of the circulation rate by using
31 high efficiency drift eliminators since the 1970's.
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4 Some countries limit the amount of water drift emitted to the atmosphere. In the case of
5 Spain, the law establishes a maximum percentage of 0.05% of the circulating water
6 mass flow rate as the limit for the drift without referring to the method of measurement
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9 (Real Decreto 865/2003 (2003)).
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13 The standards in some countries specify the method to measure the drift loss from
14 cooling towers. The method adopted by the British Standard BS 4485.2 (1988) and by
15 the Japanese Industrial Standard JIS B 8609 (1981) is the Thermal Balance Method.
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17 The amount of drift loss is estimated by taking the difference between the quantity of
18 make-up water flow and the sum of the purge flow and evaporation loss. In order to
19 calculate evaporation loss it is necessary to include the water and ambient air conditions
20 measured in a mass and energy balance.
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29 The American Cooling Technology Institute uses the Isokinetic Drift Test Code ATC-
30 140 (1991): The Heated Glass Bead Isokinetic system (HGBIK) involves a sampler
31 which draws in effluent air at the same velocity as it is flowing at each individual
32 sampling location. HGBIK consists of the sampler (tube and canister combined),
33 umbilical cord (vacuum line, power cord and thermocouples leads), condensate trap and
34 control panel. A vacuum pump is used as the air moving device. The circulating water
35 must contain, either naturally or by artificial salting, a usable tracer element at levels
36 adequate to assure the ability to measure the concentration of the sample solutions. The
37 volume of drift water sampled can be calculated using the ratio of the micrograms
38 trapped in the concentration of tracer in the circulating water.
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4 The American Cooling Technology Institute in the Isokinetic Drift Test Code ATC-140
5 also refers to the Sensitized Surface Methods. Wilber and Vercauteren (1986) describe
6 their methodology. The air stream is forced around collection planes covered with
7 sensitive paper, upon which droplets impact and are recorded. Water droplets impinging
8 on this sensitive paper cause a chemical reaction in which a precipitate is formed,
9 leaving a droplet size-dependent stain. The processing of these exposed sensitive papers
10 consisted of measuring the stain diameters by means of a digital imaging processing
11 procedure that groups the counts of all stains by size ranges. Once the stain sizes are
12 counted and grouped according to size, calibration curves for specific droplet sizes are
13 employed via computer programmes to generate the original droplet sizes from which
14 the stains were formed.
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27 The method described in the Australian Standard AS 4180.1 (1994) is the Chloride
28 Balance Method, also cited as Chemical Balance Method. This method, in essence,
29 consists of the measurement of the rate of decrease in the concentration of a tracer
30 chemical added to the circulating water. An initial dose of the tracer is added to the
31 cooling water. When this material is uniformly mixed with the circulating water, a
32 sample is removed and analysed. After a period of time, a second sample is removed
33 and analysed. Drift loss may be calculated using the equations that take into account
34 evaporation.
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45 An experimental determination of drift loss from a cooling tower with six different drift
46 eliminators will be carried out in this study. These drift eliminators are the same
47 previously analysed from the point of view of thermal performance in Lucas et al.
48 (2009). Following the conclusions of Golay et al. (1986), the chemical balance method
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4 was selected as one of the most suitable to measure drift on a cooling tower where high
5 water loading conditions could be originated. This experimental information will
6 increase the knowledge to relate the geometry and types of droplet eliminators with the
7 amount of drift. Australian Standard methodology is taken as a reference, but some
8 modifications are proposed to reduce uncertainty obtained with some eliminators' drift
9 measurement. Up to now, there is no available criterion for designing drift eliminators
10 in order to optimise both drift emissions and the cooling tower's thermal performance.
11 Based on the information available for the eliminator tested, a selection criterion is
12 proposed.
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2. Method

The chemical balance method, or also called indirect method, has its origin in the work of Campbell (1969). He presents the mass balance associated with the evolution of a tracer in a cooling tower in which evaporation is not considered. He proposes the differential equation for mass conservation of the tracer and calculates the amount of drift over a period of time knowing the evolution of tracer concentration. He concluded that unaccounted losses of circulating water can be a serious source of error. These losses will be erroneously accounted for as drift loss. Subsequent work by Kessick et al. (1975) used this method with different tracers, in particular, boron and chromium. Later, Maclaine-Cross and Behnia (1992) improve the measurement accuracy by incorporating the amount of water evaporated to equations describing a methodology for their resolution. They perform their work considering the chloride ion as a tracer, obtained from the dissolution of sodium chloride. This work was taken as reference for the development of standard AS-4180.1 Drift loss from cooling towers – Laboratory measurement. Part 1: Chloride balance method. Australian Standards.

2.1 Chemical Balance Method

The tests consist of three defined intervals between sampling instants, the initial interval, or "Make-Up Period", the interval when the tracer is dissolved "Dissolution Period" and "Drift Measurement Period", when usually tracer concentration decreases in the circulating water. Figure 1 shows a typical evolution of the concentration during a test. In the initial interval (1-2), the tracer concentration increases as a result of that the make-up water, which compensates the loss of water evaporated and water drift, and adds mass tracer maintaining the total amount of water present constant. Next, in the

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4 “Dissolution Period” (2-3), a known amount of tracer is dissolved by the tester and there
5 is a substantial increase in concentration. From that moment it is usual that the tracer
6 concentration decreases (3-4). The make-up water compensates both the water
7 evaporated and water drift however, in this case, the mass of tracer that leaves the
8 cooling tower exceeds the addition of the water supply because water drift contains a
9 high concentration of tracer. Figure 2 shows the most significant variables for the
10 equation system.
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19 [Figure 1]

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22 [Figure 2]

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26 For conservation of water mass, the increase in the circulating water mass, dM_c / dt ,
27 equals the flow rate of the make-up water, \dot{M}_m , minus the drift loss rate, \dot{M}_d , and
28 evaporation rate, \dot{M}_e .
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$$\frac{dM_c}{dt} = \dot{M}_m - \dot{M}_d - \dot{M}_e \quad (1)$$

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36 The circulating water mass, M_c , may be used to calculate the circulating tracer mass as
37 $c_c M_c$. For conservation of tracer mass, the rate of increase in the circulating tracer
38 mass, $d(c_c M_c) / dt$, will equal the sum of tracer addition by the tester, \dot{m}_t , and from the
39 surroundings, \dot{m}_s , and make-up water, $c_m \dot{M}_m$, minus the drift loss rate, $c_c \dot{M}_d$. This may
40 be expressed by the following equation:
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$$\frac{d(c_c M_c)}{dt} = \dot{m}_t + \dot{m}_s + c_m \dot{M}_m - c_c \dot{M}_d \quad (2)$$

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50 Substituting Equation 1 into Equation 2 and rearranging gives,
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$$M_c \frac{dc_c}{dt} = \dot{m}_t + \dot{m}_s + c_m \dot{M}_e + (c_m - c_c) \left(\dot{M}_d + \frac{dM_c}{dt} \right). \quad (3)$$

Deriving Equation 3 has required no assumptions except that all necessary terms have been included for conservation of water and tracer. If it were possible to accurately measure the derivatives and flows in equation 3, drift loss measurement could be based just on solving this equation at a particular moment. The derivatives and flows are generally very difficult to measure, and Maclaine-Cross and Behnia (1992) propose a methodology to calculate drift loss rate. The major assumptions that are used may be summarised as:

1. Drift loss, M_d , does not vary during the test. If it does, the test gives a weighted average between t_3 and t_4 .
2. Tracer is washed from the inlet air into the circulating water at a constant rate m_s . If the tracer in the inlet air is due to recirculation of exhaust air, a wind change may cause it to vary. Recirculation should be less than 1% of airflow for well-designed and installed towers, making possible error be less than 1% of drift loss.
3. Tracer concentration in the make-up water, c_m , is constant. Mains water is unlikely to vary in concentration by more than 1% between samples causing an error typically 0.5% of measured drift loss.
4. $\frac{dM_c}{dt}$ is negligible. M_c varies because of expansion of the circulating water with temperature variation during the test, however, the tests are performed without thermal load and this expansion is not significant

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4 5. The evolution of the concentration is linear in the three intervals in which the
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6 test is divided.
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9 Equation 3 may be now integrated with respect to time for each of the three periods of
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11 time and then divided by the corresponding time period to give the following three
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13 equations:

$$14 \quad M_c \frac{(c_{c2} - c_{c1})}{(t_2 - t_1)} = \dot{m}_s + c_m \dot{M}_{e12} + (c_m - \frac{c_{c2} + c_{c1}}{2}) \dot{M}_d \quad (4)$$

$$15 \quad M_c \frac{(c_{c3} - c_{c2})}{(t_3 - t_2)} = \dot{m}_s + c_m \dot{M}_{e23} + (c_m - \frac{c_{c2} + c_{c3}}{2}) \dot{M}_d + \frac{m_t}{t_3 - t_2} \quad (5)$$

$$16 \quad M_c \frac{(c_{c4} - c_{c3})}{(t_4 - t_3)} = \dot{m}_s + c_m \dot{M}_{e34} + (c_m - \frac{c_{c3} + c_{c4}}{2}) \dot{M}_d \quad (6)$$

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22 where \dot{M}_{e12} , \dot{M}_{e23} and \dot{M}_{e34} are average values of the evaporation rate over the times
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24 indicated by subscripts.
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28 Subtracting Equation 6 from Equation 5 and rearranging gives the following expression
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30 for the mass of circulating water,
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$$32 \quad M_c = \frac{m_t + (t_3 - t_2) \left[(c_m (\dot{M}_{e23} - \dot{M}_{e34}) - \dot{M}_d \frac{c_{c2} - c_{c4}}{2}) \right]}{c_{c3} - c_{c2} + (c_{c3} - c_{c4}) \frac{(t_3 - t_2)}{(t_4 - t_3)}} \quad (7)$$

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39 Subtracting Equation 4 multiplied by $\dot{M}_{e34} / \dot{M}_{e12}$ from Equation 6 and rearranging gives

$$40 \quad \dot{M}_d = 2M_c \frac{\frac{c_{c3} - c_{c4}}{t_4 - t_3} + \frac{c_{c2} - c_{c1}}{t_2 - t_1} \frac{\dot{M}_{e34}}{\dot{M}_{e12}}}{c_{c3} + c_{c4} - (c_{c2} + c_{c1}) \frac{\dot{M}_{e34}}{\dot{M}_{e12}} - e_d} \quad (8)$$

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47 where $e_d = 2(\frac{\dot{m}_s}{\dot{M}_d} + c_m)(1 - \frac{\dot{M}_{e34}}{\dot{M}_{e21}})$. Equation 7 and 8 both have small terms containing the
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49 make-up water concentration, c_m . It will be additionally assumed that,
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4 6. $(t_3 - t_2)(c_m(\dot{M}_{e23} - \dot{M}_{e34}) - \dot{M}_d \frac{c_{e2} - c_{e4}}{2})$ is negligible. This is typically less than

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7 0.03% of m_i .

