WELDING RESEARCH

SUPPLEMENT TO THE *WELDING JOURNAL*, JANUARY 1991

Sponsored by the American Welding Society and the Welding Research Council

Effect of Climatic Conditions on Diffusible Hydrogen Content in Weld Metal

A method for predicting atmospheric influence on diffusible hydrogen for climates worldwide is presented

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Introduction

Historical Background and Research Initiatives

As long ago as 1960 (Ref. 1), Zitter reported that the moisture content in the air surrounding the arc has an effect on the hydrogen content of the weld metal. Subsequently, other researchers (Refs. 2-4) have confirmed that indeed the diffusible hydrogen content (HD) increases with the increasing water vapor partial pressure (p_{H_2O}) of the air. Figure 1 shows this relationship for three different basic covered electrodes (Ref. 2), with the diffusible hydrogen increasing as the square root ($\sqrt{p_{H_2O}}$) of the water vapor partial pressure increases.

Despite this knowledge (Refs. 1-3), the influence of the atmospheric moisture has been hitherto disregarded in the control of hydrogen-induced cracking when welding steel, for the following reasons:

1) In the 1960s and 1970s, welding activity in temperate zones was high in relation to that in tropical and subtropical countries where there can be a combination of high temperature (t) and high relative humidity (RH), both leading to a high water vapor partial pressure (p_{H_2O}) according to:

$$p_{H_2O} = \frac{\text{RH} \times \text{saturation water vapor pressure}}{100\%} \quad (1)$$

In Europe, the t and RH variation is not high enough to have led to technological problems in the past.

2) In the U.S., the moisture content in the electrode coating was the technological criterion for the control of consumables to avoid cracking. Unlike the British practice (BS 5135), where the hydrogen content must be known to choose a preheat temperature, extensive tables (Ref. 5) compiled from practical experience have been used in the U.S. Therefore again, the problem did not arise.

3) In the 1970s, before the widespread use of electrodes with very low moisture in their coatings and with great resistance to moisture absorption, most electrodes then in use gave diffusible hydrogen contents around 10-15 mL/100 g. At such levels, the effect of atmospheric moisture is not very significant from the practical viewpoint. Consider the climates I and II marked in Fig. 1 and their effects on the relative change of diffusible hydrogen contents for electrodes 4A, 4B and 4C.

However, the situation is different now and the effect of the climatic conditions can no longer be ignored because of the combination of the following significant developments:

1) Since the mid-1970s, low moisture content/moisture-resistant electrodes have been used increasingly, and numerous fabrication specifications require that the diffusible hydrogen content must be controlled either to 10 mL/100 g max or to 5 mL/100 g max. Appropriate welding

KEY WORDS

Diffusible H Content
Climate Effect
H_2O Vapor Pressure
Weld Metal
Basic SMA Electrodes
υM-Nomogram
H-Prediction
H-Induced Cracking
Math. Relationship
Climate Data

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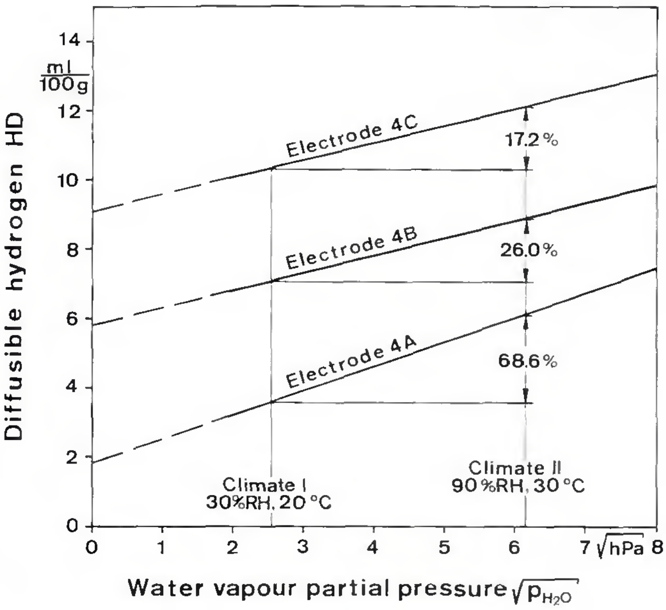

Fig. 1 — Effect of atmospheric moisture on the hydrogen content in the weld metal deposited from basic covered electrodes. Measured values after Refs. 2 and 7. (1hPa = 1.450 · 10^{-2} psi).

procedures developed for such hydrogen levels enable economic savings to be made by decreasing the preheat temperature required to avoid cracking.

