

Technology Report

Fundamental Concepts of Environmental Testing

Techniques in Electricity and Electronics

Part 1: Fundamental concepts of physics and chemistry regarding heat and humidity

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This article is the first in a four-part series on basic issues concerning reliability and quality control in electricity and electronics. The issues to be covered deal mainly with “temperature and humidity testing”, and are primarily directed toward beginning technicians who are participating in environmental testing.

The series is organized as follows:

Part 1: Fundamental concepts of physics and chemistry regarding heat and humidity

Part 2: Concepts concerning the behavior of standard environments and moisture required for designing temperature and humidity tests

Part 3: Concepts concerning the establishment of public test standards

Part 4: Concepts serving as reference for effectively applying environmental testing

The aim of this series is to present the fundamental concepts required for performing temperature and humidity testing, the most basic testing in the various kinds of test methods. In addition, we sincerely hope that these fundamental concepts will lay the foundation for understanding current environmental tests, designing the next generation of environmental tests, and developing new test methods.

1 Introduction

Fifteen years ago in Japan, the electrical and electronics industry used “environment” to refer to natural environments. Nowadays, though, the term is used to include other meanings. The rapid development of industrial technology has widely popularized a great variety of industrial products which have provided enormous convenience in our lives. However, this situation is also leading to immense changes in the natural environment on a global scale. It is well-known that these changes are giving rise to a variety of current social problems.

Modern industrial products have increasingly numerous opportunities to be directly and strongly influenced by environmental changes, including naturally occurring

periodic weather changes such as the changing seasons, and the environment of the geographical location, but even more by artificial environmental changes brought about by environmental changes in the rooms in which the products are placed, as well as by non-periodic operation of other products located close by. In other words, the influence of the artificial interior environment has become greater than the influence from the global natural environment. (Our own bodies are also receiving the effects of this same environmental influence on a daily basis.)

2 Physical properties of temperature and humidity

Temperature refers to thermal energy, and we can only grasp the level of thermal energy through some sort of matter. In other words, thermal energy is not matter. Because of this, we use appropriate instruments (thermometers and calorimeters) to index the order of coolness and heat and its increase and decrease, i.e. the amount of thermal energy and the level of change in that energy.

Humidity is a combination of water and dry air, and the water can easily change into a variety of forms within our life temperature zone. Occasional high and low temperatures cause the humidity values to fluctuate widely.

We know from experience that when a hot substance comes into direct contact with a cold substance, the hot one cools and the cold one warms. This change does not continue in perpetuity, but is rather one that reaches equilibrium after time, and the change stops. At this time the two substances involved are said to have reached thermal equilibrium. We should also note that as the temperature of a substance increases, molecular motion correspondingly increases in the molecules composing the substance. However, as the temperature drops, molecular motion also slows. It is well known that at extremely low temperatures, in the vicinity of -273°C , molecular motion in most molecules stops.

2.1 Molecular motion of gases

Fig. 1 illustrates the velocity of one oxygen molecule in a vacuum. As the temperature rises, the velocity increases. In other words, the higher the temperature of a gas, the greater the kinetic energy that it has (the thermal motion of the molecule increases).

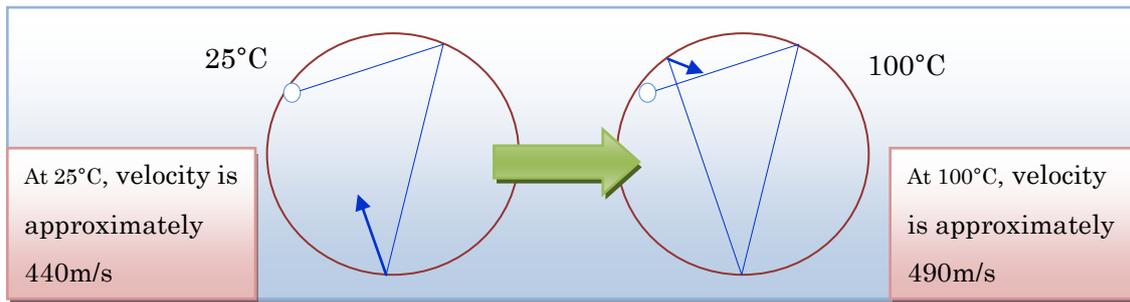


Fig.1 Velocity of one molecule of oxygen

Next, let's observe the molecular motion of groups of molecule.

2.1.1. With groups of identical molecules

Even when a number of identical molecules form a gas, the velocity of all the molecules making up the gas is not equal. Each of the molecules conforms to the uniform velocity distribution ⁽¹⁾ determined by the temperature. As Fig. 2 clearly shows, the higher the temperature, the more the distribution is inclined toward an area of greater velocity. For example, the velocity distribution of N₂ molecules in nitrogen gas is as shown in Fig. 2. When most of the molecules are temporarily at the average velocity *v* for that temperature, the value of *v* for the N₂ molecules changes to 425 m/s at 0°C, 910 m/s at 1,000°C, and 1,220 m/s at 2,000°C.