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9 7. $(\frac{m_s}{\dot{M}_d} + c_m)(1 - \frac{\dot{M}_{e34}}{\dot{M}_{e21}})$ is negligible. This is typically less than 1% of c_{e3} .

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12 The above simplifications lead to the equations used to calculate the amount of
13 circulating water and the drift loss rate, in the same way as it appears in the Australian
14 Standard (1994):
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$$M_c = \frac{m_i}{c_{e3} - c_{e2} + (c_{e3} - c_{e4}) \frac{(t_3 - t_2)}{(t_4 - t_3)}} \quad (9)$$

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$$\dot{M}_d = 2M_c \frac{\frac{c_{e3} - c_{e4}}{t_4 - t_3} + \frac{c_{e2} - c_{e1}}{t_2 - t_1} \frac{\dot{M}_{e34}}{\dot{M}_{e12}}}{c_{e3} + c_{e4} - (c_{e2} + c_{e1}) \frac{\dot{M}_{e34}}{\dot{M}_{e12}}} \quad (10)$$

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31 The ratio, $\frac{\dot{M}_{e34}}{\dot{M}_{e12}}$ of mean evaporation rate during the drift measuring period, can be
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33 estimated by means of MacLaine-Cross and Banks' linearised theory (1981).

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$$r_e = \frac{\dot{M}_{e34}}{\dot{M}_{e12}} = \frac{EWBD_3 + 4 \cdot EWBD_{3b} + EWBD_4}{EWBD_1 + 4 \cdot EWBD_{1b} + EWBD_2}, \quad (11)$$

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40 The Effective Wet Bulb Depression is defined as:

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$$EWBD_j = T_j - Twb_j + Tw_j - Twb_j \quad (12)$$

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44 where T_j is the dry bulb ambient temperature, Twb_j is the wet bulb ambient temperature
45 and Tw_j the circulating water temperature. The mean Effective Wet Bulb Depression for
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47 each period shall be calculated as one-sixth of the sum of the initial, the final, and four
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49 times the middle value of the effective wet bulb depression
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6 *2.2 Experimental Set-Up*
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10 Experiments were carried out in a test facility assembled on the roof of a laboratory at
11 the Universidad Miguel Hernández in the city of Elche, southeast of Spain (see Figure
12 3). The main device of this test plant is a forced draft cooling tower with a cross-
13 sectional area of $0.70 \times 0.48 \text{ m}^2$, a total height of 2.597 m and a packing section that is
14 1.13 m high. The packing material consists of fiberglass vertical corrugated plates.
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16 Water pressure nozzles are used to distribute the water uniformly over the packing and
17 the air is circulated counter-flow by an axial fan. Although the pilot plant has a thermal
18 load simulation system consisting of an electrical heater located in a water tank, for tests
19 it will not be turned on. The fan's motor is equipped with a variable speed control,
20 which allows the change of the air mass flow rate, while sprayed water mass flow rate
21 can be changed manually by means of a balancing valve.
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33 [Figure 3]
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35
36 The amount of drift from the cooling tower was experimentally investigated for six
37 different drift eliminators (see Figure 4). Drift eliminators A, B and C, present a zig-zag
38 structure and consist of fiberglass plates separated at distances of 55, 37 and 30 mm
39 respectively. Drift eliminator D is made of plastic as a honeycomb, while drift
40 eliminator E is a 45° tilted rhomboid mesh also made of plastic. Drift eliminator F has
41 the same structure as eliminator E with a 45° tilted lower half and a 135° tilted upper
42 half.
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51 [Figure 4]
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6 A general-purpose data-acquisition system was set up to carry out the experimental
7 tests. All data was monitored with an HP 34970A Data Acquisition Unit. Specific
8 software was written and compiled for the system, supporting up to 36 inputs, with 16
9 bits A/D, 9600 bauds transmission speed and programmable gain for individual
10 channels. The sensors used during the experiment are shown in Figure 5. The
11 specifications of the measuring devices are shown in Table 1.
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19 [Figure 5]
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23 [Table 1]
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27 *2.3 Experimental Procedure*

28 The reference document for defining the experimental procedure is the Australian
29 Standard AS-4180.1 (1994). Annex A shows the experimental methodology described
30 in this document that determines the length of test periods and the amount of tracer to
31 dissolve in detail. However, it has been found that the lower the drift values, the higher
32 the relative uncertainty on the measured value. Even it happens that the level of
33 uncertainty exceeds the obtained drift value. This situation is considered inappropriate
34 to present results. In fact, the authors of the standard described the following
35 recommendations to reduce the uncertainty in measurement, Maclaine-Cross and
36 Behnia (1993):
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- 46 • Reduce the amount of water present in the circuit to a minimum.
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- 48 • Increase the accuracy of chemical analysis of the tracer.
- 49
- 50 • Increase the time periods of the trial.
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4 Among the three options for improvement, the possibility of reducing the water is
5 justified for measurements in industrial installations where the cooling system may have
6 some importance. In the case of the pilot plant the circuit through the electrical heaters
7 is closed since the tests are done without thermal load, see Figure 5, minimising the
8 amount of water present in the system.
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15 To establish the implications of modifying the test duration and precision of the analysis
16 on the value of the uncertainty, a simulation model in EES (Engineering Equation
17 Solver (2010)) is developed. This model includes all the necessary equations to
18 determine drift loss and enables the calculation of measurement uncertainty according
19 to ISO guide (1993) for uncertainty calculation, once the test data and information on
20 the accuracy of the sensors is incorporated.
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29 Following the methodology described above when the drift eliminator B is installed, as
30 an example, with initial considerations for a water flow rate $5.2 \text{ m}^3/\text{h}$, an estimated
31 amount of water of 90 l and an initial concentration of the water intake of $0.573 \text{ g Cl} /$
32 $\text{kg H}_2\text{O}$ (that is $0.8 \text{ g NaCl} / \text{kg H}_2\text{O}$), defines the time intervals and quantity NaCl to
33 dissolve ($m_{\text{NaCl}}=3.057 \text{ gr}$, $\Delta t_1=3115 \text{ s}$ y $\Delta t_2=6231 \text{ s}$). So, “make-up period” duration is 1
34 hr and “drift measurement period” duration is 2 hr. The values of the test are presented
35 in Table 2.
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45 [Table 2]
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4 Drift loss ratio ($100 \cdot \dot{M}_d / \dot{M}_c$) for Drift Eliminator B is $0.05777 \pm 0.01862\%$, showing
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6 combined standard uncertainty. This means that drift loss ratio is calculated with a level
7
8 of uncertainty on the measured value of 32%.

9
10 Measurement uncertainty is associated mainly to the uncertainty in the determination of
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12 tracer. The technique used is the ion selective electrode. It has been chosen among
13
14 others such as silver nitrate titration, conductivity or mass spectroscopy to fulfill the
15
16 dual purpose of covering the entire measurement range and maintaining a low level of
17
18 uncertainty ($\pm 2\%$ of the measured concentration). It was decided to maintain the
19
20 measurement technique and perform several tests on samples. Thus, Type A evaluation
21
22 of uncertainty of the ISO guide is selected to refer the calculation to the method of
23
24 evaluation of uncertainty by the statistical analysis of series of observations, where the
25
26 experimental variance of the mean is affected by the number of samples

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29
$$s^2(\bar{X}_i) = \frac{s^2(X_i)}{N}$$
 where N is the number of samples.
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33 Another option to reduce uncertainty is to increase the duration of the test. The EES
34
35 model is used to analyse the influence of the duration of the "Drift Measurement
36
37 Period", setting operating conditions during the test and the level of drift loss. For this it
38
39 is necessary to adjust the concentration at the end of the measure to achieve the same
40
41 level of drift loss. Figure 6 is constructed by performing the calculations changing the
42
43 test duration and number of samples for Drift Eliminator B and the example described
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45 above.

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47 [Figure 6]
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4 The final decision for the procedure used is a compromise between acceptable
5 uncertainty, duration of the test and the number of water samples. The procedure starts
6 with a test according to Australian standard and, depending on the results obtained, a
7 second test where both duration of the test and the number of samples to be taken will
8 be considered. The loop is completed when the uncertainty of the measure is an order of
9 magnitude lower than the measure itself. An additional criterion adopted is that the
10 duration of the test shall not exceed 24 hr in order to reduce the number of tests failed
11 due to external agents such as rain or power failures. If in this time uncertainty is not
12 successfully reduced to an acceptable value, the number of samples will be increased.

13
14 It was preferred to increase the test duration instead of increasing the number of samples
15 since the latter takes more time and effort in the laboratory. Figure 7 shows a scheme
16 with the methodology to be followed.

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29 [Figure 7]

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34 Using Figure 6, it was decided to carry out a second test with a "Drift Measurement
35 Period" of 6 hr, which makes a total duration for the test of 27 000 s, and taking a
36 sample. The most representative values of the test are shown in Table 3.

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42 [Table 3]

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46 Drift loss ratio for Drift Eliminator B is now 0.05510 ± 0.00562 %, where relative
47 combined standard uncertainty is reduced to 10.199%.

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6 **4. Results**
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9 This section show the results of drift measurement initially without and then with the
10 different drift eliminator installed. It was considered of interest to measure without drift
11 eliminator to evaluate the improvement obtained by the presence of each eliminator.
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16 Table 4 lists the main variables of the various tests highlighting the drift values obtained
17 and relative combined uncertainty. The results shown have been obtained in accordance
18 with Australian Standard and then, if the uncertainty is a lower order of magnitude, it
19 proceeds according to the scheme shown in Figure 7.
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26 As a sample, since these graphs were obtained for all tests, Figure 8 shows the evolution
27 of the most significant temperature during the test of drift eliminator A. From this data
28 Mean Effective Wet Bulb Depression and mean evaporation rate during the tests were
29 calculated.
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36 [Table 4]
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40 [Figure 8]
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43 Also represented in Figure 9 we find the evolution of the tracer concentration in the case
44 where the tests were carried out with the procedure described in Australian Standard.
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49 [Figure 9]
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5 In those tests in which levels of uncertainty obtained are higher than desired, the so-
6 called "long test" must be carried out. To define the new test conditions the ESS model
7 is used. The graph of relative combined uncertainty as a function of test duration and
8 number of samples taken is constructed in the same manner as in the example shown
9 previously for drift eliminator B.