2) The applications of the higher strength microalloyed and low-alloyed steels have been increasing in diversity and sophistication, and their successful exploitation has been related to welding with electrodes with diffusible hydrogen not exceeding 5 mL/100 g.

3) With the rapid industrialization of the tropical countries, quite sophisticated welding operations have been undertaken in India, Indonesia, Latin America, the Philippines and other countries where a combination of high temperature (ca. 30°C/86°F) and high RH (*ca.* 85%) leads to a high p_{H_2O} (Equation 1). It emerged that under such climatic conditions, an electrode which in Europe conforms to the requirement of maximum 5 mL/100 g can no longer consistently satisfy the above condition.

The Program of Investigations

This paper brings together two separate strands of research which were carried out totally independently but complementary to each other:

1) Over a number of years at Oerlikon in Zurich (Switzerland) and Eisenberg (Germany), numerous data for diffusible hydrogen were accumulated for E7018 electrodes as a result of routine quality control carried out according to IIW standard procedures (Ref. 6). These data were used in a research program that revealed the effect of climatic conditions on the diffusible hydrogen content in the weld metal.

2) At the Technical University of Brunswick (Germany), a doctoral research project was carried out to develop a nomogram (Ref. 7) from which the content of diffusible hydrogen can be predicted, without testing, in any part of the world with the known climatic conditions (t°C, %RH), provided a test result is available for a given electrode under one known climatic condition. The economic benefit of such a theoretical method is self-evident.

Variation in the Diffusible Hydrogen Content for E7018 Electrodes *(Program A)*

Test Conditions

The test pieces were welded according to the standard IIW procedures (Ref. 8). For the sake of speed, the hydrogen content was determined using the Oerlikon-Yanaco analyzer based on gas chromatography (Ref. 9), which enables quicker generation of data than hydrogen-gas collection either over mercury or other liquids.

The electrodes tested were E7018 (Tenacito R) and E7018-G/1%Ni (Tenacito 38R) in three sizes: 3.25-, 4- and 5-mm diameter (1/8-, 5/32- and 3/16-in.). All electrodes were manufactured and treated to comply with the requirement of a maximum of 5 mL/100 g of hydrogen. They were tested immediately after baking or redrying.

Test Results

As would be expected, the results accumulated over a period of four years (between January 1, 1984, and December 31, 1987) showed some scatter. This is represented by the data given in Table 1 which, however, shed no light whatsoever on the reasons for the variations observed.

Subsequently, all available data have been plotted in two different ways:

1) Starting with January 1, 1984, a day was assigned to each value. To simplify matters, each month was assumed to have 30 days, and a year consisted of 360 days. For the period January 1, 1984, to December 31, 1987, there is a total of 1440 days. Figure 2 shows the plot of the individual measurements over the period

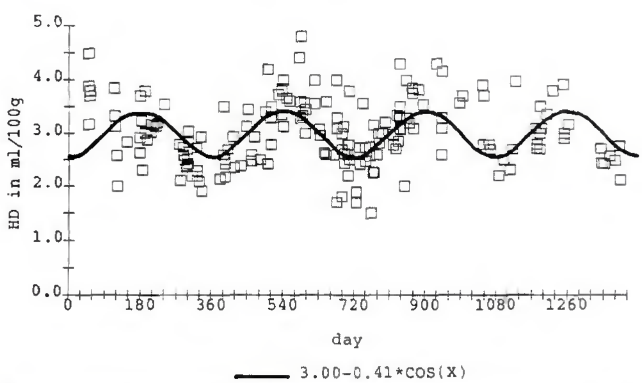

Fig. 2 — Fluctuations of the diffusible hydrogen content in weld metal deposited with electrodes in the 3.2-5.0-mm-diameter range between January 1, 1984, and December 31, 1987 (1440 days).

