

Engineer Technical  
Letter No. 1110-2-253

26 September 1980

Engineering and Design  
MEASUREMENT OF DISSOLVED GASES TO  
DETERMINE THE DEGREE OF NITROGEN  
SUPERSATURATION

1. Purpose. The purpose of this letter is to provide information on the types of in situ and laboratory methods available to measure dissolved gases in rivers and reservoirs. Information is also provided to help select locations for in situ measurement and proper techniques for sample collection and preservation.

2. Applicability. This letter applies to all field operating activities having Civil Works responsibilities.

3. Reference and Bibliography.

a. References.

- (1) ER 15-2-10. Committee on Water Quality.
- (2) ETL 1110-2-239. Nitrogen Supersaturation.

b. Bibliography.

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#### 4. Statement of Problem.

a. Supersaturation of atmospheric gases has been identified as a potential environmental problem associated with releases from certain Corps impoundment projects. This supersaturated condition can develop when the flow experiences significant changes in pressure and temperature as it passes through a spillway or outlet works and an energy dissipating structure.

b. Most incidents of supersaturation have been observed downstream of a spillway discharging into a highly submerged (deep) stilling basin. In general, hydropower turbines have not been associated with this problem. However, Garton et al. (1973), found that supersaturated levels up to 130 percent were produced at times below turbines. Another source of supersaturation is the discharge of cooling water, particularly from thermal power generation (Lee and Martin, 1975). This condition results from the lowering of solubility of all gases in water as the water temperature increases.

c. Spillway operation can induce supersaturation when air, entrained as small bubbles, is trapped in the water as it flows down the spillway. This air is forced into solution by the hydrodynamic pressure developed in the flow as it plunges into and passes through the stilling basin. The dissolved gas content can be increased to levels exceeding saturation with respect to the surface. When this water flows downstream, it can remain supersaturated for long distances. The rate of equilibration with the atmosphere in the normal river environment is dependent on the

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d. Fish mortality attributed to this gas problem has been experienced in the North Pacific Division and downstream of the partially completed Harry S. Truman project in the Missouri River Division. These incidents of fish mortality were found to result from gas bubble disease which is caused by subjecting fish to prolonged periods of gas supersaturation.

## 5. Gas Solubility.

a. The equilibrium solubility of gases in fresh water is dependent on two factors; the water temperature and the partial pressure of the gas in equilibrium with the liquid. The solubility of all gases in water declines with increasing temperature. Thus water that is saturated with a gas, when warmed quickly, can become supersaturated. This can result in a problem when cooling water is discharged from thermal power generating stations. On the other hand, water supersaturated with gas can often be brought to a saturated or sub-saturated condition by cooling. This is important for preservation and transport of samples for analysis.

b. The dependence of gas solubility on the partial pressure of the gas in equilibrium with the liquid is described by Henry's law (Castellan, 1964).

$$X_i = \frac{1}{K_i} p_i$$

where  $X_i$  is the mole fraction of the gas "i" in solution (solubility),  $K_i$  is the Henry's law constant for substance "i" at a given temperature, and  $p_i$  is the partial pressure of the gas "i" (in atmospheres) in equilibrium with the liquid.

c. Alternatively, Henry's Law can be expressed using a volumetric solubility coefficient  $a_i$  (or  $B_i$  in Weiss papers) as:

$$C_i = P_i a_i$$

where  $C_i$  is the concentration of gas "i" in of dry gas at standard temperature and pressure (STP),  $P_i$  is the partial pressure of gas "i" in atmospheres and  $a_i$  is the Bunsen solubility coefficient of gas "i" in dry gas at STP per solution at the equilibrium temperature. It should be emphasized that  $P_i$  is the total partial pressure of the gas "i." At the water surface,  $P_i$  is the atmospheric pressure minus the water vapor pressure at that temperature times the percentage of that gas in the atmosphere. The percentage composition of nitrogen in the atmosphere is about 78 percent. Thus, the partial pressure of nitrogen

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at a dry atmospheric pressure of 1 atmosphere (760 torr) neglecting water vapor would be 1.0 times 0.78 or 0.78 atmospheres (592 torr).

d. When one considers the gas phase or bubble at depth, however, it is necessary to add the hydrostatic pressure of the water column to obtain the partial pressure of the gas in the bubble. For example, in fresh water at a depth of 34 feet, the hydrostatic pressure of the water column is approximately one atmosphere. The water at this depth is thus subjected to a total pressure of about two atmospheres and the gas phase at this depth is under a partial pressure of nitrogen of 1.56 atmospheres ( $2 \times 0.78$ ) assuming the water is in equilibrium and the surface partial pressure of nitrogen is 0.78 atmospheres. Since the Henry's law constant is to a first approximation independent of pressure, the equilibrium solubility of nitrogen at 34 feet is therefore expected to be about twice that at the surface.

e. The presence of salts in water decreases gas solubility. However, unless highly saline water is being analysed (salinity in excess of 5 parts per thousand), this effect is small and can be neglected. Solubility tables which include the effect of salinity are available in Weiss (1970).