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14 Table 5 lists the main variables of the tests that required modification of the duration
15 and/or number of sampling. Figure 10 shows the evolution of the tracer concentration in
16 these tests.
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22 [Table 5]
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26 [Figure 10]
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30 Figure 11 shows the summary of the values of water drift for different droplet
31 separators and level of uncertainty.
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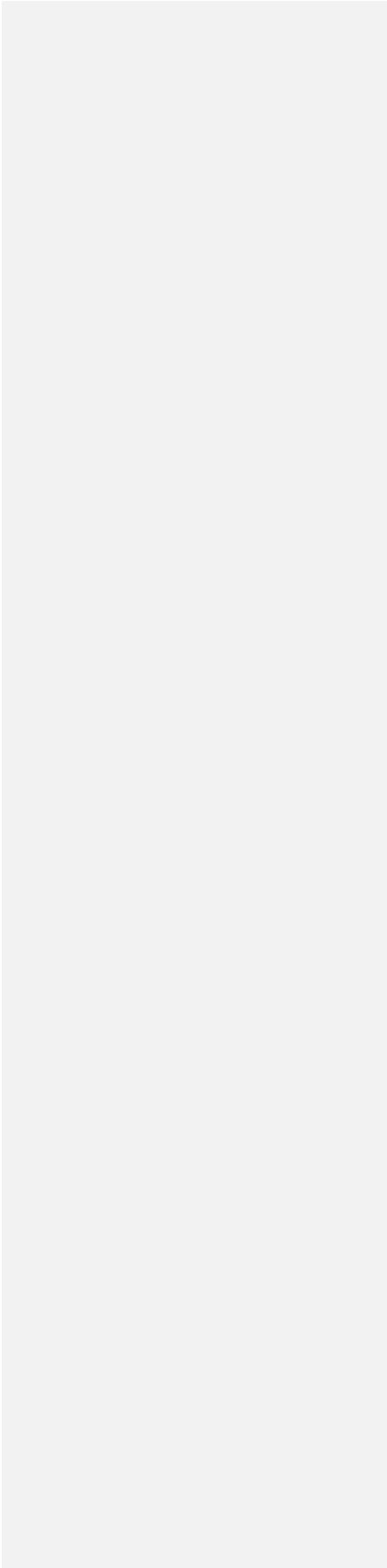
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36 [Figure 11]
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42 The first observation that can be done is that the level of drift when no drift eliminator is
43 installed is very substantial (0.3936%). The installation of a drift eliminator, even in the
44 worst case, reduces the water drift level by less than half. Specifically, for drift
45 eliminator A a reduction of 59% was obtained, 86% for drift eliminator B, 90% for drift
46 eliminator D, 96% for C and E and 97% for F. Within drift eliminators A, B and C,
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which have the same structure with the difference in the number of plates, it can be seen how the level of drift is reduced by increasing the density of the plates, as seemed likely. Eliminators E and F, that have the same mesh, reach similar drift levels. Reaching a level slightly below eliminator F, which has a division in the middle of the height at which the mesh is rotated 180 °.

Taking as reference the value limit of 0.05% which marks the Spanish Legionellosis Law, eliminators C, D, E and F provide lower values than those set by the regulations and, therefore, would be acceptable for installation.



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6 **5. Conclusions**
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8
9 The presence of the drift eliminator mainly affects two aspects of cooling towers: their
10 thermal performance and the amount of water drift loss.
11

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13 The physical configuration of the drift eliminator influence on the thermal performance
14 of the cooling tower was studied in a previous work.
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16
17 The main objective of this paper was the experimental determination of drift loss from a
18 cooling tower without drift eliminators and fitted with six different drift eliminators.
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23 The literature describes numerous techniques and devices to measure cooling tower drift
24 emissions, diverse in terms of sophistication, basic principles of operation and
25 measurement capabilities. The results indicated that no single device is superior to the
26 alternatives over the entire range of cases tested.
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32 Chemical Balance is the selected method and Australian Standard methodology is taken
33 as a reference. Some modifications are proposed to reduce uncertainty by means of
34 increasing the duration of the test and the number of water samples.
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40 The first observation that can be made is that the level of drift, when no drift eliminator
41 is installed, is very substantial (0.3936%). The installation of a drift eliminator, even in
42 the worst case, reduces the water drift level to less than half of the situation without an
43 eliminator. Specifically, a reduction of 59% was obtained for drift eliminator A, 86%
44 for drift eliminator B, 90% for drift eliminator D, 96% for C and E and 97% for F.
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49 Within drift eliminators A, B and C, which have the same structure with the difference
50 in the number of plates, it can be seen how the level of drift is reduced by increasing the
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4 density of the plates, as seemed likely. Eliminators E and F, that have the same mesh,
5 reach similar drift levels. Reaching a level slightly below eliminator F, which has a
6 division in the middle of the height at which the mesh is rotated 180°. Taking as
7 reference the value limit of 0.05% which marks the Spanish Legionellosis Law,
8 eliminators C, D, E and F provide lower values than those set by the regulations and,
9 therefore, would be acceptable for installation.
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17 In order to place the results obtained with literature data mentions that Ashrae (2004)
18 establishes the range in which drift losses are between 0.2 and 0.002%.

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20
21 Missimer and Wheeler (1997) present a revision paper on the available drift
22 measurement. They concluded that the rate of drift loss of industrial cooling towers had
23 been reduced from 0.05% to 0.004% of the circulation rate by using high efficiency drift
24 eliminators since the 1970's. Thus, it should be noted that water drift losses obtained
25 with different drift eliminators installed in the pilot plant are within the range generally
26 reflected in literature.
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34 It is important to note that the drift values achieved by an eliminator in the plant with
35 certain operating conditions are restricted to those operating conditions. This means that
36 the drift is not a property of the eliminator, but the amount of water emitted by a tower
37 involves other elements such as the distribution system, fan and air flow distribution
38 inside the tower or filling.
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46 One issue to show at this point is that the results obtained from the measurements of
47 drift made in the pilot plant and data from literature suggest that the available
48 technology can achieve levels significantly lower than the upper limit set by legislation.
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51 This may lead to a reduction of the limits imposed by law.
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5 Once the results of drift emitted by a cooling tower with different eliminators and the
6 influence of their installation on the thermal behaviour of the tower are made available,
7 setting up a selection criterion should be considered.
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11 Up to now there is no available criterion for designing drift eliminators in order to
12 optimise both collection efficiency and the cooling tower's thermal performance.
13

14
15 Chan and Golay (1977) developed a numerical technique to design a drift eliminator for
16 a particular cooling tower by setting a pressure drop limit and then choosing the
17 geometry that released less water. This shows that these authors gave priority to energy
18 implications beyond environmental issues.
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24 However, this criterion is not valid in facilities subject to legislation that limits the
25 amount of drift. In cases where there is a maximum for emissions, the proposed
26 criterion is to select from among those separators that allow the installation to comply
27 with the legislation in force, one that offers better thermal performance.
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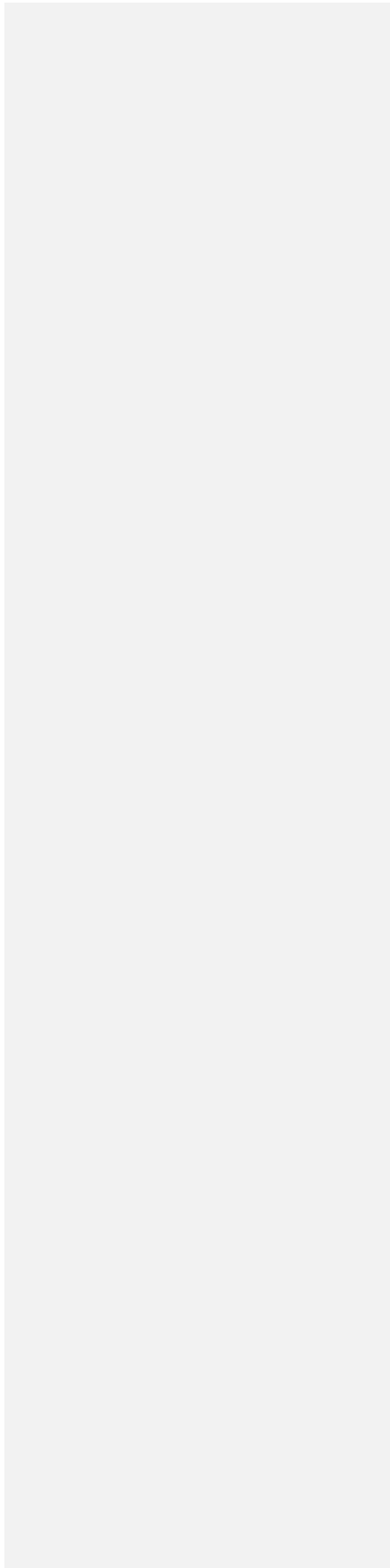
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34 Figure 12, obtained from Lucas et al. [9], shows the obtained tower characteristic
35 correlations for the tested drift eliminators. The higher the tower characteristic, the
36 greater the tower's cooling capacity. Although it depends on the mass flow ratio of
37 water and air, it can be seen how for almost the entire range studied the tower with
38 separator A is the one with a greater cooling capacity, followed by separating E and F,
39 then D and finally C and B.
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48 In response to the proposed criteria, the eliminators tested in the pilot plant which have
49 achieved a level below the maximum drift imposed by Spanish laws are C, D, E and F.
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51 Also taking into account the thermal behavior, the choice is between eliminators E and
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F since they have a similar behaviour among them and improve the separators obtained with C and D.



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4 ANNEX A
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8 a) Turn off or isolate water treatment chemicals (if any) from the system under test.

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10 b) Establish the mass of chloride in the circulating water. If the mass is greater than one-
11 tenth of the mass of sodium chloride to be added (at least 2g for each kilogram of
12 circulating water or 80 times the chloride mass dissolved in 1 kg of make-up water)
13 reduce by bleeding, draining or other effective method that will reduce this mass to
14 below one-tenth of the mass of sodium chloride to be added. Ensure the water circuit is
15 filled to the correct level.
16
17

18 c) Check to ensure the normal operation of the bleed-off (if any) and make-up water.