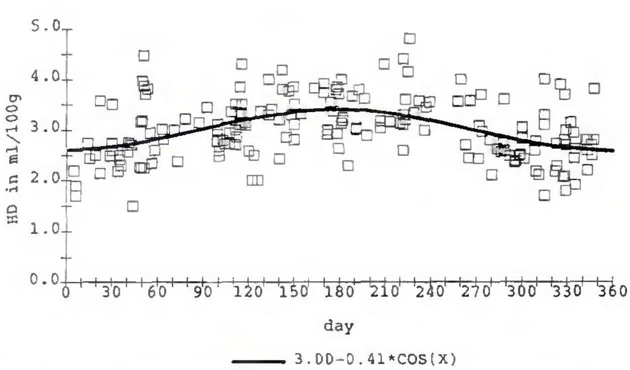

Fig. 3 — Yearly fluctuations of the diffusible hydrogen content in weld metal deposited with electrodes in the 3.2-5.0-mm-diameter range.

Table 1—Variation in the Diffusible Hydrogen Data Accumulated over Four Years of Routine Quality Control

Diameter (mm)	Number of Tests	Mean Value HD (mL/100 g)	Standard Deviation HD (mL/100 g)
3.25	81	2.89	0.60
4.00	68	2.98	0.58
5.00	38	3.27	0.58
All sizes	187	3.00	0.61

Table 2—The Results of Regression Calculations Using the Function y = a + b cos(x)

Electrode Diameter (mm)	Number of Tests	a HD[(a)]	b HD	r[(b)]	σ[(c)] HD	$F^{(d)}_{calc.}$	$F^{(e)}_{min}$
3.25	81	2.91	−0.38	0.43	0.55	18.1	6.69
4.00	68	2.99	−0.42	0.51	0.51	23.3	7.01
5.00	38	3.21	−0.36	0.46	0.52	9.8	7.40
All sizes	187	3.00	−0.41	0.48	0.54	55.4	6.81

a HD is in mL/100 g_{DM}.
b r is the correlation coefficient.
c σ is the standard deviation of the values from the regression curve.
d F is the variance ratio or Snedecar's ratio F.
e $F_{min.}$ is the minimum F-values required for 99% significance (γ = 0.01).

of 1440 days. Despite some scatter, periodic fluctuations in the plot can be perceived.

2) The diffusible hydrogen contents recorded on the same date every year throughout the four-year period were collected. Here again, each month was assumed to have 30 days. Figure 3 shows the plot of the results over a period of 360 days. Here the trend appears to be for higher values to occur in the summer months (days 150–240) and for the lower values to cluster during the winter months (days 1–60 and 300–360).

Mathematical Analysis

In the search for a mathematical function to describe the observed fluctuations (Figs. 2 and 3), it was found that the following function would be appropriate:

$$y = a + b \cos(x) \qquad (2)$$

Table 2 gives the results obtained for the regression calculations carried out using the above function (Equation 2). In Table 2, the F-value is very important in deciding whether or not the curve has a significant fit with the test results.

If

$$F > F_{p-1, N-p; 1-\gamma}$$

where $F_{p-1, N-p; 1-\gamma}$ is taken from the F distribution, then the hypothesis that the regression curve represents a good fit with the pairs of values is correct. Table 2 also gives the specified minimum F-values at 99% significance level (γ = 0.01), which were obtained from the F-distribution table.

From the same table, it is evident that for each electrode size, as well as for all the sizes taken together

$$F_{calculated} > F_{min.}$$

Therefore, it is considered that the selected regression curve (Equation 2) represents a significant fit into the experimental data. Figure 2 illustrates the fit of the curves for all sizes obtained by the regression calculations for the fluctuations over the period of four years, and Fig. 3 shows the fit of the curve for all sizes for the period of 360 days, using the data recorded on the same date each year. The paths of the regression curves through the distribution of the diffusible hydrogen levels show: 1) peaks occur in the summer when the maximum values are recorded, and 2) troughs occur in the winter when the minimum values are recorded.

Accounting for the Observed Fluctuations

Bearing in mind the previous reports (Refs. 1–4) on the effect of atmospheric humidity on the diffusible hydrogen content, a study was made to find out whether or not the water vapor partial pressure (p_{H_2O}) varies according to the cosine relationship in the course of a year. Figure 4 shows the change in the atmospheric water vapor partial pressure (p_{H_2O}) over one year in Zurich. The average p_{H_2O} was calculated according to Equation 2 from the average monthly temperature and relative humidity levels.