## 6. Measurement Methods.

a. Two devices are commercially available to measure dissolved gas concentrations in the field. The gas saturometer appears to be the most reliable, but has the disadvantage of being limited to surface measurements. The gas tensionometer is more versatile in that it can be used to obtain measurements at depth. Experience suggests, however, that the electronic components of the tensionometer require more care and service. Appendix A contains a further description of these devices.

b. Calibration of the saturometer or tensionometer and verification of measurements are difficult. Obviously, standard solutions for calibration do not exist nor would such a concept be practicable. Calibration can only be accomplished indirectly by obtaining a measurement in a free flowing stream and simultaneously collecting a sample for laboratory analysis. This should be accomplished prior to any data collection effort.

c. To maintain confidence in the accuracy of the measurements, two saturometers or a saturometer and a tensionometer should be employed in the field. The two units, submerged side-by-side, should provide essentially the same value. If a difference is observed between two saturometers, the one with the lower value will generally be in error. However, a difference between a saturometer and a tensionometer, or between two tensionometers, points out that a problem exists, but will not identify the unit in error. One or more samples, the number depending on the complexity of the stream, should be collected for

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laboratory analysis during each field exercise. Analysis of these samples will provide verification of the data obtained with the field equipment. Section 8 contains a discussion of the problems and procedures associated with sample collection and handling.

d. Several procedures are available for laboratory analysis. These include gas chromatographs, mass spectrometers, and the Van Slyke method. A limited description of the laboratory techniques is found in Appendix B. Gas Chromatographic (GC) analysis should be readily available, more accurate, and the least expensive of the laboratory procedures. A portable gas chromatograph has been used by personnel of CRREL and the Hydraulics Laboratory, WES, but should be considered for field office use at this time.

7. Sampling Location. Whether in situ or laboratory methods are chosen for analysis, the most critical factor in obtaining good dissolved gas data is the choice of sampling location. None of the in situ or laboratory methods available are capable of accurately measuring dissolved gases when free gas bubbles are present. It is therefore desirable to choose a site where bubbles are not visible in the water. At any potential site, a sample of the water should be collected and visually inspected before the site is accepted. The chosen site will typically be at least several hundred meters downstream of any structure or "whitewater" and may in some cases be considerably further downstream. Multiple measurement stations will be required to adequately define the lateral distributions and vertical profiles of dissolved gases since many streams will not be fully mixed at the sampling cross section.

#### 8. Sample Collection and Handling for Laboratory Analysis.

a. Samples collected for laboratory analysis should be obtained at the same depth and simultaneously with a reading of the field instrument. The sampling tube (Kemmerer or Van Dorn) should be cooled to a temperature equal to or less than the temperature of the water to be collected. This can be easily accomplished by hanging the tube at the sampling depth long enough to cool, pulling it to the surface to purge the encased water, then lowering it to the sampling depth again to obtain the sample. When the sample is brought to the surface, it should be inspected for bubbles. If bubbles are present or are formed when the sample is transferred, it should be discarded and another sample obtained.

b. Two methods are available for shipping the sample to the laboratory. The sample can be carefully poured into a cold BOD bottle and transported to the laboratory at temperatures just above freezing. This method is the best choice if analysis is to be performed by GC with a Swinnerton stripping chamber. If the sample freezes, it is unuseable. If it warms during transport and vibration causes bubbles to form, the sample must be discarded. Furthermore, the sample should be analyzed within 24 hours after reaching the laboratory. Another alternative is

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shipment of the samples in 50 gas-tight syringes. This method has the advantage that any bubbles that form are retained within the syringe. Thus bubble formation does not necessarily indicate that the sample must be discarded. If this procedure is chosen, the syringes should be filled to overflowing, the plunger inserted and water expelled through the needle until 25 remains. The remaining 25 should be filled with helium either in the field or once the samples arrive at the laboratory. This procedure is best suited to the headspace analysis method used in conjunction with GC.

9. Recommendations. The Nitrogen Supersaturation Work Group of the Corps Committee on Water Quality (ER 15-2-10) evaluated the options available for measurements of dissolved gas concentrations on site and in the laboratory. If temperature and dissolved oxygen measurements indicate that the stream is vertically mixed, the satumeter is the recommended device for field measurement. However, if the temperature and dissolved oxygen measurements change with depth, the tensionometer should be used, but with caution because it has not been fully field tested. The accuracy of either device should be determined before field measurements are taken. Furthermore, confidence in the field measurements can be maintained only if one or more samples are collected each day of the field exercise for laboratory analysis. It is recommended that laboratory analysis be conducted by GC equipped with a Swinnerton stripping chamber. In most cases, it will be necessary to have these analyses performed by a commercial laboratory. Determine beforehand that the selected laboratory is capable of performing the analysis and that the appropriate quality control procedures are enforced.

10. Additional Information. Should further information be needed contact members of the Corps of Engineers Committee on Water Quality (ER 15-2-10).

FOR THE CHIEF OF ENGINEERS:



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4 Appendixes

App A - In Situ Methods

App B - Laboratory Methods

App C - Carbon Dioxide

Considerations

App D - Gas Solubility Tables

APPENDIX A

Detailed Description of In Situ Methods

Methods currently available for in situ measurement of total dissolved gas pressure include the gas saturometer and the gas tensionometer. These are theoretically the same instrument but differ in the nature of the pressure measuring device. A detailed description of each method including a reference to the original work, a description of the equipment needed, a short discussion of the analytical principle used, an example of the calculations required, and any specific information on precision, interference, advantages, disadvantages, etc. are given below.