19
20 d) Start the system and run for a minimum of half an hour prior to any tests being
21 carried out.
22

23 e) Note-

24 i) date

25 ii) cooling tower manufacturer

26 iii) equipment type

27 iv) test location

28 v) model number

29 vi) serial number

30 vii) nominal airflow rate as provided by the manufacturer, and

31 viii) circulating water flow rate

32
33 f) Estimate the volume of circulating water in cubic meters and convert to a mass by
34 multiplying it by the density of water.
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36
37 g) Estimate the make-up water chloride measurement time (t_2-t_1) as the greater of 1800 s
38 or 50 times the circulating water mass divided by the water mass flow rate.
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4 h) Shut off bleed water, sample the circulating water, and note the time. The chloride
5 concentration in kg NaCl per kg H₂O is c_1 and time t_1 (write this time on the sample
6 container label). Measure inlet wet bulb and dry bulb temperatures and the circulating
7 water temperature.
8
9

10
11 i) On expiry of half the make-up chloride measurement time, measure the inlet wet bulb
12 and dry bulb temperatures and the circulating water temperature.
13
14

15 j) On expiry of the make-up water chloride measurement time, measure the inlet wet
16 bulb and dry bulb temperatures and the circulating water temperature. Sample
17 circulating water and note the time. The chloride concentration in kg NaCl per kg H₂O
18 is c_2 and time t_2 (write this time on a sample container label).
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22 k) Add at a controlled rate to the circulating water in the tower basin, the sodium
23 chloride solution (pre-dissolved in water to make a solution of an approximate NaCl
24 concentration of 0.25 kg/l) over a period of approximately one minute. Wait five
25 minutes after the make-up water control valve has reopened, which indicates the correct
26 operating liquid volume.
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31 l) Measure the inlet wet bulb and dry bulb temperatures and the circulating water
32 temperature. Sample circulating water and note the time. The chloride concentration in
33 kg NaCl per kg H₂O is c_3 and time t_3 (write this time on a sample container label).
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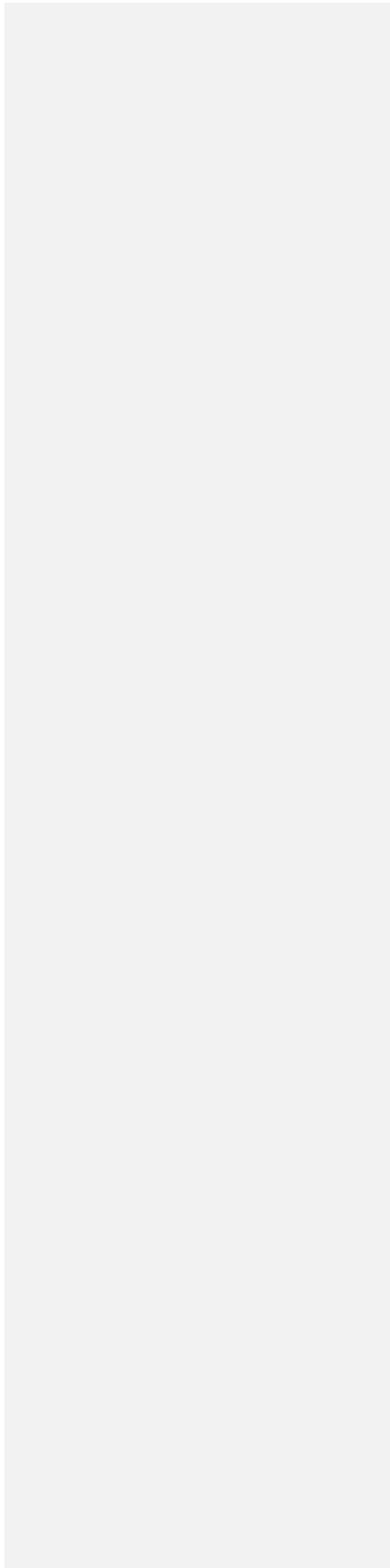
37 m) Estimate the make-up water chloride measurement time ($t_4 - t_3$) as the greater of 3600
38 s or 100 times the circulating water mass divided by the water mass flow rate.
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42 n) On expiry of half the drift measurement time, measure the inlet wet bulb and dry bulb
43 temperatures and the circulating water temperature.
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46 o) On expiry of the drift measurement time, measure the inlet wet bulb and dry bulb
47 temperatures and the circulating water temperature. Sample circulating water and note
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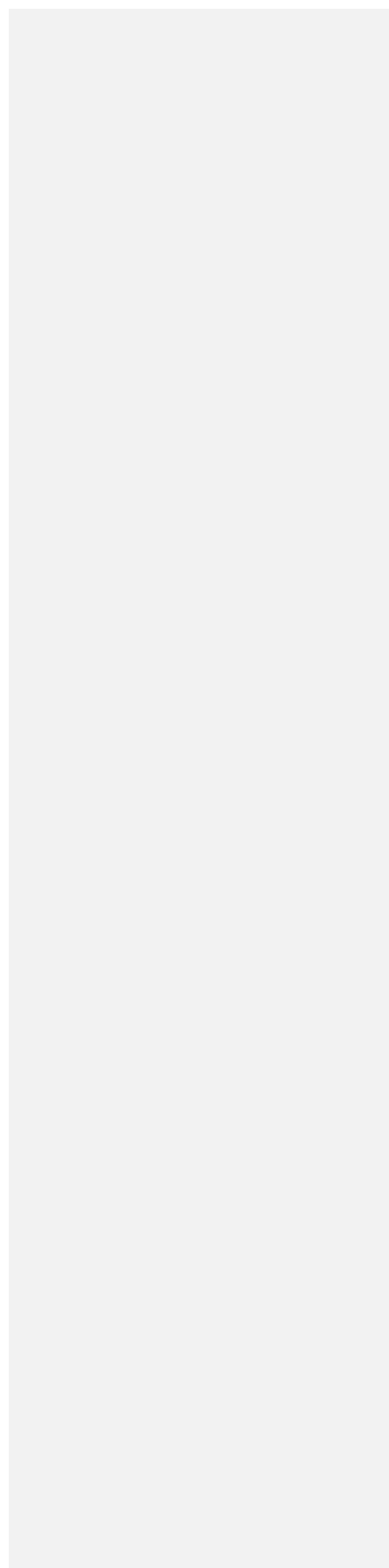
the time. The chloride concentration in kg NaCl per kg H₂O is c_4 and time t_4 (write this time on a sample container label).



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Nomenclature

<i>M</i>	<i>mass of water</i>	<i>(kg)</i>
<i>m</i>	<i>mass of tracer</i>	<i>(kg)</i>
<i>c</i>	<i>concentration of tracer</i>	<i>(kg tracer/kg)</i>
<i>t</i>	<i>time</i>	<i>(s)</i>
<i>EWBD</i>	<i>Mean Effective Wet Bulb Depression</i>	<i>(°C)</i>
<i>r_e</i>	<i>Mean evaporation rate during measuring period</i>	<i>(-)</i>
<i>T</i>	<i>dry bulb ambient temperature</i>	<i>(°C)</i>
<i>T_{wb}</i>	<i>wet bulb ambient temperature</i>	<i>(°C)</i>
<i>T_w</i>	<i>water temperature</i>	<i>(°C)</i>

Subscripts

<i>c</i>	<i>circulating</i>
<i>m</i>	<i>make-up water</i>
<i>d</i>	<i>drift</i>
<i>e</i>	<i>evaporation</i>
<i>t</i>	<i>tester</i>
<i>s</i>	<i>surroundings</i>

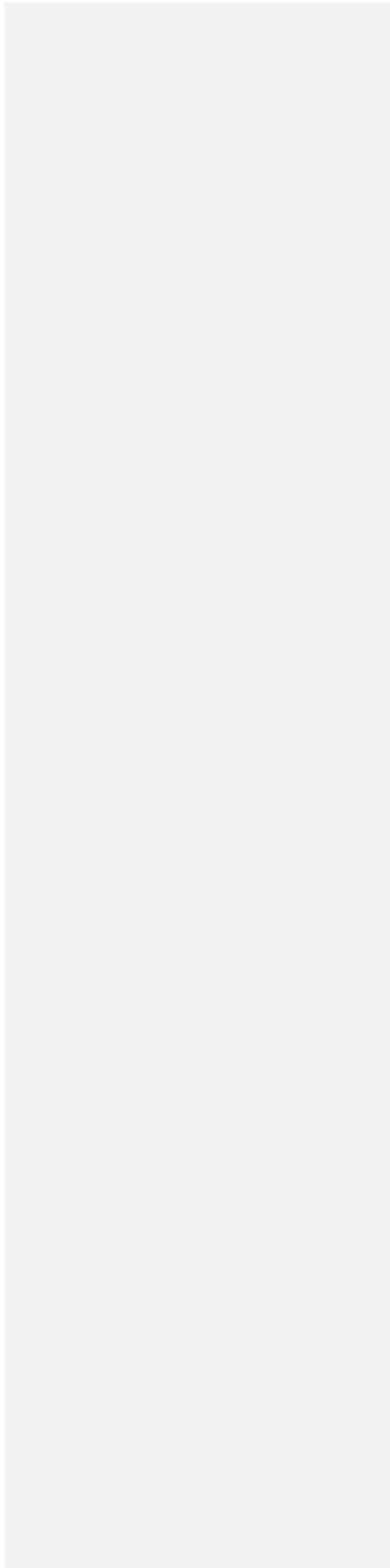


Table 1

Sensor devices' specifications

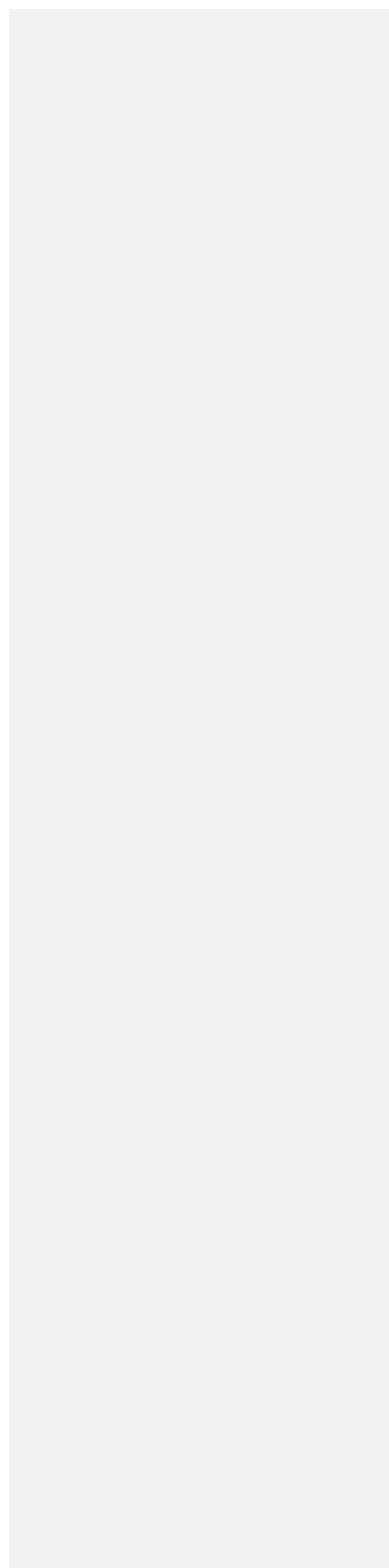
Parameter	Sensor	Range	Accuracy
Water temperature	Pt 100 type RTD	-200°C – 600°C	0.08°C
Water flow rate	Oval wheel flow meter	2 – 20 m ³ /h	0.4 % f.s.
Outlet Air velocity	Vane anemometer	0.5 – 20 m/s	0.1 m/s±1.5% m.v.
Outlet Air temperature	Capacitive	-20°C – 80°C	0.3°C
Outlet Air Relative Humidity	Capacitive	0 – 100%	±2%
Ambient temperature	Pt 1000 type RTD	-50°C – 50°C	0.2°C
Ambient Relative Humidity	Capacitive	0 – 100%	3% (10-90%) / 4% (0-10%, 90-100%)
Wind Velocity	Cup anemometer	0 – 50 m/s	0.3 m/s
Atmospheric pressure	Solid State	794 a 1050 mbar	5 mbar