The curve in Fig. 4 is clearly such that, like the one describing the data in Fig. 3, it can be well determined by a cosine function. As expected, the maximum and minimum values do not coincide exactly with the middle and the end of the year, but are shifted by approximately one month later in each case. Despite this displacement, it is considered that the results of regression calculations are satisfactory.

Consequences for Electrode Users Worldwide

High quality electrodes, with low moisture in their coatings and with great resistance to moisture absorption, may be produced and QC-tested on one location, but they may be used worldwide. In Europe, *e.g.,* Zurich or Eisenberg, such electrodes may conform comfortably to the requirement of maximum 5 mL/100 g—Figs. 2 and 3. However, the data considered earlier indicate that the p_{H_2O} of the atmosphere has an effect on the diffusible hydrogen content: the greater the water vapor partial pressure, the higher the diffusible hydrogen content.

For a better appreciation of the variation in the climatic conditions, and of the differences between central Europe (Zurich, Switzerland) and locations nearby offshore construction sites, the calculated (Equation 1) water vapor partial pressure (p_{H_2O}) is plotted in Figs. 5 and 6. The average monthly temperatures and relative humidities needed for the calculation were taken from the *World Weather Guide* (Ref. 10). In the latter case, the averages were calculated with the values recorded in the morning and at midday.

Figure 5 (northern hemisphere) shows that the average p_{H_2O} in Nigg (northern Scotland) is nearly the same as in Zurich, and in Gibraltar it is nearly twice as high as in Zurich. For the other locations in this figure, the summer/winter fluctuation for p_{H_2O} is important. The highest values for p_{H_2O} are recorded in Sharjah (Emirates, Persian Gulf).

In Fig. 6 (southern hemisphere) it can be seen that p_{H_2O} is more regular over the year than in Fig. 5, and that the highest

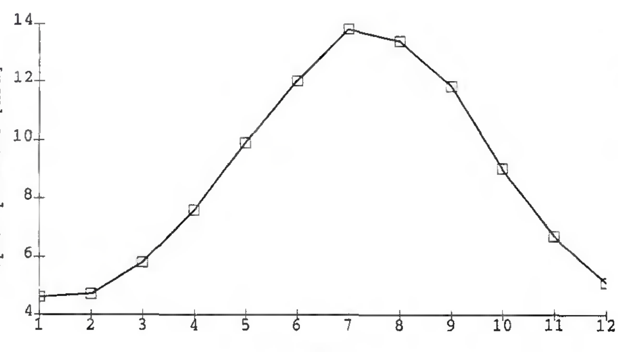

Fig. 4—Variations of atmospheric vapor pressure over a period of one year in Zurich, Switzerland. (1hPa = 1.450 · 10^{-2} psi).

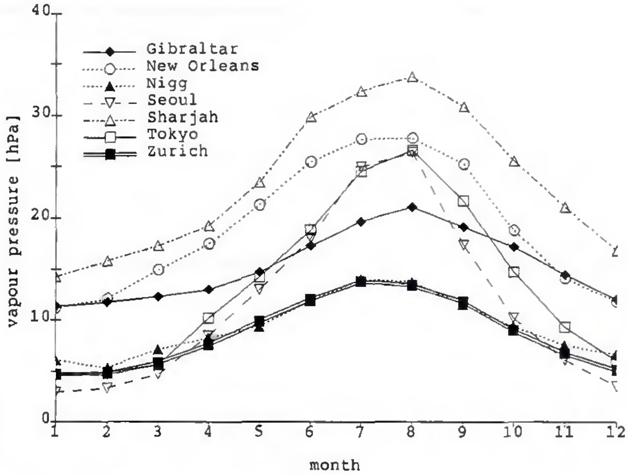

Fig. 5 — Variations of atmospheric vapor pressure over one year for selected locations in the northern hemisphere (Ref. 10).

