Moisture levels in compressed breathing air

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Moisture levels in compressed breathing air

T G Anthony & P R Clarke
QinetiQ Limited
Fort Road
Gosport
Hampshire
PO12 2DU

The purity and quality of compressed breathing gases are specified to cover both the physiological and engineering safety aspects of the gas. Information relating to the permissible water content for compressed air at pressures less than 40 bar, as set out in BSEN 12021, is confusing. Consequently HSE contracted QinetiQ to develop guidance for the diving industry regarding the maximum permissible water content for compressed air at pressures less than 40 bar. A relationship, based on the Magnus equation, between the pressure within a compressed air system, the ambient temperature, the water content (ie volumetric humidity) and the pressure dew point (ie temperature at which liquid water or ice will form) was used to identify operational guidelines. Two tabular format operational guidelines, one simple and the other flexible in use, have been developed for the water content of compressed air at pressures less than 40 bar. The 'simple' tabular system is proposed as the preferred system.

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Executive Summary

The purity and quality of compressed breathing gases are specified to cover both the physiological and engineering safety aspects of the gas. The presence of high water content within a compressed gas is of concern if free water is able to form, this could result in internal corrosion or the freezing of valve components.

BS EN 12021 specifies the permissible water content for compressed air at supply pressures < 40 bar. Although technically correct, BS EN 12021 does not provide easily understood values (i.e. levels in $mg \cdot m^{-3}$) that take account of the actual supply pressure and ambient temperature.

The Health and Safety Executive (HSE) have contracted QinetiQ at Alverstoke to provide guidance for the diving industry (Contract 6091) on maximum permissible water content for compressed air at pressures less than 40 bar.

A relationship has been identified, based on the Magnus equation (BS EN 1339 pt3), between the pressure within a compressed air system, the ambient temperature, the water content (i.e. volumetric humidity) and the pressure dew point (i.e. temperature at which liquid water or ice will form). The relationship was used to generate the operational guidelines presented in this report.

The water content currently specified for compressed air at pressures greater than 40 bar (BS EN 12021) are likely to result in free water condensing within a compressed gas system at the expected ambient conditions of use. Consideration should be given to reducing the maximum permissible water content of compressed air at pressures up to 200 bar to a maximum of 20 $mg \cdot m^{-3}$ (at 1.013 bar, 20 °C) and to 15 $mg \cdot m^{-3}$ (at 1.013 bar, 20 °C) for air at pressures up to 300 bar.

Two operational guidelines have been developed for the water content of compressed air at pressures less than 40 bar:

- A simple tabular system for all conditions of use (based on a pressure dew point of -11 °C as per BS EN 12021) is presented (Table 4-3, Page 10).
- A flexible tabular system allowing for ambient temperature conditions (based on a pressure dew point 5 °C less than the ambient temperature as per BS EN 12021) is presented (Table 4-4, Page 11).

The 'simple' tabular system is proposed as the preferred system.

It is recommended that:

- The diving, and other relevant industries, is made aware that, at pressures greater than 40 bar and expected ambient conditions of use, compressed air to BS EN 12021 may result in free water condensing within a compressed gas system.
- The diving, and other relevant industries, should use Table 4-3 of this report as guidance for the maximum permissible water content of compressed air at pressures less than 40 bar.
- At the next revision of BS EN 12021, consideration should be given to revision of the specified water content, and that data within Table 4-3 of this report is included as the maximum permissible water content for pressures less than 40 bar.

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Introduction

1.1 Breathing gas quality

The purity and quality of compressed breathing gases are specified to cover both the physiological and engineering safety aspects of the gas. Toxic gas levels are specified to cover the safety of a gas in physiological terms. Other constituents, such as organic compounds in high oxygen content gases, are limited to prevent combustion and mechanical/engineering effects.