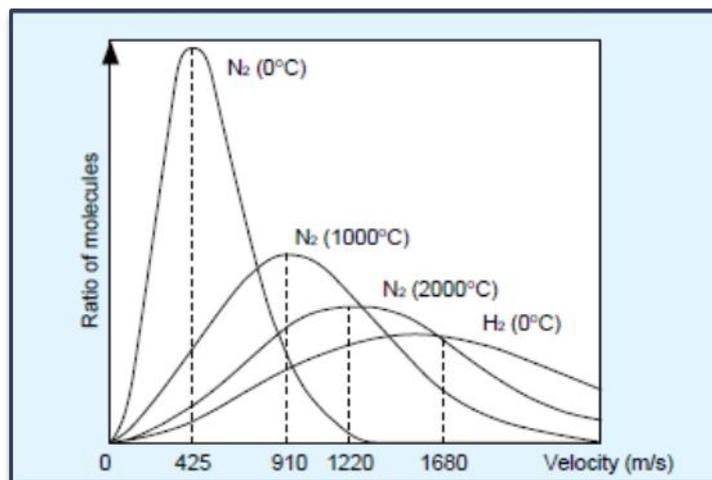


Fig.2 Temperature and distribution of molecular velocity

2.1.2. With groups of different type of molecules

Even at the same temperature, the velocity distribution of groups of molecules with lower molecular weight has a distribution more inclined toward an area of greater velocity than groups of molecules with greater molecular weight. For example, when comparing hydrogen molecules (molecular weight, 2) with nitrogen molecules

(molecular weight, 28) as in Fig. 2, at the same temperature of 0°C, the velocity v of the H_2 molecules is 1,680 m/s, but the velocity v of the N_2 molecules is 425 m/s.

The higher the temperature, the greater the average molecular velocity v is. This value of v is known to be in proportion to the square root of absolute temperature T . The average velocity can be found with the following formula, in which M is the molecular weight.

$$V = \sqrt{\frac{3RT}{M}} \quad (\text{Where } R \text{ is the gas constant})$$

This type of temperature change creates thermal stress by changing the velocity distribution of the molecules composing the substance that is in thermal equilibrium, i.e., stable. Therefore, changing the temperature of a substance causes repeated changes in velocity at the molecular level, so the substance is not static even though its macro stability can be observed. From the micro standpoint, a substance is normally in an unstable condition. The greater the change in temperature, the greater the loss of stability is. To put it the other way around, the smaller the change in temperature, the greater the relative stability is.

Next, let's consider humidity. When dealing with the subject of moisture content, the prerequisite for humidity, we must bear in mind the characteristics of water. Water is at its greatest density at 4°C (1 atm, 3.98°C), and undergoes phase changes according to the temperature. In other words, depending on the temperature, water will exist as water vapor (gaseous phase), water (liquid phase), or ice (solid phase). Within our life temperature zone we don't often see liquids freeze (with the exception perhaps of only glacial acetic acid ⁽²⁾ and benzol ⁽³⁾).

By the way, when discussing phase change, we must not forget the existence of intermolecular force.

First of all, when a gas is cooled or compressed, it becomes a liquid (in rare instances changing directly to a solid). For example, when air is compressed and cooled, it becomes liquid air, and when carbon dioxide is cooled, it becomes a snow-like solid (dry ice). These phenomena indicate that the molecules attract each other. This force is called intermolecular force, or Van der Waals force (Van der Waals, 1837 to 1923). This intermolecular force is created only when molecules are contiguous, and is rarely created when the intermolecular distance is great. Therefore, in solids and liquids, intermolecular force results in molecules being held almost immobile or merely able to flow. When the substance becomes a gas, the molecule can fly about almost freely (Although within the range of mean free path ⁽⁴⁾). For example, butane (C_4H_{10}) boils at

10°C, and at room temperature is a gas, but is a liquid in a gas lighter. This is because the butane is compressed and put into the lighter, forcibly reducing the intermolecular distance between the butane molecules. This compression creates intermolecular force, forming a liquid and making it possible to insert 200 times as much butane into the lighter.