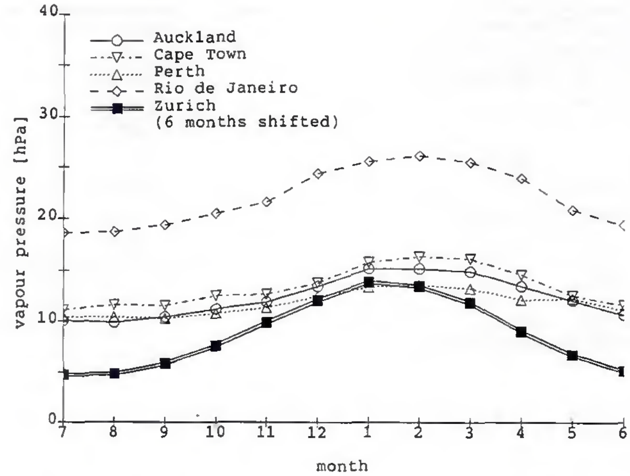

Fig. 6 — Variations of atmospheric vapor pressure over one year for selected locations in the southern hemisphere (Ref. 10).

values are compiled for Rio de Janeiro. It should be borne in mind that temperature and relative humidity can deviate markedly from the average values, depending on the weather. In addition, temperature and relative humidity are subject to the well-known fluctuations between daylight and nighttime. These fluctuations are sometimes quite considerable. However, if the weather remains stable, it can be assumed that the atmospheric water vapor partial pressure will not change too much.

Now, with the knowledge presented above, it would appear that the only correct way to proceed is to always test the electrodes under the same climatic conditions in which they would be used in production welding. However, this is expensive if not prohibitive because each electrode user operating under different climatic conditions would have to possess suitable equipment and laboratory staff for the determination of the diffusible hydrogen content. However, the research (Ref. 7) carried out under Program B has obviated this necessity and economic encumbrance. A theoretical method has been developed (Ref. 7) for the prediction of diffusible hydrogen under any climatic conditions, provided that one measured value is known in one climate. This is described in the next section.

A Method for Predicting the Diffusible Hydrogen Content under any Climatic Conditions *(Program B)*

The Basis of Method

Extensive research work was carried out at Brunswick University (Ref. 7) on the effect of ambient humidity on the weld metal hydrogen content. The data generated and those of others (Refs. 1-4) were analyzed together, and this has led to the elaboration of a predictive nomogram.

All the results showed that the dependence of the effective metal hydrogen content on the sources of moisture can be described by the following equation:

$$HD = (HD)_0 + E\sqrt{p_{H_2O}} \qquad (3)$$

This equation incorporates two physical elements: $(HD)_0$ is the base hydrogen content originating solely from the moisture in the electrode coating, and $E\sqrt{p_{H_2O}}$ is the hydrogen content supplied by the water vapor partial pressure prevailing in the surrounding atmosphere at the time of welding.

The coefficient E is a measure of the susceptibility of a given electrode arc to the penetration by the ambient humidity. As can be seen in Fig. 1, the higher the base hydrogen content at $\sqrt{p_{H_2O}} = 0$, the lower is the slope of the curves (E). This means that the influence of the ambient humidity decreases with the increasing moisture content of the electrode coating. This change in the slope (E) has been taken into account in the elaboration of the nomogram.

The Predictive Nomogram

Figure 7 gives the nomogram in reproducible form. The nomogram is applicable to basic low-hydrogen covered electrodes (AWS Classifications EXX15-X, EXX16-X and EXX18-X — validity for EXX28 is not yet checked) in the as-dried state (as baked in manufacture or redried, as recommended by the manufacturer, prior to use). Using the nomogram and the climatic data available, it is possible to predict diffusible hydrogen contents in the different climates without the need to conduct experimental tests, provided one value for the hydrogen content is known (*e.g.*, a QC test result) in one climate.

The nomogram in Fig. 7 is composed of two parts:

Part A — *The left side.* This gives a standard diagram in which the relative humidity (%) curves are plotted in terms of temperature (t in °C) on the abscissa and the

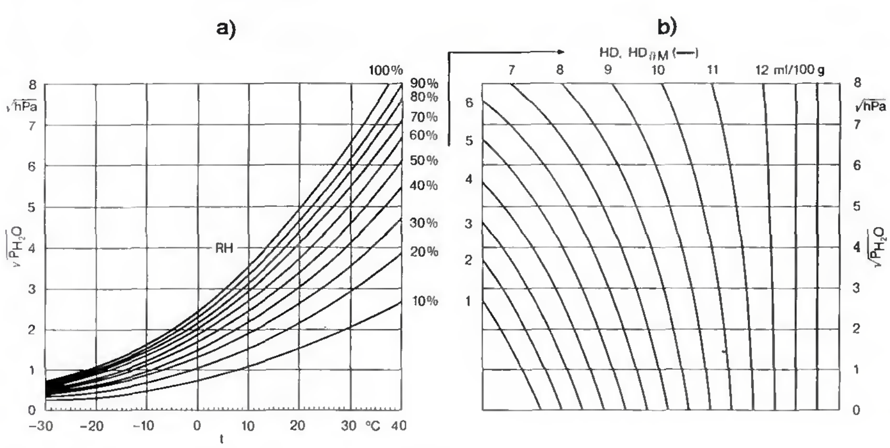

Fig. 7 — υM-Nomogram for the prediction of diffusible hydrogen content in weld metal at any given climate.