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Table 2

Evolution of the variables in the test. Drift Eliminator B

Id.	time	Conc. g Cl/kg H ₂ O	Tdb	Twb	Tw
1	10:30	0.573	10.8	8.372	9.18
1b	11:00		12.63	9.046	9.95
2	11:30	0.616	12.9	8.743	9.75
3	12:00	16.625	12.37	8.759	9.65
3b	13:00		13.28	9.16	10.32
4	14:00	15.924	12.27	8.772	9.86



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Table 3

Evolution of the variables in the test. Drift Eliminator B Modified

Id.	Time	Conc. g Cl/kg H ₂ O	Tdb	Twb	Tw
1	9:30	0.616	10.89	8.43	9.42
1b	10:00		10.99	8.50	9.10
2	10:30	0.658	11.13	8.64	9.34
3	11:00	18.875	12.64	8.90	10.07
3b	14:00		12.44	8.72	9.45
4	17:00	16.455	13.09	9.07	9.96

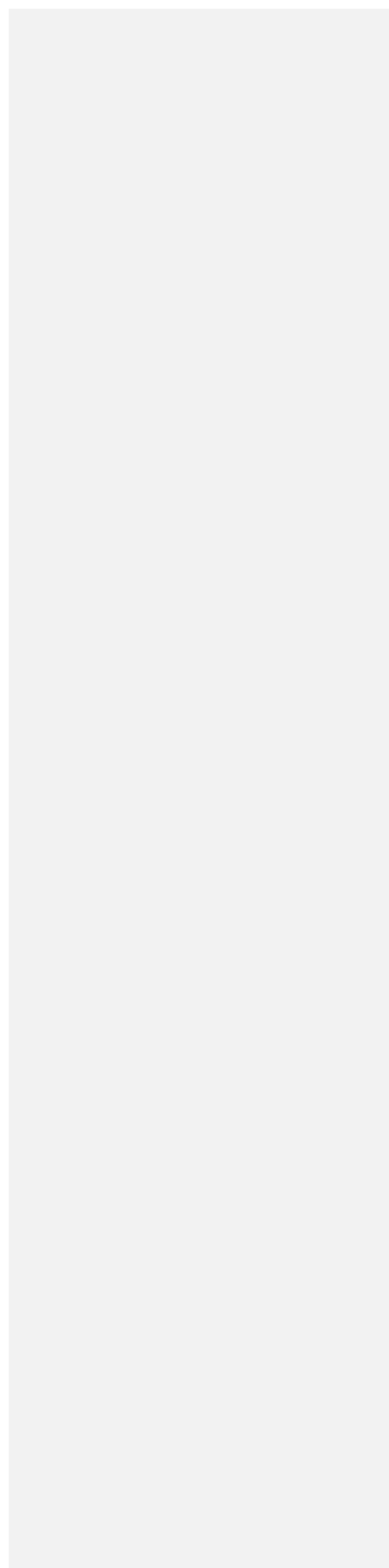


Table 4

Evolution of the main variables of the water drift loss tests

Drift eliminator	No drift Eliminator	A	B	C	D	E	F
Concentration C_{c1} (gr Cl/kg H ₂ O) t= 0 min.	0.552	0.549	0.572	0.512	0.531	0.658	0.508
Concentration C_{c2} (gr Cl/kg H ₂ O) t= 60 min.	0.573	0.634	0.616	0.554	0.574	0.637	0.529
Concentration C_{c3} (gr Cl/kg H ₂ O) t= 90 min.	16.476	17.134	16.625	16.966	16.964	16.349	16.347
Concentration C_{c4} (gr Cl/kg H ₂ O) t= 210 min.	11.614	15.096	15.924	16.943	16.561	15.945	16.242
re	1.267	1.454	1.450	1.149	1.521	0.845	0.913
Drift Loss Ratio. $100 \cdot \dot{M}_d / \dot{M}_c$	0.39361	0.16098	0.05777	0.00809	0.03709	0.02725	0.01057
Relative combined uncertainty	3.909%.	10.42%.	32%	232.26%	50.44%	70.60%.	182.68%.

Table 5

Evolution of the main variables of the water drift loss “long tests”

Drift eliminator	C	D	E	F
Total test duration (min)	1470	990	1530	1530
Number of samples	1	1	1	3
Concentration Cc1 (gr Cl/kg H2O) t= 0 min.	0.486	0.467	0.508	0.467
Concentration Cc2 (gr Cl/kg H2O) t= 60 min.	0.550	0.594	0.571	0.531
Concentration Cc3 (gr Cl/kg H2O) t= 90 min.	17.113	16.412	17.049	17.262
Concentration Cc4 (gr Cl/kg H2O) t= 210 min.	16.518	16.094	15.605	16.540
r_e	1.369	1.863	0.7887	0.9123
Drift Loss Ratio. $100 \cdot \dot{M}_d / \dot{M}_c$	0.01550	0.03894	0.01556	0.01180
Relative combined uncertainty	9.483%	13.174%	12,21%.	11,27%.

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4 **Figure Captions**

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5
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7 Figure 1. Evolution of the tracer concentration during a test

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11 Figure 2. Chemical Balance main variables

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15 Figure 3. View of pilot test facility assembled at Universidad Miguel Hernandez, Elche
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17 (Spain)

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21 Figure 4. Drift eliminators tested. Left side from up to down: Drift eliminator A, Drift
22 eliminator B, Drift eliminator C. Right side from up to down: Drift eliminator D, Drift
23 eliminator E and Drift eliminator F.

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29 Figure 5. Schematic diagram of counterflow cooling tower

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33 Figure 6. Relative combined uncertainty evolution of Drift Eliminator B, by changing
34 test time and number of samples

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39 Figure 7. Experimental procedure scheme

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43 Figure 8. Evolution of water temperature and wet and dry ambient temperature over the
44 test of the drift eliminator A

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49 Figure 9. Evolution of the tracer concentration in the case where the tests were carried
50 out with the procedure described in Australian Standard
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Figure 10. Evolution of the tracer concentration in the long tests

Figure 11. Values of water drift for different droplet separators and level of uncertainty

Figure 12. Tower characteristic vs. water to air mass flow ratio for the correlations of the six drift eliminators tested

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Figure 1
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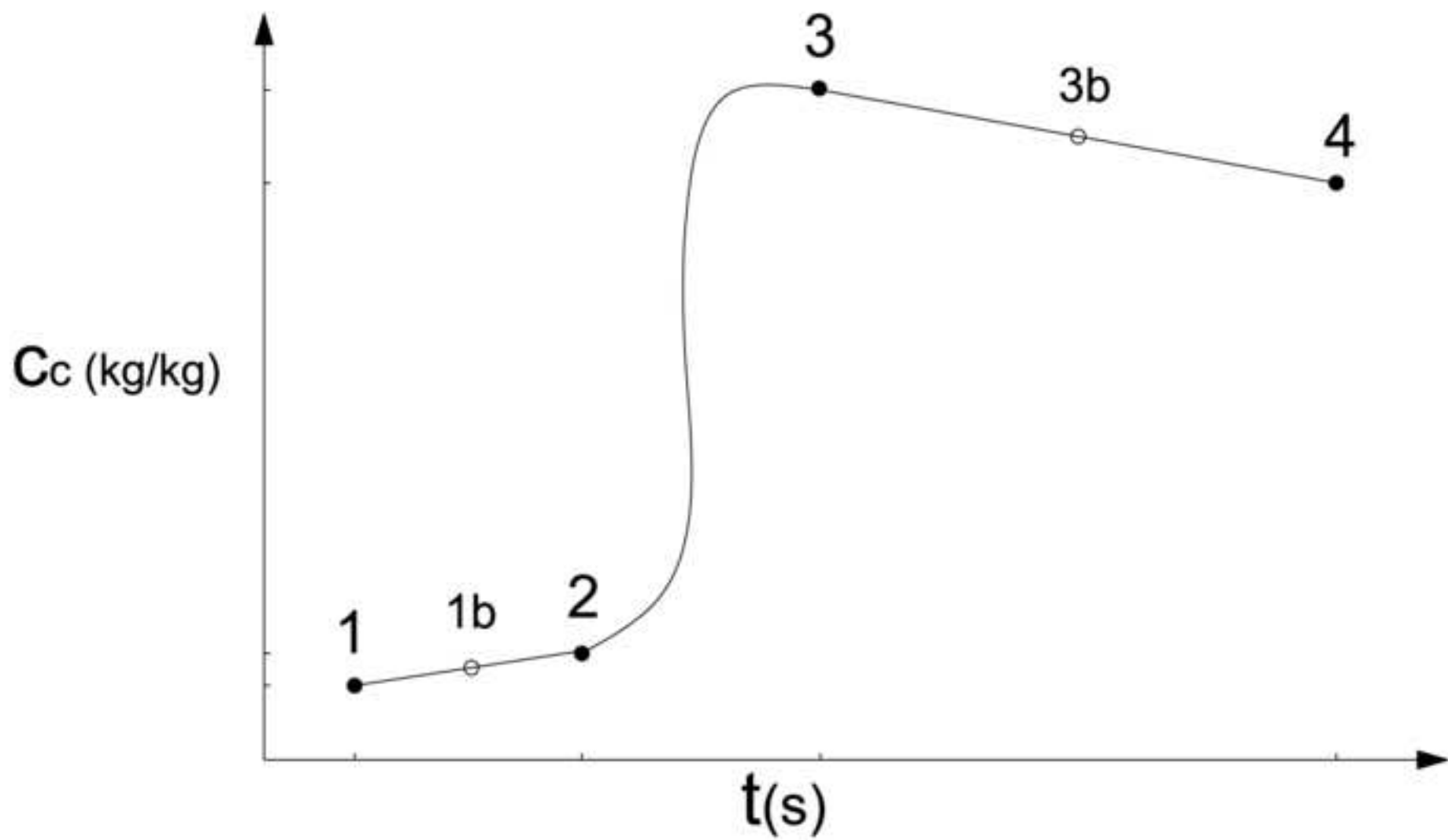