1. Gas Saturometer (Weiss). The gas saturometer is a relatively inexpensive, field portable device which measures the total gas pressure directly. The device consists of a metal framework upon which is wound about 100 feet of silastic tubing. This tubing is permeable to all gases but not to liquid water. When this device is submerged, the gases in the water equilibrate with the volume of gas present in the tubing and the total dissolved gas pressure in solution is read on a pressure gauge. This pressure includes the contribution of water vapor pressure ( $P_v$ ). The gauge reads positive pressure for supersaturated waters and negative pressures for undersaturated waters. The gauge reads the sum of the partial pressures all gases present in solution including nitrogen, oxygen, argon, carbon dioxide (usually very low) and water vapor and measures it relative to atmospheric pressure. Thus it is necessary to know the atmospheric pressure at the time of the measurement and also the water temperature. The total relative saturation is calculated by the following equation:

$$\frac{P_B + \Delta P}{P_B} \times 100 = \text{Total Gas Saturation}$$

where  $P_B$  is the atmospheric pressure in torr (mm Hg)

and  $P$  is the saturometer reading in torr.

Thus the percent saturation obtained is relative to existing atmospheric pressure at the site and the water surface, no matter at what depth the device is placed.

Determination of the nitrogen supersaturation (nitrogen + argon) requires, in addition to the measurement of total gas pressure, a separate measurement of dissolved oxygen concentration. This can be obtained by either the standard Winkler technique or with a calibrated dissolved oxygen probe.

Having measured the dissolved oxygen concentrations along with total gas pressure, the following calculations can be used to obtain dissolved nitrogen saturation.

Percent oxygen saturation is determined by converting the measured concentration of dissolved oxygen in mg/l to ml/l and then dividing by the saturation concentration at the measured water temperature which can be obtained from Table D-1. The formula for this calculation is shown below:

$$\text{Percent } O_2 \text{ saturation} = \frac{O_2 \text{ measured (mg/l)} (0.70 \text{ ml/mg}) (100)}{O_2 \text{ saturation (ml/l) at measured H}_2\text{O temp \& pressure}}$$

The conversion factor 0.70 ml/mg is the reciprocal of the density of gaseous oxygen at 0°C and 760 torr (STP). The percent nitrogen (including argon) is then obtained as follows (Nebeker 1976):

$$\text{Step (1) } P(O_2) = O_2 \text{ (mg/l)} \frac{(0.70 \text{ ml/mg})}{B(O_2)/1 \text{ atmosphere}} \times (0.76 \text{ torr}/(\text{atmosphere} \times \text{ml}))$$

$$\text{Step (2) } P(N_2) = P_B + \Delta P - (P(O_2) + P_v)$$

$$\text{Step (3) Percent } N_2 = \frac{P(N_2)}{0.79 (P_B - P_v)} \times 100$$

where  $P(O_2)$  = oxygen pressure (torr)

$B(O_2)$  = Bunsen coefficient for oxygen (1/1 atmosphere), table D-5

$$0.76 = 760 \text{ (torr/atmosphere)} \times \frac{1}{1000 \text{ ml}}$$

$P(N_2)$  = nitrogen pressure (torr), including Argon

$P_B$  = barometric pressure (torr)

$\Delta P$  = saturometer reading (torr)

$P_v$  = water vapor pressure (torr), table D-4

0.79 = Percent  $N_2$  + Ar in dry air

The final result, percent N, is the percent nitrogen saturation (including argon).



A detailed description of the procedure to use the saturometer is given below.

After arrival on site, the protective cover is removed and the membrane sensor immersed in the water to a depth of one foot. The sensor is shaken vigorously throughout the measuring period to dislodge bubbles which tend to cling to the membrane and cause artificially low results. For those saturometers equipped with a jet pump, the use of this device should reduce the amount of shaking required. Equilibrium will generally be achieved within 15 minutes but for highly supersaturated water, it may take somewhat longer. When the gauge does not show a change for a minute, the equilibrium point has been reached. The pressure reading obtained at equilibrium is recorded as a measure of total dissolved gas pressure difference ( P ) and used in calculations presented earlier.

The major sources of error associated with use of the saturometer for gas saturation measurements are (a) high pressure leaks, (b) condensation of water inside the silastic tubing and (c) gas bubbles clinging to the outside of the tubing. The symptom of the high pressure leak is a topping out of all readings, or erratic behavior of the pressure gauge, and length of time required for the system to equilibrate. In other words, many readings will be found at a given P, but none above this value. To locate the source of leakage, the tubing is pressurized and inspected visually in much the same manner as used to find leaks in inertubes.

To minimize condensation problems, the saturometer should be dried periodically by placing the device in an electric oven at 80°C for one hour and storing in an area of low humidity.

The clinging of gas bubbles to the outside of the tubing is a problem since the final reading will be representative of an unknown degree of equilibration with the bubbles as well as the dissolved gas. This will result in artificially low readings. In order to minimize this problem, the saturometer must be shaken vigorously throughout the measurement. This is difficult because of the time required to reach equilibrium (generally about 15 minutes). Unless the analyst is patient, readings below the correct values will be reported. The newer models of the saturometer have a manually operated water-jet pump. This pump is used under supersaturated conditions to dislodge bubbles and may reduce the time for the system to come to equilibrium.

2. Gas Tensionometer (D'Aoust). The principle of operation of the gas tensionometer is identical to that of the Weiss saturometer. In this system the pressure gauge has been replaced by a pressure transducer and the size of the device has been reduced markedly (D'Aoust et al., 1976). The measurement technique is also similar and, because of its lower dead space, the time required to reach equilibrium has been reduced. This device is capable of measuring the total gas pressure at depth whereas the Weiss instrument can only be used for surface measurements.

The gas tensionometer reads the absolute gas pressure whether in the water or air. Thus the total dissolved gas pressure is read no matter at what depth the device is placed. The tensionometer can also be used to measure water temperature and atmospheric pressure.