The presence of high water content within a compressed gas is of concern from two perspectives:

- Free water in a pressurised gas system may provide an environment for corrosion to occur. The corrosion products may increase the risk of secondary toxic contamination and of particulate matter blocking filters and valve mechanisms. Also, in the extreme, corrosion may reduce the pressure integrity of a system.
- At reduced ambient temperatures or during the fall in temperature with adiabatic expansion of gas through a valve or regulator, any water present may freeze. The formation of ice in valves and regulator mechanisms is likely to prevent normal function, this in turn may cause the gas flow to be either restricted or to free flow.

Thus, the water content of compressed breathing gases (including compressed air) has to be specified at levels to prevent the formation of liquid water.

1.2 Water condensation with pressure

In a gas mixture of which water is a constituent, the water vapour, as with any other gas or vapour present, will comply with Dalton's Law; the water vapour pressure, as a partial pressure, will increase with increasing absolute pressure of the mixture. However, as the pressure increases, the water vapour pressure (partial pressure) will eventually equal the saturated vapour pressure and water will start to condense., Further compression of the mixture (increased pressure) will not raise the water vapour pressure and excess water will condense. If the ambient temperature is below the freezing point of water it will be deposited as ice – it should be noted that the freezing point of water reduces with increasing pressure; falling from 0 °C at 1 bar to -9 °C at 1000 bar.

To avoid the formation of liquid water or ice within a pressurised system the specified water content of the gas (e.g. compressed air) needs to be such that, at the intended working pressure (charge pressure) and temperature of use, the vapour pressure will be less than the saturated vapour pressure. On this basis, the specified level may be allowed to vary with the charge pressure, the required (specified) level increasing with a reduction in working pressure. Similarly the specified level may also vary depending on the minimum expected ambient temperature; the higher the ambient temperature the greater the permissible water content.

1.3 Problems with BS EN 12021

The current British and European Standard for compressed breathing air is BS EN 12021 [1]. Within this standard, the maximum permissible water content for compressed air at pressures ≥ 40 bar is specified as in Table 1-1. These levels, being specified in units that may be read directly off analytical instruments, are comparatively easy to apply and understand by both analytical laboratories and during the analysis of the gas under operational diving conditions.

Nominal pressure bar	Maximum water content of air at atmospheric pressure and 20 °C $mg \cdot m^{-3}$
40 to 200	50
> 200	35
Note: The water content of the air supplied by the compressor for filling 200 bar or 300 bar cylinders should not exceed 25 $mg \cdot m^{-3}$	

Table 1-1: The maximum water content of compressed air at atmospheric pressure for nominal pressures ≥ 40 bar as specified in BS EN 12021

Unfortunately although BS EN 12021 specifies permissible water content for compressed air at supply pressures < 40 bar the presentation is confusing and not easily understood or applied by lay users and under operational conditions.

BS EN 12021 para. 6.3.2 states:

'*Air for compressed air line breathing apparatus shall have a dew point sufficiently low to prevent condensation and freezing. Where the apparatus is used and stored at a known temperature the pressure dew point shall be at least 5 °C below the likely lowest temperature. Where the conditions of usage are not known the pressure dew point shall not exceed -11 °C.'*

Although technically correct the BS EN 12021 statement does not provide easily understood values (i.e. levels in $mg \cdot m^{-3}$) that take account of the actual supply pressure and ambient temperature.

Accordingly the Health and Safety Executive (HSE) have contracted QinetiQ at Alverstoke to provide guidance for the diving industry (Contract 6091) on maximum permissible water content for compressed air at pressures less than 40 bar.

1.4 Aim

The aim of this report is to:

- Simplify the water content requirements of BS EN 12021 for compressed air at supply pressures < 40 bar
- Provide practical industry guidance on the required water content of compressed air at supply pressures < 40 bar.

2 Definitions

2.1 Terminology

A range of terminology has been used for moisture measurement. For this report all terms, definitions and symbols used have been taken from BS 1339-1:2002 'Humidity – Part 1: Terms, definitions and formulae' [2].

The water content of a compressed gas may be specified using a range of terms and conditions, typically these are either dew point (°C) at normobaric pressure (1013 mbar, 101.3 kPa) or as a 'volumetric humidity' i.e. mass per unit volume ($mg \cdot m^{-3}$) at 1013 mbar and at either 15 or 20 °C. For this report, and to be consistent with existing standards [1, 2], volumetric humidity is the preferred term.