water vapor partial pressure of the air ($\sqrt{p_{H_2O}}$ in hPa) on the ordinate. This diagram is analogous to a similar diagram in the AWS D1.1 Code.

Part B — *The right side.* This gives in diagrammatic form the calculated dependence of the diffusible hydrogen content on the $\sqrt{p_{H_2O}}$, as in Fig. 1.

The variable of $\sqrt{p_{H_2O}}$ binds the two parts together into one nomogram.

The meaning of the symbols on the nomogram are:

HD (HD[1]) is the diffusible hydrogen content in the weld metal.

p_{H_2O} is the water vapor partial pressure in the surrounding air, or the absolute humidity.

t (t[1]) is the temperature in °C.

RH (RH[1]) is the relative humidity in %. When the nomogram is used, a clear distinction must be made between the hydrogen values documented. HD (HD[1]) is the measured diffusible hydrogen content, and $HD_{\upsilon M}$ is the predicted diffusible hydrogen content.

Example of Usage

Assume the following situation: Data available — HD = 2.5 mL/100 g_{DM} — a QC test result obtained at t^1 = 20°C, RH^1 = 30%; Information required — a hydrogen content at t = 30°C and RH = 80%

Procedure Steps are as follows:

1) Use the left-side diagram A in Fig. 8 and plot on it the climatic data under which the hydrogen measurement was carried out: t = 20°C and RH = 30%. For 20°C, mark a point at 30% RH.

2) From this point, draw a horizontal line toward the right-side diagram B and mark with a point the HD = 2.5 mL/100 g value where this horizontal line meets this value between the appropriate curves for 2 and 3 mL/100 g.

3) Draw a vertical line on diagram B through this point. On this vertical line, the predicted hydrogen contents ($HD_{\upsilon M}$) can now be read off for any climate where welding is to be carried out.

4) On the left-side diagram A, plot the coordinates of the climate in question: t = 30°C and RH = 80%. For 30°C, mark a point at 80% RH.

5) From this point, draw a horizontal line to the right-side diagram B.

6) Where this horizontal line intersects the vertical line drawn under Step 3, read off the predicted hydrogen content: $HD_{\upsilon M}$ = 5.3 mL/100 g.

At the chosen climatic condition of 30°C/80%RH, the predicted HD-content of the electrode will be slightly out of the specified hydrogen level of less than 5 mL/100 g.

1. Denotes that these three factors are related and used as the base for prediction at other climatic conditions.

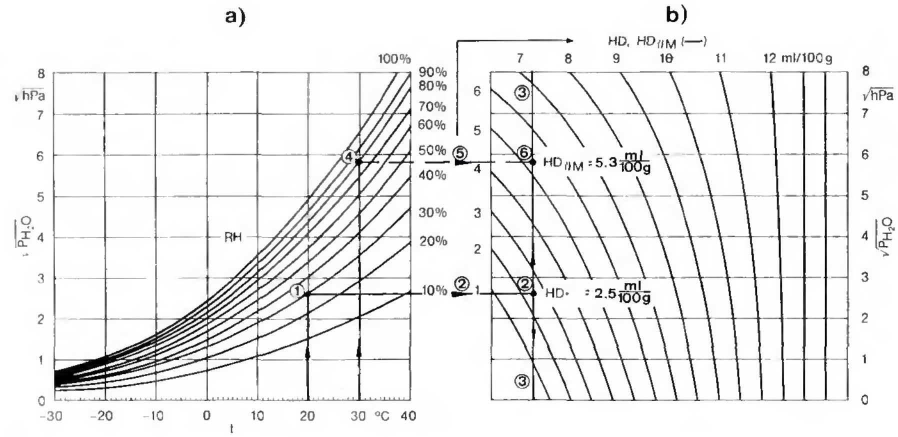

Fig. 8 — Example: Prediction on the diffusible hydrogen content in weld metal.