This device is quite easy to use and operator error associated with the saturometer should be reduced with this device. It is also capable of being connected to a recording device to allow continuous monitoring at a single site or interfaced with a remote data collection system.

To calculate total gas saturation, the dissolved gas pressure (in torr) is taken from the digital output of the device, divided by the measured atmospheric pressure (in torr), which is the reading at the surface before immersion, and the resultant multiplied by 100. This value is the total gas saturation. Delta P ( $\Delta P$ ), total gas pressure minus barometric pressure, is from a physical stand-point the more relevant parameter.

To obtain the nitrogen saturation, calculations are identical to that presented for the saturometer (Appendix A-1), and require measurement of  $O_2$ .

The operation of the device is as follows. The device is unpacked and the battery voltage checked to insure sufficient power for operation. The atmospheric pressure (in torr) is obtained by taking a reading with the device before the probe is immersed in water. The probe is placed in the water to a depth of about 10 feet. This insures that bubble formation will not occur on the outside of the tubing even in highly supersaturated water. The probe is allowed to come to equilibrium with the gas dissolved in the water and a reading taken. An equilibrium condition has been established when the digital reading does not change for a minute or more. This usually takes about 10 minutes, but the length of time depends on the temperature and stirring rate. The water temperature is also recorded to enable subtraction of water vapor pressure and calculation of nitrogen saturation.

The major potential problems observed thus far with the gas tensionometer are the calibration of the temperature sensor and the development of high pressure leaks. The temperature sensor should be checked versus a calibrated thermometer before each trip to the field and adjustments made per manufacturer instructions. The development of high pressure leaks can be checked by pressurizing the sensor with syringe injections at the vent cock and observing the stability of the pressure reading, or immersing under water while pressurized and checking for a point source of bubbles.

## APPENDIX B

### Laboratory Methods

Laboratory methods available for measurement of gas saturation are given below. It is essential that the proper sample collection and handling, discussed in Section 8, be followed to enable accurate results for analyses.

1. Gas Chromatography. The principal problem in the application of gas chromatograph in the measurement of gas saturation is the presence of extremely large quantities of water compared to the amount of gas present. Several methods are available to overcome this problem.

The historical method developed by Swinnerton et al. (1962) is still in use. A specially designed apparatus strips the gases out of the water before the gases enter the gas chromatograph. The advantages of this method are its simplicity and its ability to quantitatively strip the air from solution.

Commercially available devices based on the Bellar and Lichtenberg (1974) purge and trap method for volatile organic compounds in water could also be used. Nitrogen and oxygen will not be retained on the normal Tenax trap and a molecular sieve trap must be substituted.

A head space technique developed by Leggett (1979) uses the syringe sample described in Section 8. The precision of this analysis has been reported to be about  $\pm$  three percent and good agreement has been found between oxygen values obtained by this method and the Winkler titration.

2. Mass Spectroscopy. Mass spectroscopy has occasionally been applied to the measurement of gas saturation. A specific method developed by Dyck and Johansson (1977) required prior removal of oxygen and offers no improvement in precision over the gas chromatographic procedures.

3. Van Slyke Gasometric Technique. The Van Slyke gasometric technique has been used for dissolved gas measurements for many years and is still employed in a few laboratories. A detailed description of the method has been prepared by Beiningen (1973). A major disadvantage of this method, in addition to the excessive time and manpower required, is the large amount of mercury required.

APPENDIX C

Carbon Dioxide Considerations

In waters of high alkalinity it may be necessary to take into account the contribution of dissolved CO<sub>2</sub> to the total gas pressure. Dissolved CO<sub>2</sub> is conveniently determined from alkalinity, total filterable residue, pH, and water temperature using a nomograph (Standard Methods, 14th ed. p. 297). The partial pressure exerted by dissolved CO<sub>2</sub> is calculated from solubility of pure CO<sub>2</sub> as a function of temperature (Lange's Handbook of Chemistry, 12th Edition 10-4) or from tables giving solubility from air as a function of temperature.

For example, if the water has a CO<sub>2</sub> alkalinity of 200 mg/l, the pH is 7.5, and the water temperature is 20°C, the free CO<sub>2</sub> in solution is about 13 mg/l (a total filterable residue of 265 mg/l was used assuming it to be entirely composed of Ca (HCO<sub>3</sub>)<sub>2</sub>). A direct measurement is preferable if available. Since the partial pressure CO<sub>2</sub> in the atmosphere is about 3 x 10<sup>-4</sup> atmospheres (300 ppmv) the solubility of CO<sub>2</sub> in water in equilibrium with air is about 0.5 mg CO<sub>2</sub>/l. Thus the partial pressure exerted by 13 mg CO<sub>2</sub>/l is

$$\frac{13}{0.5} \times 3 \times 10^{-4} \text{ atm} = 7.8 \times 10^{-3} \text{ atms} = 5.93 \text{ torr.}$$

The pressure contribution of CO<sub>2</sub> to the total gas pressure, if significant, should be subtracted from the saturometer reading along with that due to O<sub>2</sub> and water prior to calculation of percent nitrogen saturation.