The current standard for compressed air [1] uses the term 'water content' to cover the maximum permissible levels of water; this term has also been used in this report.

2.2 Dew point

When, due to conditions of temperature and pressure, water reaches its saturated vapour pressure it will start to condense. However, if the temperature is below the freezing point of water it will condense as ice rather than liquid water, this is the 'frost point' as opposed to the 'dew point'. The term 'dew point' is often used in a general way to refer to the scale encompassing both dew point and frost point temperatures; the general use has been applied in this report.

2.3 Symbols

The following symbols [2] have been used in this report:

dv = Volumetric humidity ($kg \cdot m^{-3}$)

f = Enhancement factor

ln = Natural logarithm

p = Pure vapour pressure of component (Pa)

p' = Actual vapour pressure of component (Pa)

ps = Pure saturation vapour pressure (Pa)

ps' = Actual saturation vapour pressure (Pa)

$p1$ = Vapour pressure equivalent to dew point at P1 (Pa)

$P1$ = Pressure of elevated (high pressure) dew point (Pa)

$p2$ = Vapour pressure equivalent to dew point at P2 (Pa)

$P2$ = Pressure of ambient (normobaric pressure) dew point (Pa)

T = Temperature (K)

t = temperature (°C)

t_{dp} = Dew point temperature (°C)

t_{fp} = Frost point temperature (°C)

3 Determination of maximum water content

In order to simplify the operational requirements, it is necessary to identify the relationship between the pressure within a compressed air system, the water content (i.e. volumetric humidity) and the pressure dew point (i.e. temperature at which liquid water or ice will form).

The relationship also needs to consider that, as with ideal and real behaviour of gases in respect of their pressure and volume relationship, saturated water vapour pressure also has ideal (pure) and real (actual) values.

BS EN 1339-1: 2002 [2] provides a relationship between actual vapour pressure (Pa) and volumetric humidity ($kg \cdot m^{-3}$), Equation 1:

$$d\,v \qquad \frac{0.002167 \quad p'}{T} \tag{1}$$

BS EN 1339-3: 2004 [3] identifies that a vapour pressure at atmospheric pressure may be converted to a vapour pressure at an elevated pressure by application of Dalton's Law; this ultimately will allow conversion of a pressure dew point to a dew point, Equation 2:

$$p_2 \qquad \frac{p_1 \; P_2}{P_1} \tag{2}$$

Thus rearranging Equation 1 and substituting into Equation 2 the vapour pressure for a given volumetric humidity at an elevated pressure becomes, Equation 3:

$$p' \qquad \left(\frac{P_2}{P_1}\right)\frac{dv\;T}{0.002167} \tag{3}$$

Where:

P_2 = Pressure at elevated pressure

P_1 = Atmospheric pressure

p' = Vapour pressure at elevated pressure

To allow for the ideal (pure) and real (actual) values for saturated water vapour pressure, an enhancement factor (f) is applied, Equation 4:

$$ps' \qquad f \;\; ps \tag{4}$$

Thus at saturation point rearranging Equation 4 and substituting Equation 3 the pure saturated vapour pressure at elevated pressure may be determined, Equation 5.

$$ps \qquad \left(\frac{P_2}{P_1}\right)\frac{dv\,T}{0.002167f} \tag{5}$$

When calculating humidity at atmospheric pressure the correction from the enhancement factor is, for most purposes, negligible. However, the enhancement factor is strongly dependent on pressure and should be included [3]. The enhancement factor applied was derived according to Hardy [4].