Table 3 — Predicted Variation in the Diffusible Hydrogen Levels Depending on the Variation in the Climatic Conditions in Various Countries[a]

	Climate						Predicted Hydrogen Levels[d] $HD_{\upsilon M}$ mL/100 g	
Location	Month	$\bar{t}$[b] °C	$\overline{RH}$[c] %	Month	$\bar{t}$ °C	$\overline{RH}$ %	min	max
Zurich	Jan	−1	81	Jul	18	67	2.2	3.6
Seoul	Jan	−4.5	64.5	Aug	26.5	76	1.8	4.9
Tokyo	Jan	3	60.5	Aug	26	79	2.2	4.9
Perth	Sep	14.5	62.5	Feb	23	48	3.2	3.6
Auckland	Aug	11	75	Jan	19.5	66.5	3.1	3.8
Cape Town	Jul	12	79	Feb	21	65.5	3.3	3.9
Gibraltar	Jan	13	75.5	Aug	25	66.5	3.3	4.4
New Orleans	Jan	12.5	77	Aug	28	73.5	3.3	5.0
Rio de Jan.	Jul	20.5	77	Jan	26	76	4.1	4.8
Sharjah	Jan	17.5	71	Aug	33.5	65	3.7	5.5

a Reference values: HD = 2.86 mL/100 g, t = 21°C, RH = 33%.
b $\bar{t}$ average monthly temperature.
c RH average monthly relative humidity.
d This applies to the weld metal deposited from E7018 electrodes.

Validation

In order to verify the accuracy of the nomogram (Fig. 7), the following two separate operations were carried out:

Operation 1 (Ref. 7): Using a starting value for a measured hydrogen content under known climatic conditions, predicted hydrogen values were estimated from the nomogram for a number of climatic conditions, for which actual measured values were also available. Figure 9 shows the comparison of the measured and predicted values, the latter having been derived from Fig. 7. Considering the fact that in this case the data were generated by different techniques (gas chromatography, the mercury method and the glycerol method converted to the mercury equivalent), the scatter is not too prohibitive. Therefore, the "υM-Nomogram" of Fig. 7 can be considered sufficiently accurate for practical applications.

Operation 2 (Ref. 6): It brings together the two strands of work (Programs A and B) by making the following comparison in Fig. 10: 1) the hydrogen contents measured in Zurich over the period of 1440 days with the best fit cosine curve which shows the average trend as in Fig. 2 and 2) the minimum-maximum lines predicted from the υM-Nomogram of Fig. 7 using the average climatic conditions at both maximum and minimum water vapor partial pressure (t, RH-values taken from Table 3 for Zurich).

It is gratifying to see that the best fit cosine curve lies within the min-max bounds predicted from the υM-Nomogram — Fig. 7.

Practical Implication

The production of very-low-hydrogen electrodes, complying with the maximum of 5 mL/100 g (or less), is a high-cost operation requiring expensive silicate binders, carefully controlled procedures, labor and time-consuming QC testing. All it takes is a humid climate to invalidate the

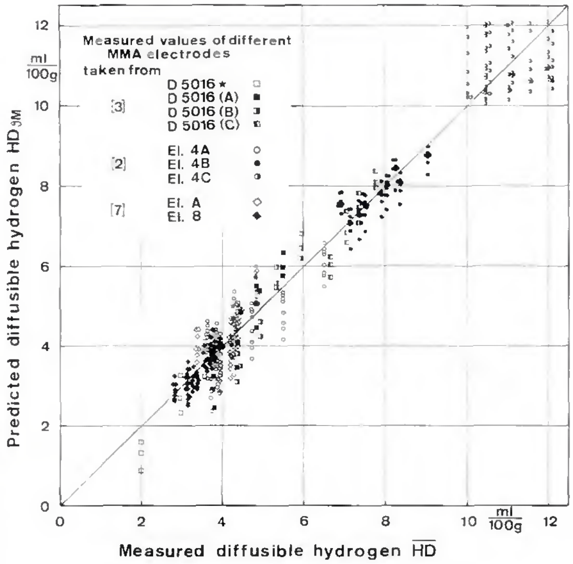

Fig. 9 — Verification of the accuracy of the υM-Nomogram shown in Fig. 7, using results obtained from various research studies (Ref. 7).