Butane (boiling point -0.5°C), is approx. 22.4L at 0°C and 1atm (gas), and in cubic form one side is 28.2cm. As a liquid at 0°C and 1atm, it is approx. 97ml and in cubic form one side is 4.6cm. Therefore the intermolecular distance in the gaseous phase is 6 times the liquid phase (28.2/4.6)

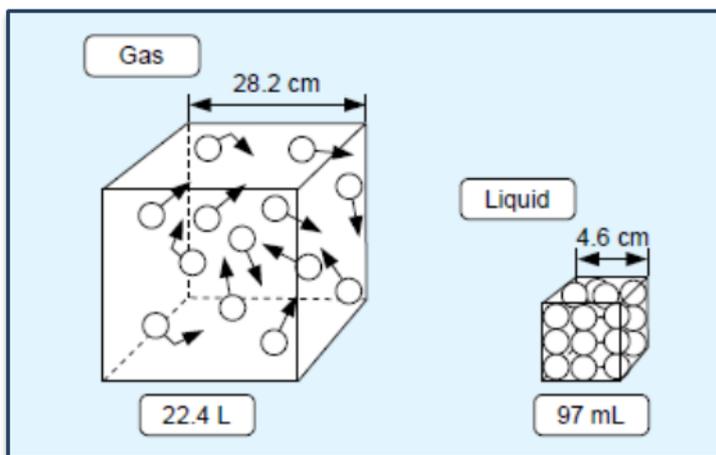


Fig.3 1 mol of butane (liquid and gas)

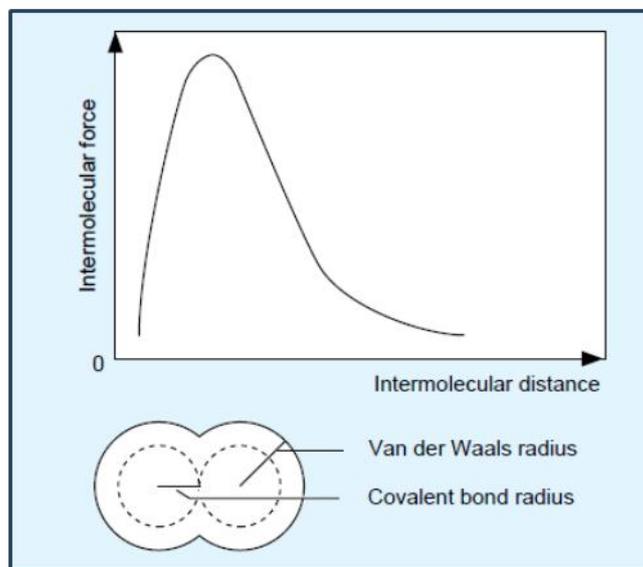


Fig.4 Intermolecular distance

Intermolecular force is strongly affected by intermolecular distance, and is inversely proportional to the intermolecular distance raised to the power of 7. For example, if the intermolecular distance is doubled, the intermolecular force becomes $1/2^7$, i.e., $1/128$. Intermolecular distance is a weaker force than chemical bonds (ionic bonds ⁽⁵⁾, covalent

bonds ⁽⁶⁾, and metallic bonds ⁽⁷⁾, but it is incomparably stronger than universal gravity. However, coming too close together creates repulsion force, so molecules can't approach closer than a certain uniform distance. The atomic radius determined from this distance is called the Van der Waals radius, which is considerably larger than the covalent bond radius.

We don't have room to go more into detail on this subject here, so if you would like to know more about it, please refer to other sources.

Incidentally, water undergoes a change in volume when changing from a liquid to a gaseous phase or to a solid phase, and because of that exerts an extremely strong mechanical force on its surroundings. Also, existing at the boundaries of the various changes are special characteristics such as the appropriate gain and loss of kinetic energy as latent heat ⁽⁸⁾ in cases in which there is no temperature change. Another current problem is that even when the amount of moisture is insufficient to cause problems as independent water, when combined with other major factors it can form a complex environment with properties that severely affect electrical and electronic products.

2.2 Vaporization and expansion

Heated water evaporates and becomes water vapor in a phenomenon known as evaporation, but this process change from the liquid phase to the gaseous phase is accompanied by expanding volume, a phenomenon known as evaporative expansion. According to the Ideal Gas Equation on the relationship between the temperature and pressure of a gas, when this expansion occurs in a closed system, the internal pressure of the system increases in proportion to the temperature. For example, at 0°C and 1 atm, 1 cm³ of water becomes 1.24 L when vaporized, in other words, it expands to 1,240 times its liquid volume. This phenomenon is shown in the following manner:

The Ideal Gas Equation

$$PV = nRT$$

We can substitute the following values:

$$P = 1 \text{ atm}$$

$$R = 0.082 \text{ atm/}^\circ\text{C} \cdot \text{mol}$$

$$T = 273^\circ\text{C, and}$$

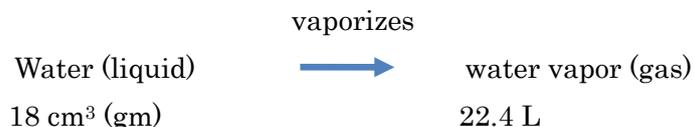
$$n = 1/18 \text{ mol/gm}$$

in the following formula:

$$V = nRT/P$$

to confirm that the result is 1.24 L.