BS EN 1339-1:2002 [2] identifies the Magnus equation in its appropriate form to determine the dew point (Equation 6) or frost point (Equation 7) from the saturated vapour pressure (*ps*, Equation 5):

$$t_{dp} \qquad \frac{243.12\ \ln(ps/611.2)}{17.62-\ln(ps/611.2)} \qquad \text{Over water} \tag{6}$$

$$t_{fp} \qquad \frac{272.62\ \ln(ps/611.2)}{22.46-\ln(ps/611.2)} \qquad \text{Over ice} \tag{7}$$

Thus a relationship has been identified between the pressure within a compressed air system, the ambient temperature, the water content (i.e. volumetric humidity) and the pressure dew point (i.e. temperature at which liquid water or ice will form). Figure 3-1 presents the relationship in graphical form for compressed air system pressures of 1, 40, 200 and 300 bar.

This relationship was used to identify the operational guidelines presented in this report.

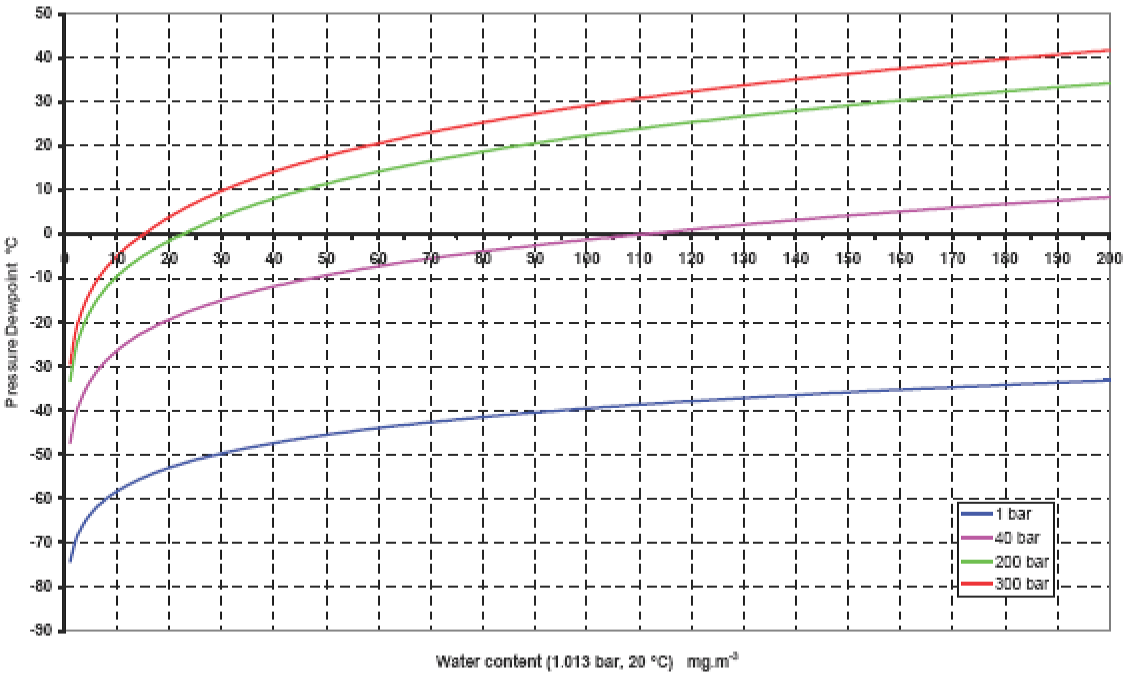

Figure 3-1: Graphical presentation of the relationship between the water content (i.e. volumetric humidity) and the pressure dew point of compressed air at 1, 40, 200 and 300 bar

4 Acceptable compressed air water content

4.1 Current standards

4.1.1 Water content: comparison across existing standards

Although Figure 3-1 provides the information required to identify appropriate water content for compressed air systems, it is not immediately obvious what the level should be, in addition errors will occur when reading levels from a graph.

The maximum permissible water content of compressed air or other gases may be specified as a volumetric humidity (i.e. in mg·m^{-3}) or as a dew point (°C) at atmospheric pressure (1.013 bar). British and European standards use volumetric humidity whilst the current Defence Standard for diving breathing gases (DEF STAN 68-284 Issue 2) [5] uses both terms.

Table 4-1 presents the levels specified in Defence Standard 68-284 together with the values obtained using the Magnus equation calculation.