APPENDIX D

Gas Solubility Tables

TABLE D-1

OXYGEN (ML/L)  
AT 100% SATURATION, 760MM PRESSURE, MOIST AIR FROM (WFSS 1970)

TEMP DEG. C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	10.22	10.19	10.16	10.14	10.11	10.08	10.05	10.02	10.00	9.97
1	9.94	9.91	9.89	9.86	9.83	9.80	9.78	9.75	9.72	9.70
2	9.67	9.64	9.62	9.59	9.56	9.54	9.51	9.49	9.46	9.44
3	9.41	9.38	9.36	9.33	9.31	9.28	9.26	9.24	9.21	9.19
4	9.16	9.14	9.11	9.09	9.07	9.04	9.02	9.00	8.97	8.95
5	8.93	8.90	8.88	8.86	8.84	8.81	8.79	8.77	8.75	8.72
6	8.70	8.68	8.66	8.64	8.61	8.59	8.57	8.55	8.53	8.51
7	8.49	8.47	8.44	8.42	8.40	8.38	8.36	8.34	8.32	8.30
8	8.28	8.26	8.24	8.22	8.20	8.18	8.16	8.14	8.12	8.10
9	8.08	8.06	8.04	8.02	8.01	7.99	7.97	7.95	7.93	7.91
10	7.89	7.87	7.86	7.84	7.82	7.80	7.78	7.76	7.75	7.73
11	7.71	7.69	7.67	7.66	7.64	7.62	7.60	7.59	7.57	7.55
12	7.53	7.52	7.50	7.48	7.47	7.45	7.43	7.41	7.40	7.38
13	7.36	7.35	7.33	7.32	7.30	7.28	7.27	7.25	7.23	7.22
14	7.20	7.19	7.17	7.15	7.14	7.12	7.11	7.09	7.08	7.06
15	7.05	7.03	7.02	7.00	6.99	6.97	6.96	6.94	6.93	6.91
16	6.90	6.88	6.87	6.85	6.84	6.82	6.81	6.80	6.78	6.77
17	6.75	6.74	6.72	6.71	6.70	6.68	6.67	6.66	6.64	6.63
18	6.61	6.60	6.59	6.57	6.56	6.55	6.53	6.52	6.51	6.49
19	6.48	6.47	6.45	6.44	6.43	6.42	6.40	6.39	6.38	6.37
20	6.35	6.34	6.33	6.31	6.30	6.29	6.28	6.27	6.25	6.24
21	6.23	6.22	6.20	6.19	6.18	6.17	6.16	6.14	6.13	6.12
22	6.11	6.10	6.08	6.07	6.06	6.05	6.04	6.03	6.01	6.00
23	5.99	5.98	5.97	5.96	5.95	5.93	5.92	5.91	5.90	5.89
24	5.88	5.87	5.86	5.84	5.83	5.82	5.81	5.80	5.79	5.78
25	5.77	5.76	5.75	5.74	5.73	5.71	5.70	5.69	5.68	5.67
26	5.66	5.65	5.64	5.63	5.62	5.61	5.60	5.59	5.58	5.57
27	5.56	5.55	5.54	5.53	5.52	5.51	5.50	5.49	5.48	5.47
28	5.46	5.45	5.44	5.43	5.43	5.42	5.41	5.40	5.39	5.38
29	5.37	5.36	5.35	5.34	5.34	5.32	5.31	5.30	5.30	5.29
30	5.28	5.27	5.26	5.25	5.25	5.23	5.22	5.21	5.20	5.19

TABLE D-2

NITROGEN (ML/L)  
AT 100% SATURATION, 760MM PRESSURE, MOIST AIR FROM (WFISS 1970)

TEMP DEG. C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	18.42	18.37	18.32	18.28	18.23	18.18	18.14	18.09	18.04	18.00
1	17.95	17.90	17.86	17.81	17.77	17.72	17.68	17.63	17.59	17.54
2	17.50	17.46	17.41	17.37	17.32	17.28	17.24	17.20	17.15	17.11
3	17.07	17.03	16.98	16.94	16.90	16.86	16.82	16.78	16.74	16.70
4	16.65	16.61	16.57	16.53	16.49	16.45	16.41	16.38	16.34	16.30
5	16.26	16.22	16.18	16.14	16.10	16.07	16.03	15.99	15.95	15.91
6	15.88	15.84	15.80	15.77	15.73	15.69	15.66	15.62	15.58	15.55
7	15.51	15.48	15.44	15.41	15.37	15.34	15.30	15.27	15.23	15.20
8	15.16	15.13	15.09	15.06	15.03	14.99	14.96	14.93	14.89	14.86
9	14.83	14.80	14.76	14.73	14.70	14.67	14.63	14.60	14.57	14.54
10	14.51	14.48	14.44	14.41	14.38	14.35	14.32	14.29	14.26	14.23
11	14.20	14.17	14.14	14.11	14.08	14.05	14.02	13.99	13.96	13.93
12	13.90	13.87	13.84	13.82	13.79	13.76	13.73	13.70	13.67	13.65
13	13.62	13.59	13.56	13.53	13.51	13.48	13.45	13.43	13.40	13.37
14	13.34	13.32	13.29	13.26	13.24	13.21	13.19	13.16	13.13	13.11
15	13.08	13.06	13.03	13.00	12.98	12.95	12.93	12.90	12.88	12.85
16	12.83	12.80	12.78	12.75	12.73	12.70	12.68	12.66	12.63	12.61
17	12.58	12.56	12.53	12.51	12.49	12.46	12.44	12.42	12.39	12.37
18	12.35	12.32	12.30	12.28	12.25	12.23	12.21	12.19	12.16	12.14
19	12.12	12.10	12.07	12.05	12.03	12.01	11.99	11.96	11.94	11.92
20	11.90	11.88	11.86	11.83	11.81	11.79	11.77	11.75	11.73	11.71
21	11.69	11.67	11.65	11.63	11.60	11.58	11.56	11.54	11.52	11.50
22	11.48	11.46	11.44	11.42	11.40	11.38	11.36	11.34	11.32	11.30
23	11.28	11.26	11.25	11.23	11.21	11.19	11.17	11.15	11.13	11.11
24	11.09	11.07	11.05	11.04	11.02	11.00	10.98	10.96	10.94	10.92
25	10.91	10.89	10.87	10.85	10.83	10.82	10.80	10.78	10.76	10.74
26	10.73	10.71	10.69	10.67	10.66	10.64	10.62	10.60	10.59	10.57
27	10.55	10.53	10.52	10.50	10.48	10.47	10.45	10.43	10.42	10.40
28	10.38	10.37	10.35	10.33	10.32	10.30	10.28	10.27	10.25	10.23
29	10.22	10.20	10.19	10.17	10.15	10.14	10.12	10.11	10.09	10.08
30	10.06	10.05	10.03	10.02	10.00	9.99	9.97	9.96	9.94	9.93