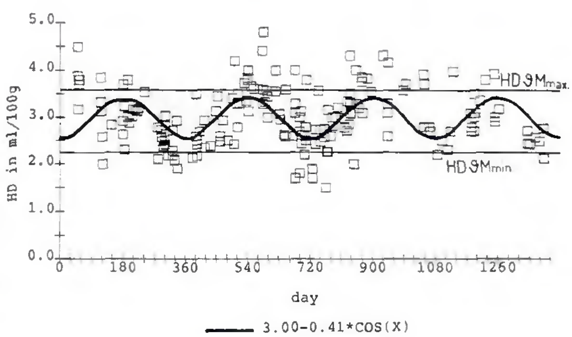

Fig. 10 — Diffusible weld metal hydrogen content of 3.2-5.0-mm-diameter electrodes over a period of 1440 days. These are the actual measured values and calculated extreme values for minimum and maximum P_{H_2O} in the atmosphere in Zurich, Switzerland.

specified low-hydrogen properties when production welding is carried out.

It is possible that ambient humidity can influence the drying of the electrode coatings, and consequently, the value of the base hydrogen content $(HD)_0$ as expressed in Equation 3. However, up to now there has been no information published on the extent of this influence, if any. Therefore, for now, only the effect of the ambient humidity acting through the welding arc on the weld metal hydrogen content will be considered.

One thing is clear: as the water vapor partial pressure (p_{H_2O}) raises the hydrogen content (Equation 3), it is necessary to start with a low base value $(HD)_0$ to secure compliance with the maximum of 5 mL/100 g. This can be achieved by elevating the electrode baking temperature.

To illustrate how climatic conditions in different parts of the world can affect the hydrogen content of a given E7018 electrode, Table 3 has been compiled using the nomogram in Fig. 7. An electrode which yielded HD = 2.86 mL/100 g at t = 21°C and RH = 33% (see validation section above) was chosen as a realistic starting point. Using these base values in the nomogram of Fig. 7, the respective $HD_{\upsilon M}$ values for minimum and maximum p_{H_2O} at different locations throughout the world could be predicted. It is clear that for some places the 5 mL/100 g limit might become critical. It should be noted that the stated minimum and maximum values are average monthly values. However, it is known that daily temperature and humidity readings might differ significantly from these values due to changing weather conditions. Therefore, the $HD_{\upsilon M}$ values indicated are to be considered as a rough approximation. From Table 3, it is also clearly seen that locations in lower latitudes usually have higher HD values.

Therefore, great care should be taken when welding procedures qualified in cooler temperate zones by multinational construction companies are transferred to production welding in some tropical countries. In Central or Northern Europe, for example, with a given E7018 electrode, the preheat temperature may be established for a given joint thickness in a given steel to avoid hydrogen-induced cracking. Such a suitable electrode was shown to give HD = 3-4 mL/100 g in the procedure qualification record. However, under conditions prevalent in Rio de Janeiro, the same electrode is likely to give the diffusible hydrogen content of HD = 5-5.5 mL/100 g. There should be no surprise if cracking occurs and the noncompliance with preheat requirements need not be invoked. The same would apply to any naval repair welding carried out in tropical bases using procedures approved in a moderate climate.

Conclusions

1) Earlier reports have been corroborated. The absolute atmospheric humidity, *i.e.*, the water vapor partial pressure (p_{H_2O}) of the air, has an effect on the diffusible hydrogen content in the weld metal deposited from basic covered electrodes (AWS EXX16-X and EXX18-X).

2) The summer-winter fluctuations in the QC test results for the hydrogen content were correlated with similar fluctuations in the atmospheric p_{H_2O}.

3) A predictive nomogram was developed to estimate the diffusible hydrogen content under any climatic conditions when one value is known under one climatic condition.

4) A given batch of very-low-hydrogen electrodes, conforming to the maximum of 5 mL/100 g on one location, may fail to comply with this requirement on another location where the climate is extra humid. Unless this is realized, production welding difficulties (hydrogen-induced cracking) and contractual problems (validity of certification) may arise.

5) To comply with the maximum hydrogen level of 5 mL/100 g with the increasing moisture level in the air surrounding the arc, it is necessary to further lower the moisture content in the coating by increasing the drying temperature.

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