Volumetric humidity (1.013 bar, 15 °C) mg·m^{-3}	1.013 bar dew point specified in DEF STAN 68-284 °C	1.013 bar calculated dew point Magnus Equation (7) °C
50	-46	-45.5
35	-49	-48.5
25	-52	-51.2
16	-55	-54.7
7	-61	-61.0
5	-64	-63.4

Table 4-1: Water content specified in DEF STAN 68-284

4.1.2 Risk of condensation with current standards

It was expected that the water content specified in BS EN 12021 (Table 1-1) were such that condensation would not occur at low ambient temperatures and maximum supply pressures. However, this does not appear to be the case; pressure dew points calculated from the specified maximum water levels (50, 35 and 25 mg·m^{-3}) together with intermediate and additional levels are presented in Table 4-2.

A water content of 50 mg·m^{-3} (1.013 bar, 20 °C) at a pressure of 200 bar will result in free water condensing at temperatures ≤ 11.4 °C (highlighted in yellow in Table 4-2). Similarly a water content of 35 mg·m^{-3} (1.013 bar, 20 °C) at a pressure of 300 bar will allow free water to condense at temperatures ≤ 12.1 °C, 25 mg·m^{-3} (1.013 bar, 20 °C) of water at 200 bar will condense at ≤ 1.3 °C and at 300 bar at ≤ 7.1 °C (highlighted in yellow Table 4-2).

The values presented in Table 4-2 may also be observed graphically by interpretation of Figure 3-1, e.g. for a water content of 50 mg·m^{-3} the dew point at 1 bar (blue line) is -45.5 °C and at 200 bar (green line) is 11.4 °C.

Pressure bar	Water content mg·m^{-3} (1.103 bar, 20 °C)							
	15	20	25	30	35	40	45	50
	Pressure dew/frost point °C							
1	-55.2	-53.0	-51.2	-49.8	-48.5	-47.4	-46.4	-45.5
40	-22.4	-19.4	-17.0	-15.1	-13.4	-11.9	-10.6	-9.4
200	-5.0	-1.6	1.3	3.9	6.1	8.0	9.8	11.4
300	-0.2	3.8	7.1	9.7	12.1	14.1	16.0	17.6

Note:
Water content and associated pressure dewpoint values for levels specified in BS 12021 are highlighted in yellow.
Proposed water content and associated pressure dewpoint values are highlighted in blue.

Table 4-2: Pressure dew points for specified water content

As these temperatures (i.e. in the range 1.3 to 12.1 °C) may often be achieved during storage and use of compressed air cylinders for diving operations, it is likely that the current specified maximum water content will result in free water condensing within diving cylinders.

Ideally, the specified water content should be such that water does not condense or deposit as ice during any expected conditions of use, hence the dew point criteria specified in BS EN 12021 for supply pressures less than 40 bar. An alternative, less stringent approach, may be to identify a water content in compressed air that, at the maximum pressure, will condense directly as ice rather than liquid water, i.e. a pressure dew point less than the freezing point of water (i.e. nominally < 0 °C).

On this basis the specified water content for compressed air would be (highlighted in blue Table 4-2):

- For a maximum 200 bar supply, 20 mg·m^{-3} (i.e. a dew point of -53.0 °C at 1.013 bar). This would then not condense/freeze at 200 bar until the temperature falls < -1.6 °C
- For a maximum 300 bar supply, 15 mg·m^{-3} (i.e. a dew point of -55.2 °C at 1.013 bar). This would then not condense/freeze at 300 bar until the temperature falls < -0.2 °C.

However, in considering these levels for compressed air the practicalities of achieving this by mechanical separation and chemical filtration have to be taken into account. Although these proposed levels are theoretically justifiable they are still not ideal, and they may not be acceptable for routine commercial use.

4.2 Proposed operational guidance

4.2.1 General

In constructing operational guidance for an acceptable water content of compressed air supplied at pressures less than 40 bar it was essential that it complied with the requirements specified in BS EN 12021. It was also felt that the guidance should also be consistent with the maximum level of 500 mg·m^{-3} specified in the cancelled British Standard (BS 4001 pt1) that was superseded by

BS EN 12021. A maximum level of 500 mg·m^{-3} was used by suppliers and users of compressed air without confusion.