Figure 2
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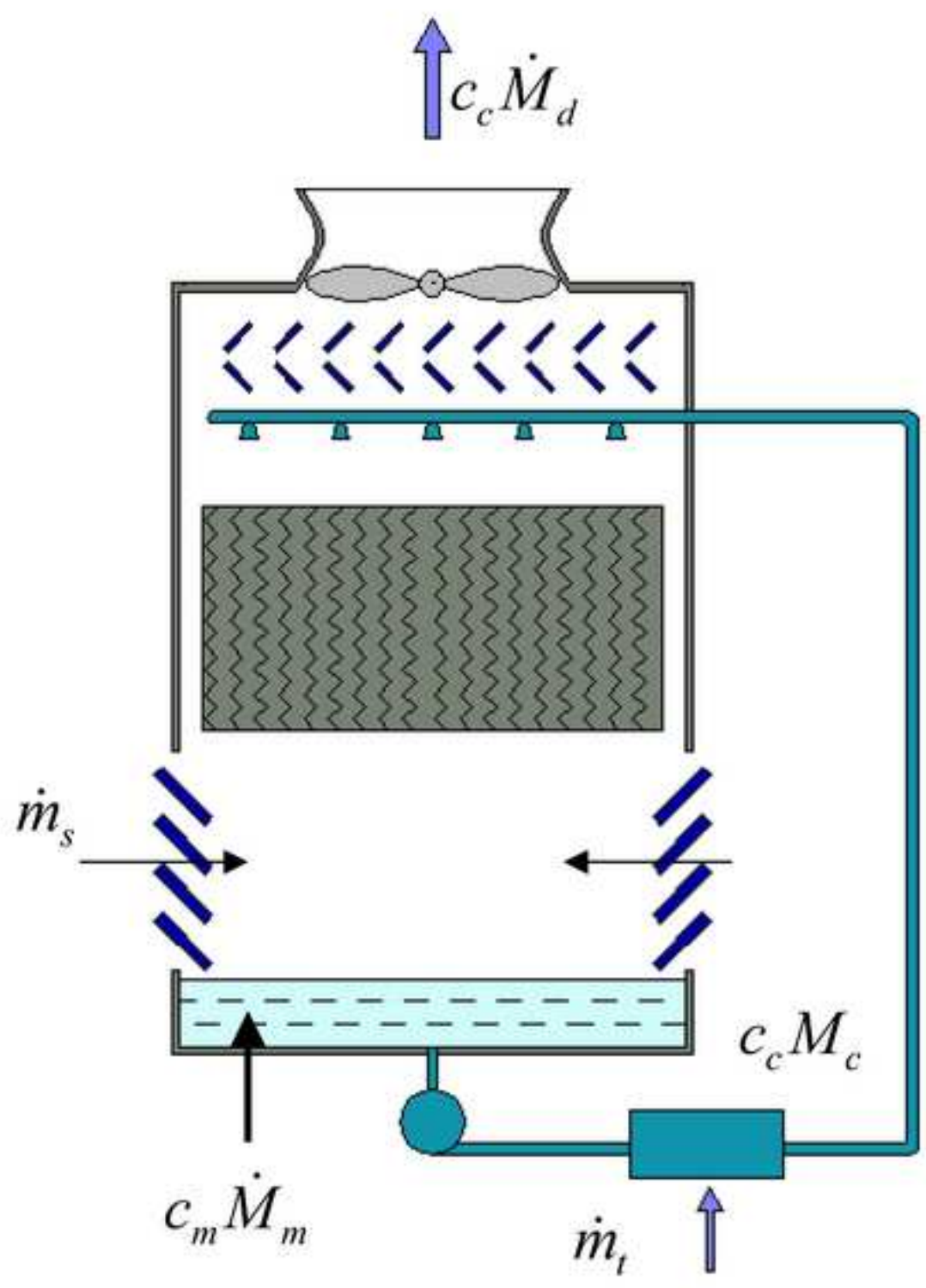


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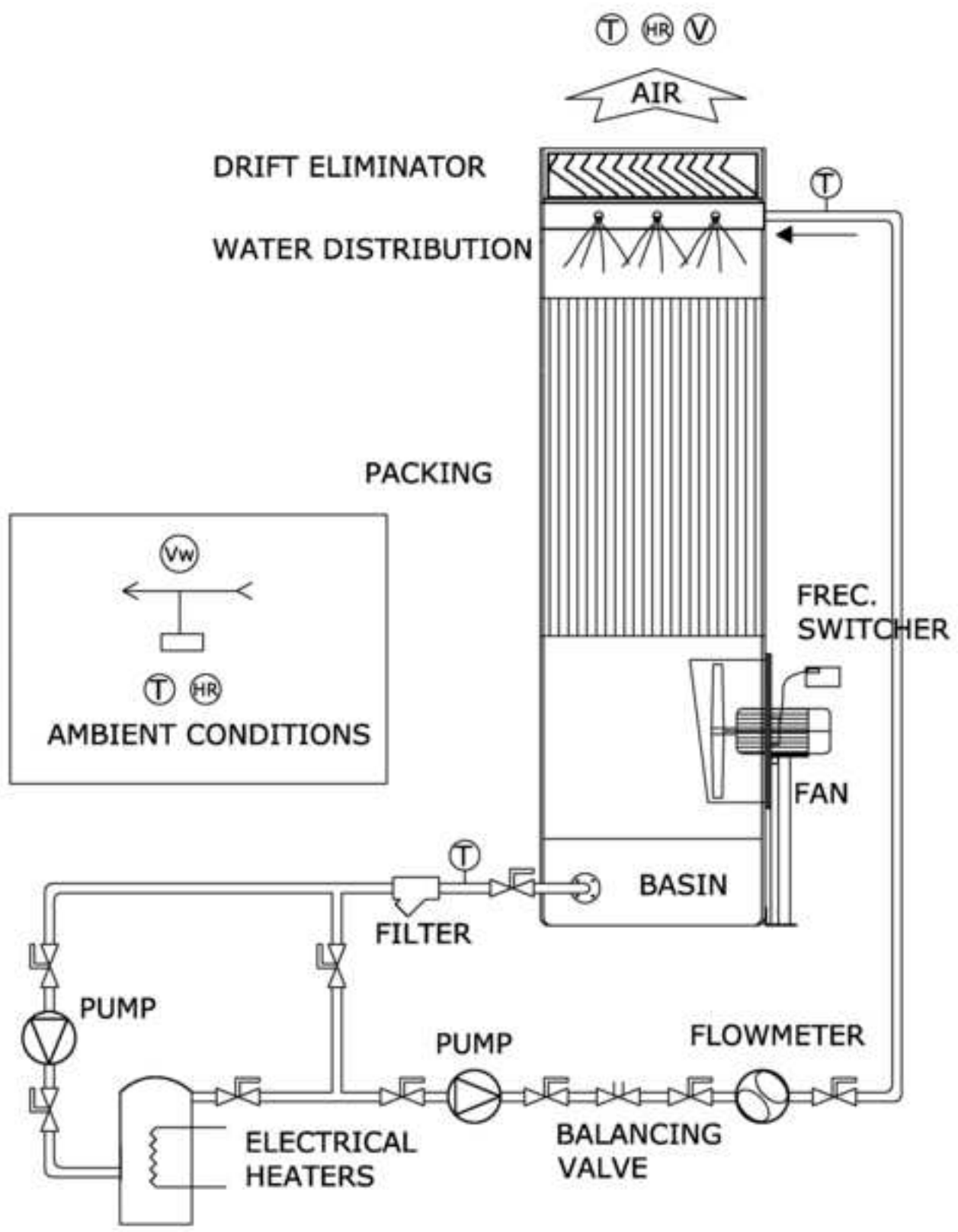