D-3

TABLE D-3

ARGON (ML/L)  
AT 100% SATURATION, 760MM PRESSURE, MOIST AIR FROM (WEISS 1970)

TEMP DEG. C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.50	0.50	0.49	0.49	0.49	0.49	0.49	0.49	0.48	0.48
1	0.48	0.48	0.48	0.48	0.48	0.47	0.47	0.47	0.47	0.47
2	0.47	0.47	0.47	0.47	0.47	0.46	0.46	0.46	0.46	0.46
3	0.46	0.46	0.46	0.46	0.46	0.46	0.45	0.45	0.45	0.45
4	0.45	0.45	0.45	0.45	0.45	0.44	0.44	0.44	0.44	0.44
5	0.44	0.44	0.44	0.44	0.43	0.43	0.43	0.43	0.43	0.43
6	0.43	0.43	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
7	0.42	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
8	0.41	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
9	0.40	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
10	0.39	0.39	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
11	0.38	0.38	0.38	0.38	0.38	0.37	0.37	0.37	0.37	0.37
12	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.36	0.36	0.36
13	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
14	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
15	0.35	0.35	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
16	0.34	0.34	0.34	0.34	0.34	0.33	0.33	0.33	0.33	0.33
17	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.32
18	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
19	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.31	0.31
20	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
21	0.31	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
22	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
23	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
24	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.28	0.28	0.28
25	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
26	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27	0.27	0.27
27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
28	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.26	0.26	0.26
29	0.26	0.26	0.26	0.26	0	0.26	0.26	0.26	0.26	0.26
30	0.26	0.26	0.26	0.26	0	0.26	0.25	0.25	0.25	0.25



TABLE D-4

VAPOR PRESSURE OF WATER  
0 - 30 DEG. C IN MM HG

TEMP DEG. C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	4.579	4.612	4.646	4.680	4.714	4.748	4.783	4.818	4.853	4.888
1	4.924	4.959	4.995	5.031	5.068	5.104	5.141	5.178	5.216	5.253
2	5.291	5.329	5.367	5.406	5.445	5.484	5.523	5.563	5.602	5.642
3	5.683	5.723	5.764	5.805	5.846	5.888	5.930	5.972	6.014	6.057
4	6.100	6.143	6.186	6.230	6.274	6.318	6.363	6.407	6.453	6.498
5	6.544	6.589	6.636	6.682	6.729	6.776	6.823	6.871	6.919	6.967
6	7.016	7.064	7.114	7.163	7.213	7.263	7.313	7.364	7.415	7.466
7	7.518	7.569	7.622	7.674	7.727	7.780	7.834	7.888	7.942	7.996
8	8.051	8.106	8.162	8.217	8.273	8.330	8.387	8.444	8.501	8.559
9	8.617	8.676	8.735	8.794	8.854	8.913	8.974	9.034	9.095	9.157
10	9.219	9.281	9.343	9.406	9.469	9.533	9.597	9.661	9.726	9.791
11	9.856	9.922	9.989	10.055	10.122	10.189	10.257	10.326	10.394	10.463
12	10.533	10.602	10.673	10.743	10.814	10.886	10.958	11.030	11.103	11.176
13	11.250	11.323	11.398	11.473	11.548	11.624	11.700	11.776	11.853	11.931
14	12.009	12.087	12.166	12.245	12.325	12.405	12.485	12.567	12.648	12.730
15	12.813	12.895	12.979	13.063	13.147	13.232	13.317	13.403	13.489	13.576
16	13.663	13.751	13.839	13.928	14.017	14.107	14.197	14.288	14.379	14.471
17	14.563	14.656	14.749	14.843	14.937	15.032	15.128	15.223	15.320	15.417
18	15.515	15.612	15.711	15.810	15.910	16.010	16.111	16.212	16.314	16.417
19	16.520	16.623	16.727	16.832	16.937	17.043	17.150	17.257	17.364	17.473
20	17.581	17.691	17.801	17.911	18.023	18.134	18.247	18.360	18.473	18.587
21	18.702	18.818	18.934	19.050	19.168	19.286	19.404	19.524	19.643	19.764
22	19.885	20.007	20.130	20.252	20.376	20.501	20.626	20.752	20.878	21.005
23	21.133	21.261	21.390	21.520	21.651	21.782	21.914	22.046	22.179	22.313
24	22.448	22.583	22.720	22.856	22.994	23.132	23.271	23.411	23.551	23.692
25	23.834	23.977	24.120	24.264	24.409	24.555	24.701	24.848	24.996	25.145
26	25.295	25.445	25.596	25.747	25.900	26.053	26.207	26.362	26.518	26.674
27	26.832	26.990	27.149	27.308	27.469	27.630	27.792	27.956	28.119	28.284
28	28.450	28.616	28.783	28.951	29.120	29.290	29.460	29.632	29.804	29.978
29	30.152	30.326	30.503	30.679	30.857	31.035	31.215	31.395	31.576	31.758
30	31.942	32.125	32.310	32.496	32.683	32.870	33.059	33.248	33.439	33.630