Two different presentations for the required water content of compressed air at pressures less than 40 bar, have been derived from the two methods of identifying an acceptable water content presented in BS EN 12021, i.e:

- *'Where the conditions of usage are not known the pressure dew point shall not exceed -11 °C'*
- *'Where the apparatus is used and stored at a known temperature the pressure dew point shall be at least 5 °C below the likely lowest temperature'*.

The two conditions lead to a simple operational guidance presentation and a flexible operational guidance presentation.

4.2.2 Simple operational guidance

Using the requirement that the water content should have a pressure dew point that does not exceed (i.e. higher temperature than) -11 °C, an extension of the levels specified in the original table in BS EN 12021 was derived. The new calculated values, together with the existing limits from BS EN 12021 (i.e. water content at 40, 200 and 300 bar), are presented in Table 4-3.

Nominal maximum supply pressure bar	Maximum water content of air at atmospheric pressure and 20 °C mg·m^{-3}
5	290
10	160
15	110
20	80
25	65
30	55
40	50
200	50
>200	35

Table 4-3: Simple presentation

This is likely to be the simplest way of interpreting the requirements of BS EN 12021 for low supply pressures and is recommended as the preferred system. However, it does not take into account ambient temperature and provide any flexibility in permitted levels based on local climatic conditions.

4.2.3 Flexible operational system

A more flexible approach to the maximum permitted water content may be created from the requirement that the pressure dew point shall be at least 5 °C less than likely lowest ambient temperature (note: For diving systems the lowest ambient temperature could be in air or in water). Thus for a given maximum pressure the maximum permitted water content may be allowed to increase with increasing ambient temperature.

Unfortunately, to allow a more flexible approach, a more complex presentation is required and has been limited to a maximum pressure of 40 bar. In deriving a system, some simplification has been attempted by defining 10 °C temperature bands; the maximum water content then being calculated, using the appropriate Magnus equation (Equations 6 and 7), for a pressure dew point 5 °C less than the lowest temperature in the band.

To further simplify the presentation and operational interpretation the permissible water levels have also been constrained to a maximum level of 500 $mg \cdot m^{-3}$ (as previously specified in BS 4001 pt1) and a minimum level of 50 $mg \cdot m^{-3}$ (as specified in BS EN 12021 for pressures of 40 bar to 200 bar).

For a pressure dew point of 5 °C less than the ambient temperature, at low ambient temperatures, the calculated maximum water content is less than the 50 $mg \cdot m^{-3}$ constraint. However, to require levels < 50 $mg \cdot m^{-3}$ would then be in conflict and illogical with respect to the levels currently specified in BS EN 12021. This conflict is consistent with the demonstrated risk of condensation with existing standards (para. 4.1.2). Although this situation is not ideal, the 50 $mg \cdot m^{-3}$ minimum level has been used to keep the recommendation in accord with BS EN 12021.

A flexible approach to permitted maximum water content is presented in Table 4-4.

Nominal maximum supply pressure bar	Maximum water content of air at atmospheric pressure and 20 °C $mg \cdot m^{-3}$ Lowest likely ambient temperature					
	<-10 °C	-10 to <0 °C	0 to <10 °C	10 to <20 °C	20 to <30 °C	≥30 °C
5	50	200	500	500	500	500
10	50	110	270	500	500	500
15	50	75	185	400	500	500
20	50	55	140	300	500	500
25	50	50	115	250	490	500
30	50	50	95	210	410	500
35	50	50	80	180	350	500
< 40	50	50	70	155	310	500

Note:
Blue shaded areas indicate minimum permitted water content of 50 $mg \cdot m^{-3}$
Green shaded areas indicate area of variable water content
Red shaded areas indicate maximum permitted water content of 500 $mg \cdot m^{-3}$

Table 4-4: Flexible presentation

4.3 Determination of water content

4.3.1 Portable hygrometers

A range of portable hygrometers are commercially available that are able to measure water content in accordance with BS EN 12021. They also cover the water content identified in the proposed simple and flexible presentations. An internet search using the term 'Portable hygrometer' will quickly identify several systems.