For example, when water (liquid) 18 cm³ evaporates, it becomes:

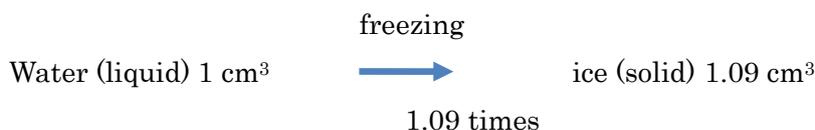


2.3 Freezing and expansion

Volume expansion due to freezing occurs on a very small scale compared to vaporization expansion, and it also relies much less on temperature. When 1 cm³ of water freezes at 0°C and 1 atm, the volume becomes 1.09 cm³, a 1.09 times increase. This value can be found in the following manner. The density of water at 0°C and 1 atm is 1 gm/cm³, so the volume of 1 cm³ of water has a weight W_L of 1 gm. When this freezes, at 0°C and 1 atm, the density d_s of ice = 0.917 gm/cm³, so the volume can be found as follows:

$$V_s = \frac{W_L}{d_s} = 1.09\text{cm}^3$$

In other words, when 1 cm³ of water (liquid) freezes:



The reason for this freezing expansion is as follows.

Within liquid water are groups of water molecules that are linked together by hydrogen bonds (bonds formed when the positively charged H atoms in the molecules form mutual electrostatic attractions with negatively charged atoms in other molecules, in this case oxygen atoms). When the temperature drops, the thermal motion of water decreases and the groups become larger, and at around 0°C most of the water molecules are linked by hydrogen bonds. Then, as the temperature drops below 0°C, the water molecules lose the ability to move freely, becoming crystallized. Therefore, the water molecules in ice form an orderly crystal lattice. This crystalline structure contains a large number of gaps, and so the volume occupied is greater than water. Most substances become denser as the temperature drops and less dense as the temperature rises. (Temperature is inversely proportional to density, forming the basis for the use of substances such as alcohol or mercury in thermometers.) This property of water differs from other substances, and is an exception to the general rule that the solid phase is less dense. When ice melts and water molecules become able to move, molecules are able to enter the gaps causing water to become denser, and so ice is able to float. (Example, icebergs)

Expressing the existence of water as humidity refers to the amount of water vapor in the air. The unit of humidity generally used as an environmental factor in environmental testing is called relative humidity, which is based on the capacity standard. Relative humidity is defined by the following formula:

$$RH = \left(\frac{e}{E} \right) \times 100 (\%)$$

Where,

RH = relative humidity,

e = the moisture content actually present of the air's uniform capacity at the uniform temperature, and

E = the maximum moisture content possible at the temperature condition in e, at the saturation moisture content in the air.

This moisture content is also shown in proportion to a certain water vapor pressure.

3 Chemical properties of temperature and moisture

Thermal energy, the index of temperature, is not matter so it is not directly involved in chemical reactions. Thermal energy can penetrate or leave matter. It can come into being and be extinguished inside matter, and can intensify or calm the motion of molecules forming matter. It can effectively speed or slow chemical reactions. At the same time, chemical reactions occurring inside matter can create new thermal energy or exhaust thermal energy as a product of the reaction. However, when the reacting substances of a chemical reaction are consumed, the reaction will stop regardless of temperature. Thermal energy plays a supporting role in relation to moisture, but the main role in this domain is the moisture itself, and its absolute mass. Most chemical reactions occur in solvents, so we can assume that water molecules play some sort of role.

3.1 The structure of the water molecule

The water molecule has an extremely wide variety of functions. We have already noted that the state of water changes according to the temperature. The water molecule is composed of one oxygen atom and two hydrogen atoms. The structure forms a tetrahedron with the oxygen atom at the center, and the hydrogen atoms receiving the two electrons from the oxygen atom are at the two peaks, i.e., the location of the protons. The distance between the center of the hydrogen atoms and the center of the oxygen atom is approximately 10–10 m (1.0Å), and the two hydrogen atoms enclose the oxygen

atom at an angle of approximately 105°.