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 ETL 1110-2-253  
 26 Sep 80

TABLE D-5

BUNSEN COEFFICIENT X 100 FOR OXYGEN  
BY R.F. WEISS 1970

TEMP DEG. C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	4.910	4.896	4.883	4.869	4.856	4.843	4.829	4.816	4.803	4.790
1	4.777	4.764	4.751	4.738	4.726	4.713	4.700	4.688	4.675	4.662
2	4.650	4.638	4.625	4.613	4.601	4.589	4.577	4.565	4.553	4.541
3	4.529	4.517	4.505	4.493	4.482	4.470	4.459	4.447	4.436	4.424
4	4.413	4.402	4.390	4.379	4.368	4.357	4.346	4.335	4.324	4.313
5	4.302	4.291	4.281	4.270	4.259	4.249	4.238	4.228	4.217	4.207
6	4.196	4.186	4.176	4.165	4.155	4.145	4.135	4.125	4.115	4.105
7	4.095	4.085	4.075	4.065	4.056	4.046	4.036	4.026	4.017	4.007
8	3.998	3.988	3.979	3.969	3.960	3.951	3.942	3.932	3.923	3.914
9	3.905	3.896	3.887	3.878	3.869	3.860	3.851	3.842	3.833	3.825
10	3.816	3.807	3.798	3.790	3.781	3.773	3.764	3.756	3.747	3.739
11	3.731	3.722	3.714	3.706	3.697	3.689	3.681	3.673	3.665	3.657
12	3.649	3.641	3.633	3.625	3.617	3.609	3.601	3.594	3.586	3.578
13	3.570	3.563	3.555	3.548	3.540	3.532	3.525	3.518	3.510	3.503
14	3.495	3.488	3.481	3.473	3.466	3.459	3.452	3.445	3.437	3.430
15	3.423	3.416	3.409	3.402	3.395	3.388	3.381	3.375	3.368	3.361
16	3.354	3.347	3.341	3.334	3.327	3.321	3.314	3.307	3.301	3.294
17	3.288	3.281	3.275	3.268	3.262	3.256	3.249	3.243	3.237	3.230
18	3.224	3.218	3.212	3.206	3.199	3.193	3.187	3.181	3.175	3.169
19	3.163	3.157	3.151	3.145	3.139	3.133	3.128	3.122	3.116	3.110
20	3.104	3.099	3.093	3.087	3.082	3.076	3.070	3.065	3.059	3.054
21	3.048	3.043	3.037	3.032	3.026	3.021	3.015	3.010	3.005	2.999
22	2.994	2.989	2.983	2.978	2.973	2.968	2.963	2.957	2.952	2.947
23	2.942	2.937	2.932	2.927	2.922	2.917	2.912	2.907	2.902	2.897
24	2.892	2.887	2.882	2.878	2.873	2.868	2.863	2.858	2.854	2.849
25	2.844	2.839	2.835	2.830	2.825	2.821	2.816	2.812	2.807	2.803
26	2.798	2.793	2.789	2.784	2.780	2.776	2.771	2.767	2.762	2.758
27	2.754	2.749	2.745	2.741	2.736	2.732	2.728	2.724	2.719	2.715
28	2.711	2.707	2.703	2.698	2.694	2.690	2.686	2.682	2.678	2.674
29	2.670	2.666	2.662	2.658	2.654	2.650	2.646	2.642	2.638	2.634
30	2.630	2.627	2.623	2.619	2.615	2.611	2.607	2.604	2.600	2.596