4.3.2 Water content and dew point

Most commercially available hygrometers present the water content of a gas as dew point. Table 4-5 presents the values for water content in $mg \cdot m^{-3}$ (1.013 bar and 20 °C) and dew point at 1.013 bar.

Water content $mg \cdot m^{-3}$	Dew point °C	Water content $mg \cdot m^{-3}$	Dew point °C	Water content $mg \cdot m^{-3}$	Dew point °C
5	-63.4	105	-39.1	210	-32.8
10	-58.3	110	-38.7	220	-32.3
15	-55.2	115	-38.3	230	-31.9
20	-53.0	120	-37.9	240	-31.5
25	-51.2	125	-37.5	250	-31.1
30	-49.8	130	-37.2	260	-30.7
35	-48.5	135	-36.9	270	-30.4
40	-47.4	140	-36.5	280	-30.0
45	-46.4	145	-36.2	290	-29.7
50	-45.5	150	-35.9	300	-29.4
55	-44.7	155	-35.6	320	-28.7
60	-44.0	160	-35.3	340	-28.2
65	-43.3	165	-35.0	360	-27.6
70	-42.7	170	-34.7	380	-27.1
75	-42.1	175	-34.5	400	-26.6
80	-41.5	180	-34.2	420	-26.1
85	-41.0	185	-34.0	440	-25.6
90	-40.5	190	-33.7	460	-25.2
95	-40.0	195	-33.5	480	-24.7
100	-39.5	200	-33.2	500	-24.3

Table 4-5: Water content $mg \cdot m^{-3}$ and dew point

5 Conclusions

Proposed guidelines for acceptable water content in compressed gases have been derived using the Magnus equation by relating volumetric humidity to saturated vapour pressure and pressure dew point.

The water content currently specified for compressed air at pressures greater than 40 bar (BS EN 12021) is likely to result in free water condensing within a compressed gas system at the expected ambient conditions of use.

Consideration should be given to reducing the maximum permissible water content in compressed air to a maximum of 20 $mg \cdot m^{-3}$ (at 1.013 bar, 20 °C) for air at pressures up to 200 bar and to 15 $mg \cdot m^{-3}$ (at 1.013 bar, 20 °C) for air at pressures up to 300 bar.

Two operational guidelines have been developed for the water content of compressed air at pressures less than 40 bar:

- A simple tabular system for all conditions of use (based on a pressure dew point of -11 °C as per BS EN 12021) is presented (Table 4-3).
- A flexible tabular system allowing for ambient temperature conditions (based on a pressure dew point 5 °C less than the ambient temperature as per BS EN 12021) is presented (Table 4-4).

For ease of use operationally and to reduce possible confusion the 'simple' tabular system is proposed as the preferred system.

6 Recommendations

It is recommended that the diving, and other relevant industries, are made aware that, at pressures greater than 40 bar and the expected ambient conditions of use, compressed air to BS EN 12021 may result in free water condensing within a compressed air system.

The diving, and other relevant industries, should use Table 4-3 of this report as guidance for the maximum permissible water content of compressed air at pressures less than 40 bar.

At the next revision of BS EN 12021, consideration should be given to revision of the specified water content, and that data within Table 4-3 of this report is included as the maximum permissible water content for pressures less than 40 bar.

7 References

[1] British Standards Institution, *Respiratory protective devices – Compressed air for breathing apparatus.* BS EN 12021:1999.

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[3] British Standards Institution, *Humidity – Part 3: Guide to the measurement of humidity.* BS 1339-3:2004.

[4] Hardy, R. *ITS-90 Formulations for Vapor Pressure, Frostpoint Temperature, Dewpoint Temperature and enhancement Factors in the range -100 °C to +100 °C.* Proceedings of 3rd International Symposium on Humidity and Moisture, Teddington, England. April 1998.

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