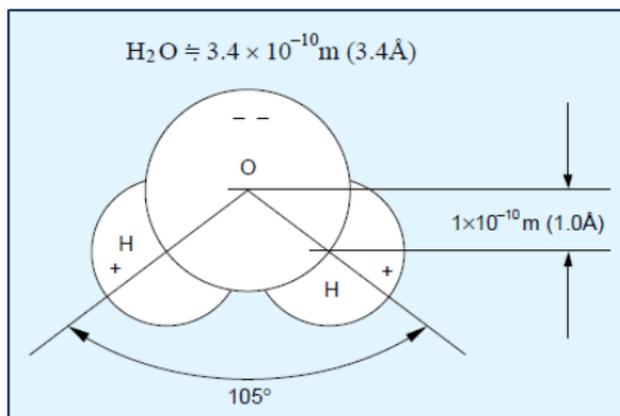
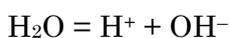


Fig. 5 The structure of water

3.2 Properties of water

The more pure the water, the lower its ability to conduct electricity, but regardless of how much it is purified, water will always have some level of conductivity. This is because an extremely small amount of H₂O ionizes into H⁺ and OH⁻ and maintains ionization equilibrium as shown in the following formula:



This ionization equilibrium is not only true for pure water, but also holds true for water in aqueous solutions of acids, bases, salts, and so on. This relationship can be shown using the equilibrium constant. In pure water and weak aqueous solutions the relationship can definitely be seen as constant, and can be described with the following formula:

$$[H^+] [OH^-] = K [H_2O] = K_w$$

This K_w is called the ionic product of water, and is a constant that changes according to the temperature. This constant value is always maintained in any sort of aqueous solution, whether pure water, acid, base, salt or other. In pure water it is $[H^+] = [OH^-]$. By measuring the electrical conductivity of pure water, this value can be established as $1.0 \times 10^{-7} \text{ mol/L}$ at 25°C. Putting this value in the above formula gives us

$$K_w = [H^+] [OH^-] = (1.0 \times 10^{-7} \text{ mol/L})^2 = 1.0 \times 10^{-14} \text{ mol}^2/\text{L}^2$$

However, as we have already noted, the ionic product changes according to temperature

and the higher the temperature the greater the value of the ionic product.

Furthermore, as a property of water, one molecule has the same characteristics as one drop or one cup of water (a giant molecule). Also, ions such as the hydrogen ion H^+ and the hydroxide ion OH^- have an extremely high mobility ratio. In other words, H^+ and $[H_3O]^+$ (oxonium) ions move toward the cathode, and the OH^- ions move toward the anode.

Water is generally very good at dissolving ionic compounds, but at room temperature reacts with metals such as sodium, potassium, and calcium. Water vapor reacts with iron to create hydrogen and form oxides and hydroxides, and hydrolyzes with substances such as nonmetallic halides and esters. (Hydrolysis is dissolution inside the molecules that compose the substance, i.e., changing the bonds inside the molecules.) A comparatively large number of substances react in this way.

4 Activation state and activation energy

When dealing with the problems of failure analysis and life of electrical and electronic parts, attention repeatedly focuses on activation energy. This is because the degradation of part functions is deeply related to the manner in which the chemical reaction proceeds.

4.1 What is activation state?

We stated in section 2-1 that the distribution of kinetic velocity (kinetic energy) of gas molecules inside a container is uniform in response to that temperature. We further noted that if the temperature of the gas inside the container is raised, the kinetic energy of the molecules tends to be greater. These phenomena are intimately related to the chemical reaction of matter. For example, even if iodine ⁽⁹⁾ is put into the container and left at room temperature, a decomposition reaction does not occur, but with a temperature of 400°C a decomposition reaction occurs as shown by the following formula:



In general, when the temperature of a gas is raised:

a) Molecular motion becomes more energetic, and the collision frequency of the molecules inside the container increases.

b) As the kinetic energy of the molecules increases, when they collide there is an increased probability of rearranging the connections between the atoms.

(This is chemical reaction.)

The molecules that have collided don't all react. Within the particles of the reactants (such as ions and molecules) only the particles above the uniform energy react. To make all the remaining particles react, more energy would have to be applied. (Refer to Fig. 6)