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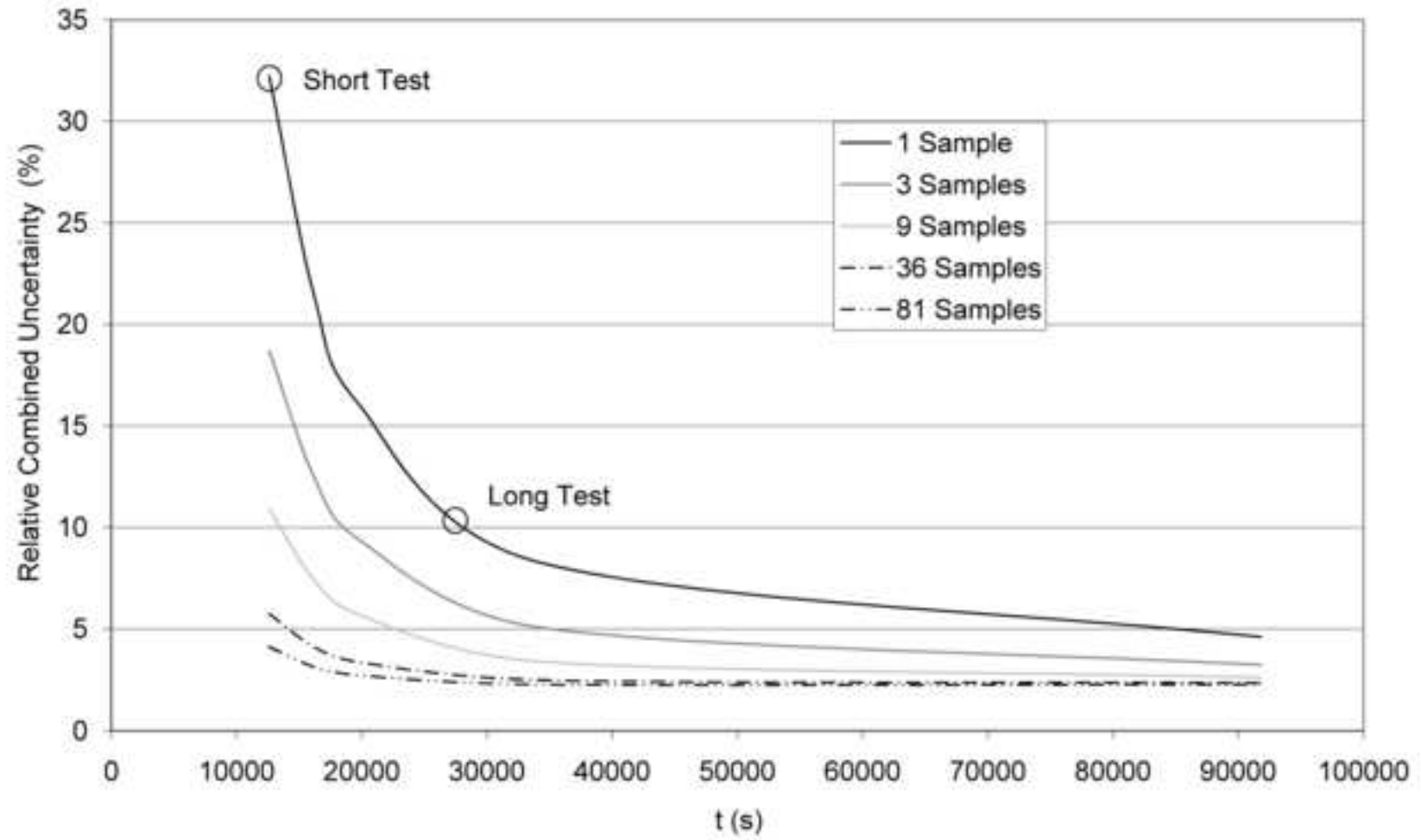


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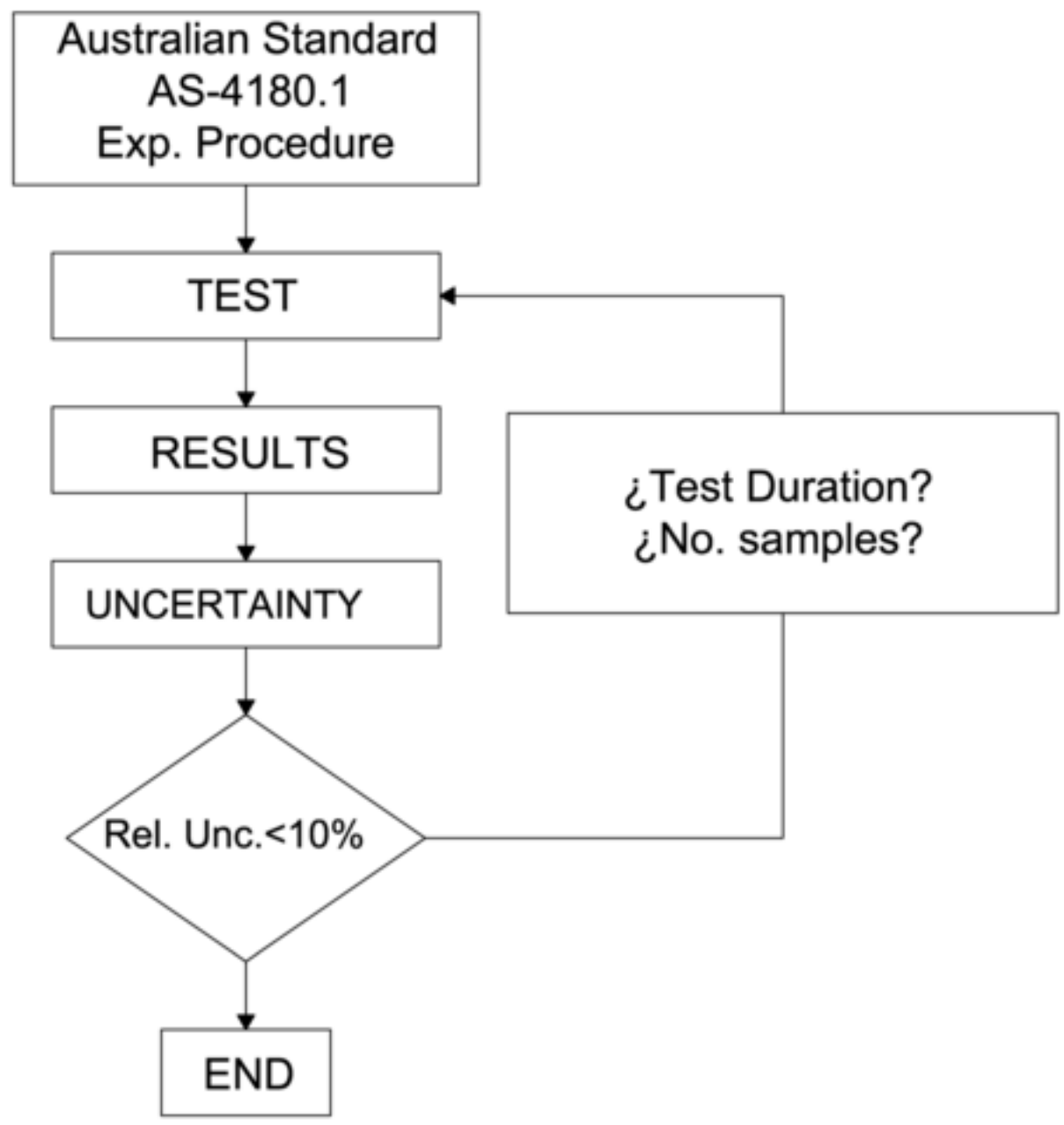


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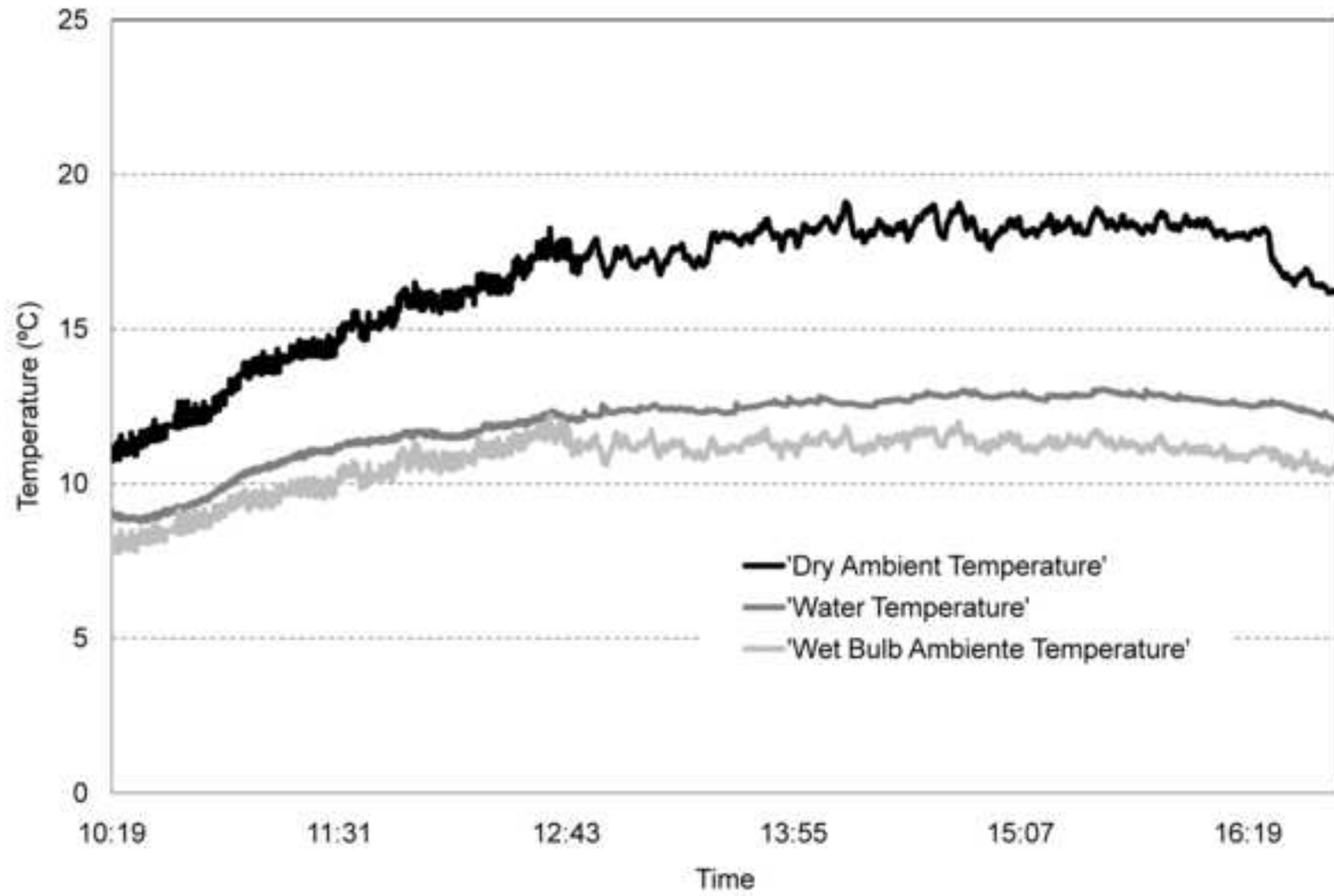