D-6

 ETL 1110-2-253  
 26 Sep 80

TABLE D-6

BUNSEN COEFFICIENT X 100 FOR NITROGEN  
BY R.F. WEISS 1970

TEMP DEG. C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	2.374	2.368	2.362	2.356	2.350	2.344	2.338	2.332	2.326	2.320
1	2.314	2.308	2.302	2.297	2.291	2.285	2.279	2.274	2.268	2.262
2	2.257	2.251	2.246	2.240	2.235	2.229	2.224	2.218	2.213	2.208
3	2.202	2.197	2.192	2.186	2.181	2.176	2.171	2.165	2.160	2.155
4	2.150	2.145	2.140	2.135	2.130	2.125	2.120	2.115	2.110	2.105
5	2.100	2.095	2.091	2.086	2.081	2.076	2.071	2.067	2.062	2.057
6	2.053	2.048	2.043	2.039	2.034	2.029	2.025	2.020	2.016	2.011
7	2.007	2.002	1.998	1.994	1.989	1.985	1.980	1.976	1.972	1.967
8	1.963	1.959	1.955	1.950	1.946	1.942	1.938	1.934	1.929	1.925
9	1.921	1.917	1.913	1.909	1.905	1.901	1.897	1.893	1.889	1.885
10	1.881	1.877	1.873	1.869	1.865	1.862	1.858	1.854	1.850	1.846
11	1.843	1.839	1.835	1.831	1.828	1.824	1.820	1.817	1.813	1.809
12	1.806	1.802	1.798	1.795	1.791	1.788	1.784	1.781	1.777	1.774
13	1.770	1.767	1.763	1.760	1.756	1.753	1.750	1.746	1.743	1.740
14	1.736	1.733	1.730	1.726	1.723	1.720	1.716	1.713	1.710	1.707
15	1.704	1.700	1.697	1.694	1.691	1.688	1.685	1.682	1.678	1.675
16	1.672	1.669	1.666	1.663	1.660	1.657	1.654	1.651	1.648	1.645
17	1.642	1.639	1.636	1.634	1.631	1.628	1.625	1.622	1.619	1.616
18	1.614	1.611	1.608	1.605	1.602	1.600	1.597	1.594	1.591	1.589
19	1.586	1.583	1.581	1.578	1.575	1.573	1.570	1.567	1.565	1.562
20	1.559	1.557	1.554	1.552	1.549	1.547	1.544	1.541	1.539	1.536
21	1.534	1.531	1.529	1.526	1.524	1.522	1.519	1.517	1.514	1.512
22	1.509	1.507	1.505	1.502	1.500	1.498	1.495	1.493	1.491	1.488
23	1.486	1.484	1.481	1.479	1.477	1.475	1.472	1.470	1.468	1.466
24	1.463	1.461	1.459	1.457	1.455	1.452	1.450	1.448	1.446	1.444
25	1.442	1.440	1.438	1.435	1.433	1.431	1.429	1.427	1.425	1.423
26	1.421	1.419	1.417	1.415	1.413	1.411	1.409	1.407	1.405	1.403
27	1.401	1.399	1.397	1.395	1.393	1.391	1.389	1.387	1.385	1.384
28	1.382	1.380	1.378	1.376	1.374	1.372	1.370	1.369	1.367	1.365
29	1.363	1.361	1.360	1.358	1.356	1.354	1.352	1.351	1.349	1.347
30	1.345	1.344	1.342	1.340	1.338	1.337	1.335	1.333	1.332	1.330

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 ETL 1110-2-253  
 26 Sep 80

TABLE D-7

BUNSEN COEFFICIENT X 100 FOR ARGON  
BY R.F. WEISS 1970

TEMP DEG. C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	5.363	5.349	5.334	5.320	5.305	5.291	5.277	5.263	5.249	5.235
1	5.221	5.207	5.193	5.179	5.165	5.152	5.138	5.125	5.111	5.098
2	5.084	5.071	5.058	5.045	5.031	5.018	5.005	4.992	4.980	4.967
3	4.954	4.941	4.928	4.916	4.903	4.891	4.878	4.866	4.854	4.841
4	4.829	4.817	4.805	4.793	4.781	4.769	4.757	4.745	4.733	4.721
5	4.710	4.698	4.686	4.675	4.663	4.652	4.640	4.629	4.618	4.606
6	4.595	4.584	4.573	4.562	4.551	4.540	4.529	4.518	4.507	4.497
7	4.486	4.475	4.464	4.454	4.443	4.433	4.422	4.412	4.402	4.391
8	4.381	4.371	4.361	4.350	4.340	4.330	4.320	4.310	4.300	4.290
9	4.281	4.271	4.261	4.251	4.242	4.232	4.222	4.213	4.203	4.194
10	4.184	4.175	4.166	4.156	4.147	4.138	4.128	4.119	4.110	4.101
11	4.092	4.083	4.074	4.065	4.056	4.047	4.038	4.030	4.021	4.012
12	4.004	3.995	3.986	3.978	3.969	3.961	3.952	3.944	3.935	3.927
13	3.919	3.910	3.902	3.894	3.886	3.878	3.869	3.861	3.853	3.845
14	3.837	3.829	3.821	3.813	3.806	3.798	3.790	3.782	3.774	3.767
15	3.759	3.751	3.744	3.736	3.729	3.721	3.714	3.706	3.699	3.691
16	3.684	3.677	3.669	3.662	3.655	3.648	3.640	3.633	3.626	3.619
17	3.612	3.605	3.598	3.591	3.584	3.577	3.570	3.563	3.556	3.549
18	3.543	3.536	3.529	3.522	3.516	3.509	3.502	3.496	3.489	3.483
19	3.476	3.470	3.463	3.457	3.450	3.444	3.437	3.431	3.425	3.418
20	3.412	3.406	3.400	3.393	3.387	3.381	3.375	3.369	3.363	3.357
21	3.351	3.345	3.339	3.333	3.327	3.321	3.315	3.309	3.303	3.297
22	3.291	3.286	3.280	3.274	3.268	3.263	3.257	3.251	3.246	3.240
23	3.235	3.229	3.224	3.218	3.212	3.207	3.202	3.196	3.191	3.185
24	3.180	3.175	3.169	3.164	3.159	3.153	3.148	3.143	3.138	3.133
25	3.127	3.122	3.117	3.112	3.107	3.102	3.097	3.092	3.087	3.082
26	3.077	3.072	3.067	3.062	3.057	3.052	3.047	3.042	3.038	3.033
27	3.028	3.023	3.019	3.014	3.009	3.004	3.000	2.995	2.990	2.986
28	2.981	2.977	2.972	2.967	2.963	2.958	2.954	2.949	2.945	2.941
29	2.936	2.932	2.927	2.923	2.919	2.914	2.910	2.906	2.901	2.897
30	2.893	2.888	2.884	2.880	2.876	2.872	2.867	2.863	2.859	2.855

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