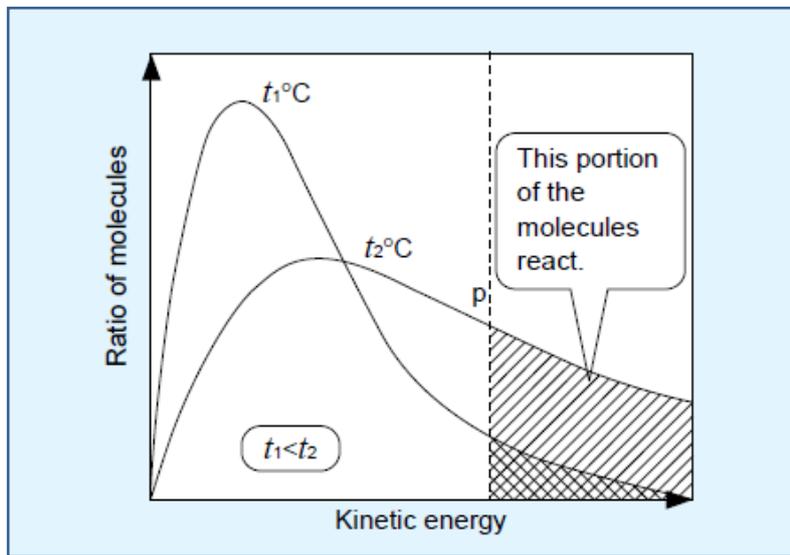


Fig.6 Energy of particles able to react

For a reverse reaction, let's look at the process that produces hydrogen iodide (HI). When high energy molecules collide in the direction shown in Fig. 7, a reaction is started. In this case, the H₂ molecules and I₂ molecules don't react directly. They first pass through an intermediate state in bonding as 2 molecules of HI.

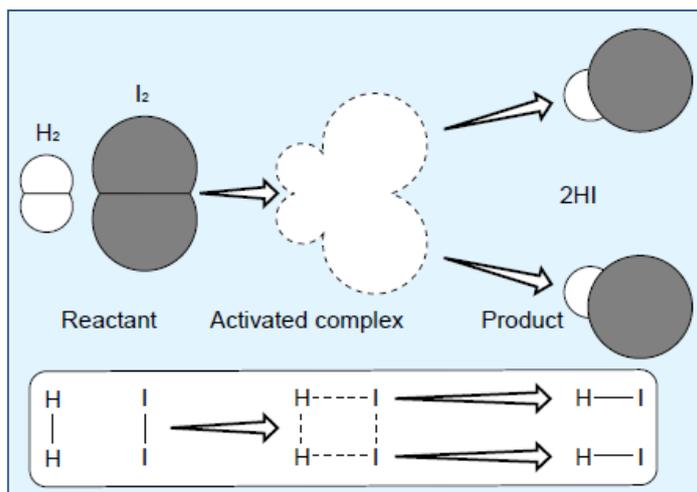


Fig.7 Model of the activated state

This intermediate state has more energy than the average energy of the original reactants (the H₂ and I₂ molecules). Once this state has been reached, energy is

immediately released and the molecules become stable product molecules (HI). This intermediate state is called the activating state. The dissolution of 2HI that we discussed earlier must also pass through this activated state. In chemistry, this type of intermediate body is called an activated complex.

4.2 Activation energy

In the reaction $A + B = AB + QkJ$ in Fig. 8, the energy (E_a) required to activate all reactants (A + B) to condition X is called the activation energy. In other words, the difference between the energy of the reactants and the energy of the activated state is the activation energy. This X immediately releases energy (E_b) and becomes a product (AB). In other words, it is also the activation energy of the reaction $AB \rightarrow A + B$. In this case, Q corresponds to added heat from outside that can raise the constant energy of the particles not yet having reached a reactive level to such a level at which they can react. This indicates that reactants in chemical changes must generally cross the peak of activation energy before they can become products.

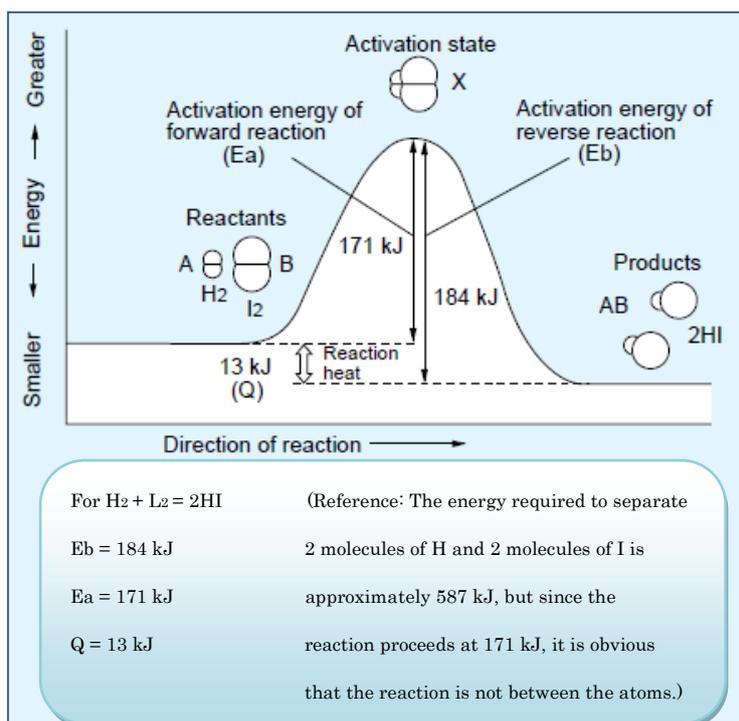


Fig.8 Activation energy

4.3 The role of temperature in reaction state

When an aqueous solution of sodium hydroxide (caustic soda) is added to hydrochloric acid, a neutralization reaction occurs, but this reaction is so extremely fast that it ends the instant that it is mixed. On the other hand, reactions involving the rusting of iron spikes and copper plates proceed slowly over a long time. However, the speed at which

chemical reactions proceed depends on the type of reaction. Even with the same type of reaction, the reaction rate will vary depending on the reacting substances and the reactant states.