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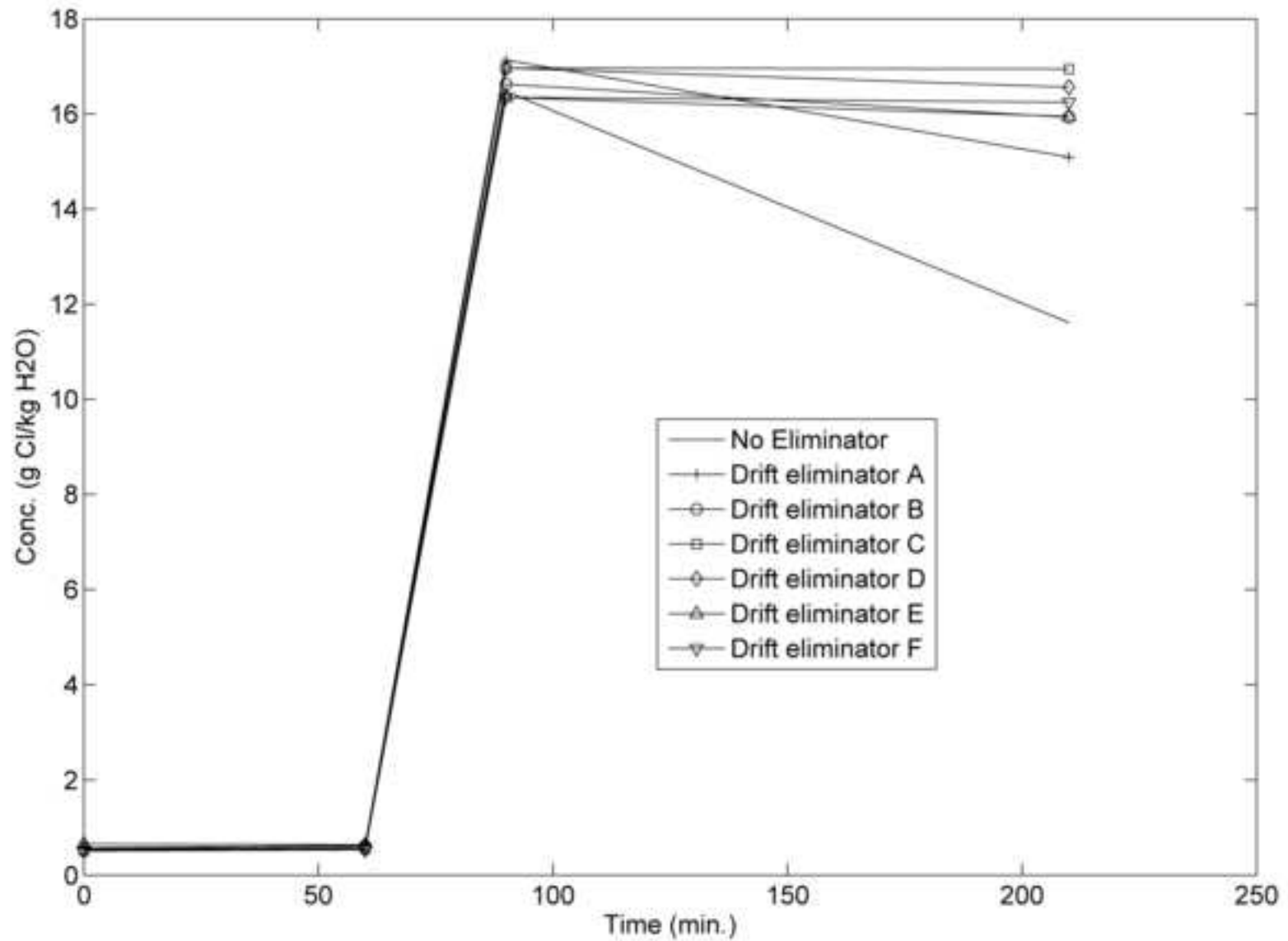


Figure 10
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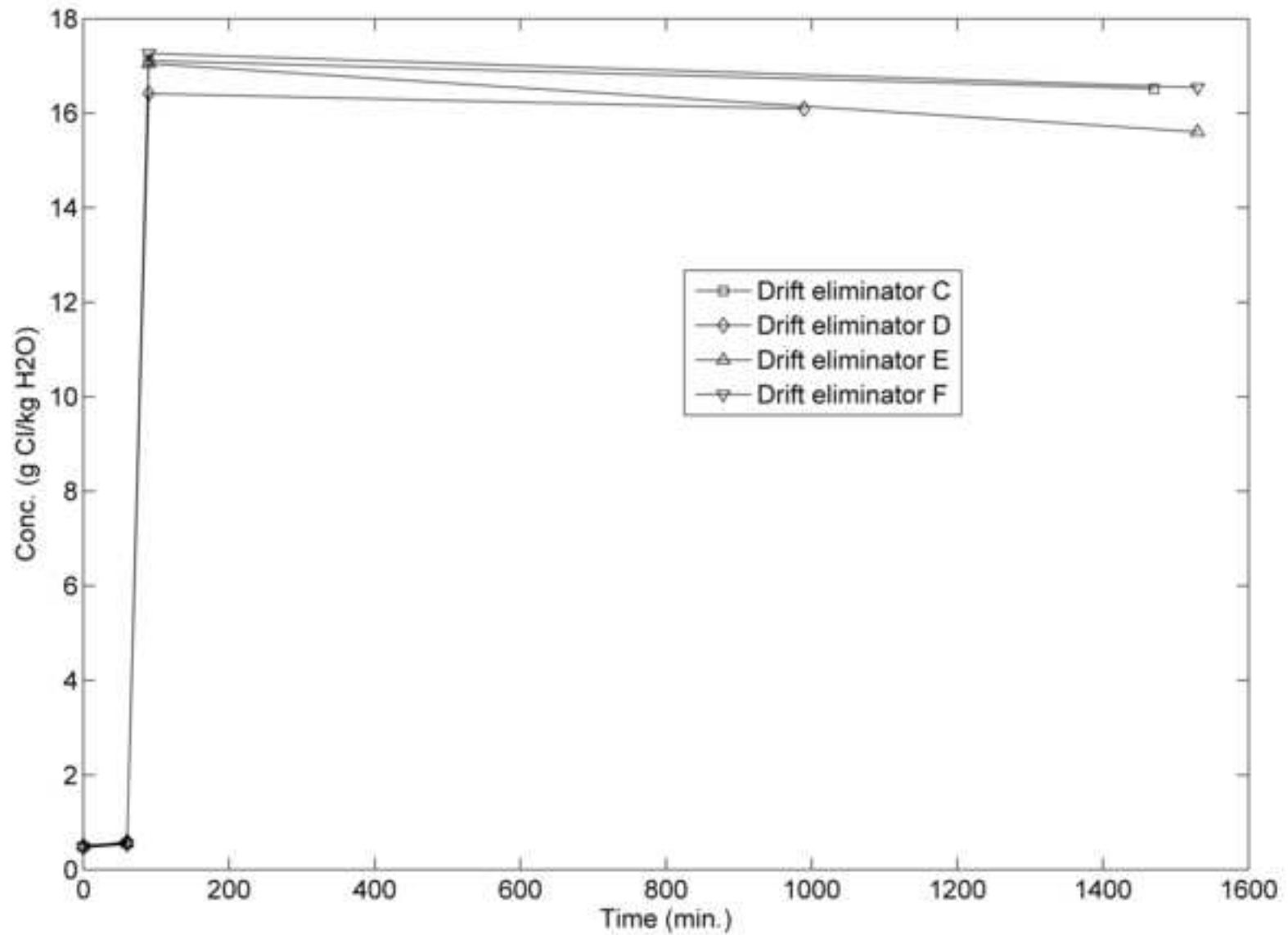


Figure 11

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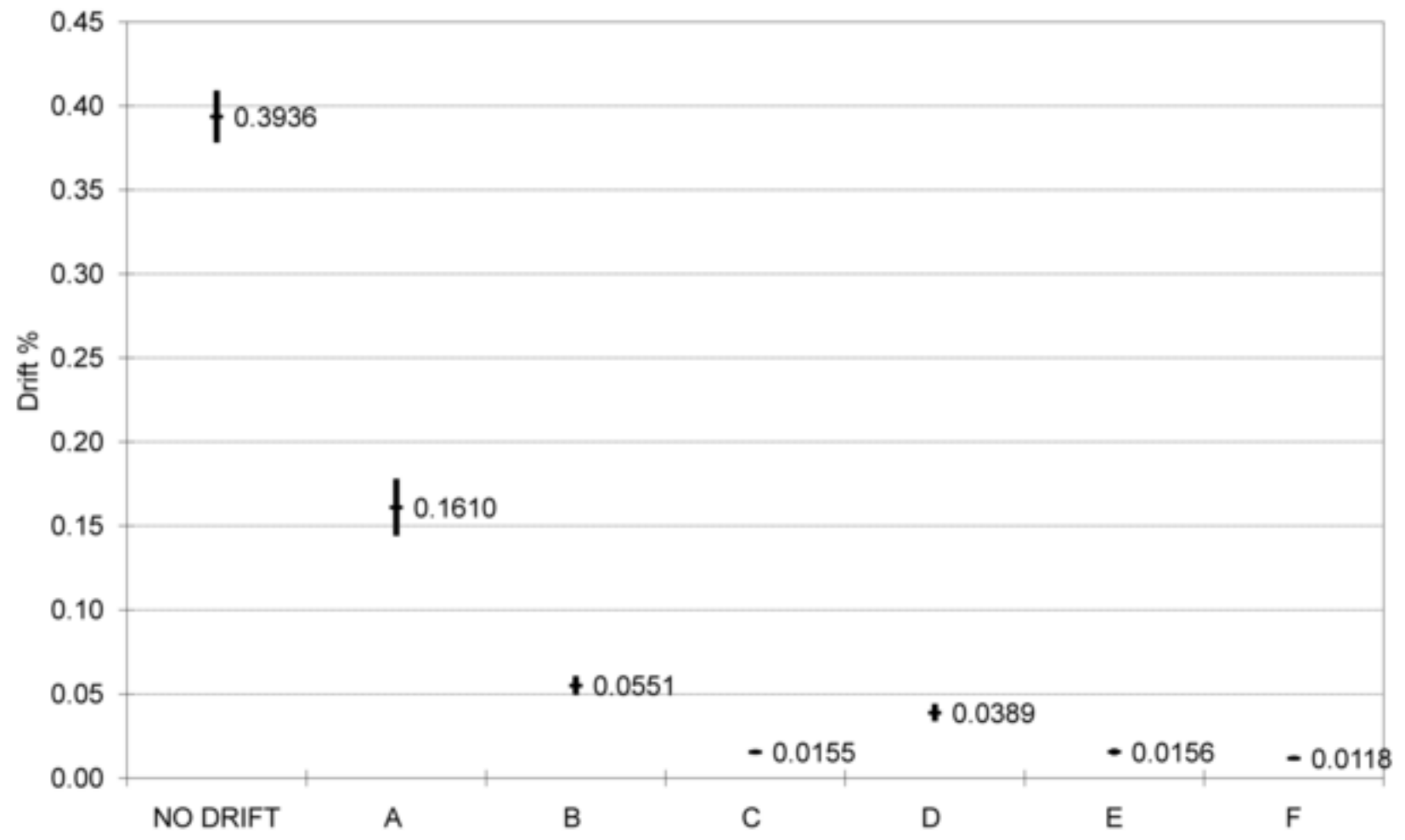


Figure 12
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