The reaction rate can be shown either in units of time of the rate at which the reactants are used up, or the rate at which the products increase. Either way, the relationship is as follows:

$$[\text{Reaction rate}] = [\text{proportional constant}] \times [\text{density of reactant or product}]$$

The proportional constant is determined by the temperature, and the formula that shows this relationship between the reaction rate and density is called the rate equation. In general, the higher the temperature the faster the reaction rate. For example, if the temperature rises 10°C the rate constant becomes 2 or 3 times greater, so such expressions as the 10°C rule are used. In 1889, the Swedish physicist Arrhenius discovered the linear relationship between the logarithm of the rate constant K ($\log K$) and the inverse number ($1/T$) of the absolute temperature T ($= 273+t^{\circ}\text{C}$) as shown in Fig. 9. This relationship is quite often used in failure analysis when analyzing chemical reactions between substances and when calculating the rate constant.

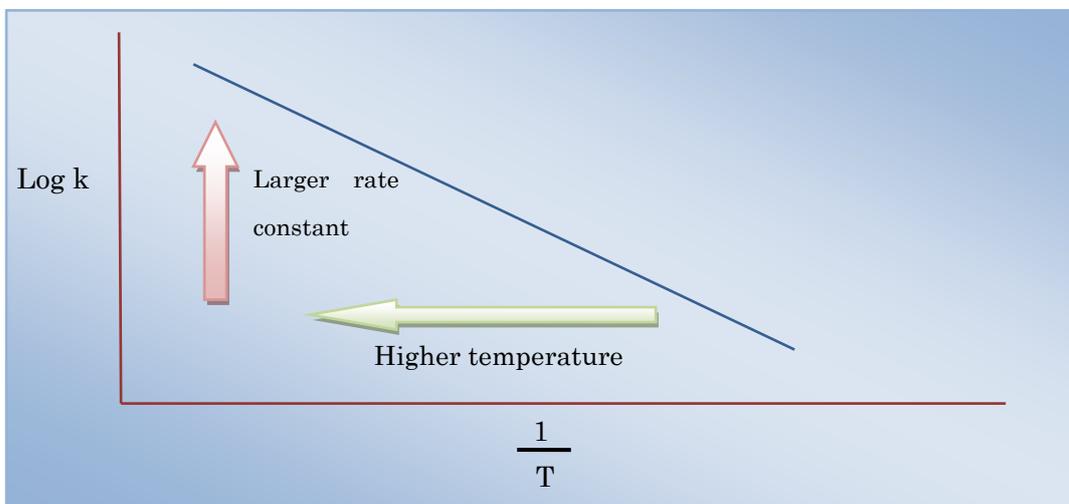


Fig.9 Relationship between the rate constant and temperature

The explanation given above forms the basis for the thermal stress and humidity stress tests that we perform, and is intimately related to the failure of many products. In the actual market environment, many electrical and electronic products fail due to physical distortion caused by differences in the amount of thermal expansion between materials used to construct the product. As a result, gaps are left at the interface of materials with

different coefficients of thermal expansion, and in extreme cases cracks are introduced into sealing material made of the same material. Moisture can penetrate through these cracks or through the surface of the material through long contact. As the moisture contacts the passageway it dissolves a variety of contaminants from the material interface, and as the water gets mixed in, it reaches the inner electrical circuits. At this point it reacts chemically with the materials forming the circuits.

Furthermore, electrical current and electrical and magnetic fields strongly recreate these reactions. The reactions are also strongly affected by temperature. In this way we can see that failure results from purely physical phenomena and chemical reactions occurring repeatedly at the same time and creating complex stress. When physical causes and chemical causes occur in succession or together, the related phenomena speed degradation of the product. If the durability of the product is exceeded, this can lead to cessation of functions and product failure.

5 Accelerated testing of temperature and humidity

In the initial stages of its development, environmental testing was used to perform simulation testing of the earth's natural environment. However, current environmental testing has come a long way from the original simulation testing, and that change is due to artificially accelerated testing. According to IEC 50 (191), an accelerated test is explained as "A test in which the applied stress level is chosen to exceed that stated in the reference conditions in order to shorten the time duration required to observe the stress response of the item, or to magnify the response in a given time duration."

However, it would be rash to decide that trustworthy reliability for the market environment has been established merely on the basis of products having endured a test that is more severe than the standard conditions. In fact, products that have passed extremely rigorous test conditions have occasionally been found to fail in quite mild environments. For example, when only temperature stress is applied to ester resins such as polyester and carbonate they show a life of tens of thousands of hours even at 150°C. When the coefficient of water absorption is also in the range of 0.1 percent, moisture absorption causes almost no changes in the substance. However, when temperature and humidity are applied at the same time, for example, an item that has a 27-year life at conditions of 20°C and 100% RH has a life of just three days at 35°C and 100% RH. In addition, if metallic ions and alkali ions are present during hydrolysis, or if copper transition elements and pigment are present during polypropylene oxidation decomposition, these kinds of substances indicate the action of an acceleration catalyst, and decomposition occurs rapidly in this situation.

When planning a test, one must grasp the appropriate details of stress, and fully comprehend the results of such matters as the types and individual combinations of stress. One should be well aware that merely increasing the severity of test conditions does not produce accelerated testing.

6 Summary

First of all, from the qualitative standpoint, product failure begins with the causes that degrade the characteristics of materials used in a product, combined with external physical and chemical causes. Next, we consider influences from the product itself and from a variety of environments in its surroundings that speed degradation and cause substances that react to be consumed, causing early degradation or cessation of product functions. A number of factors can cause product failure, but among them the most fundamental region of study concerning reliability of electrical and electronic products concerns phenomena originating in temperature and humidity (moisture content).

The matter of actually handling environmental testing as a job entails confirming product endurance under test conditions, exposing product weaknesses as early as possible, and correcting those weaknesses. Naturally, after the product has been improved, confirmation testing must be carried out. For these reasons, this discussion in Part 1, as well as in the follow-up articles, focuses thoroughly on acquiring the basic knowledge of physics and chemistry as well as knowledge about test standards.

This basic knowledge and experience is essential for providing a basis for further learning. Also, in the area of test design, ability to fully predict the details of failure and the mechanisms leading to failure before testing makes it possible to create a more effective test. Our theme in the next issue will be “Fundamental concepts of the standard condition and movement of water or moisture for performing temperature and humidity tests”, and we will be discussing standard environments, thermal stress, humidity stress and their relationship to electrical and electronic product failure.

Glossary

(1). **Velocity distribution:**

It used to be thought that when the temperature of a group of the same type of molecules was equal, their velocity would also be equal, but this can only be said of the average velocity of the individual molecules. A distribution curve of the velocity for a given instant is shown in Fig. 2. (The work of Maxwell, England, 1860, and Boltzmann, Austria, 1868 led to this conclusion.) This distribution is caused by changes in velocity when the molecules frequently and incessantly collide with each other. (Reference: The

higher the temperature, the lower the velocity distribution peak shown in Fig.2. This can be seen as indicating that when balls at various speeds collide with stationary balls, the stationary ball will be set in motion and the moving ball will stop. In this way, the gas molecules repeatedly and incessantly collide. Incidentally, regardless of how high the average velocity is increased by raising the temperature, there will always be at least some molecules that are going slower. At higher temperatures, naturally, the molecular velocity increases. The surface area of the graph peak represents the total number of molecules, which remains constant. Given that the surface area is constant, when the ends of the peak spread out, the top of the peak must become lower.)

(2). **Glacial acetic acid:**

CH_3COOH , boiling point 118°C , used as a solvent for oil and resins.

(3). **Benzol:**

C_6H_6 , boiling point 85°C , used to manufacture styrene and fenol.

(4). **Mean free path:**

For gas molecules as well as electrons within crystals, this is the average distance traveled from one collision to the next collision.

(5). **Ionic bonds:**

Bonds in which positive ions and negative ions attract each other with electrostatic force. (Example, NaCl)

(6). **Covalent bonds:**

Bonds formed when the valence electron is shared between two separate atoms. (Example, C_n)

(7). **Metallic bonds:**

Bonds in which the electrons are evenly distributed between neighboring atoms, and the metal ions form mutual attractions. This is similar to one form of ionic bond. (Example, $(\text{Na})_n$)

(8). **Latent heat:**

The amount of heat gained or lost through phase transition.

Water \longleftrightarrow water vapor 2267 kJ/kg ($539.8 \text{ kcal/kg} = 41 \text{ kJ/mol}$ at 100°C)

Water \longleftrightarrow ice 334 kJ/Kg (79.7 cal/kg)

(Reference: Why is a greater amount of heat needed to make steam than to melt ice?

The reason is that the heat to melt ice is the amount of thermal energy needed to loosen the attraction between molecules caused by the intermolecular force within each molecule. The heat to vaporize water is the amount of thermal energy needed to completely separate the molecules. Because of this, greater energy is required to vaporize water.)

(9). Hydrogen iodide (HI):

Water soluble, colorless, used as an organic synthesis reagent.