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Confirmation for activation energy of the equipment under 10-degree rule

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1. Introduction

One of the test programs in equipment qualification is a thermal aging test according to Arrhenius equation. Occasionally, 10-degree rule is utilized when performing the thermal aging test to qualify the operability of equipment. Since the comparison of conservatism differs from the aging temperature, the aging period, and the operating temperature of the equipment [1], the study to estimate the activation energy when the equipment is qualified under 10-degree rule is necessary.

2. Estimation of the activation energy

Arrhenius equation indicates that the reactivity rises exponentially with increasing temperature, whereas 10-degree rule assumes that the reactivity doubles every 10 degrees [2]. Those equations can be expressed as below

$$\frac{dR}{dt} = \exp\left(-\frac{E_a}{kT}\right) \quad (1)$$

$$\frac{dR}{dt} = \exp\left(-\frac{E_a}{kT}\right) \quad (2)$$

$$\frac{dR}{dt} = 2^{\frac{T_i - T_0}{10}} \quad (3)$$

where

R	is the reaction rate $[s^{-1}]$,
E_a	is the activation energy [eV],
t	is the time to reaction $[s]$,
k	is Boltzmann coefficient [8.617E-05 eV/K]
T, T_i, T_0	are the temperature at the certain time, ith, and initial $[K]$.

2.1 Arrhenius equations in the equipment qualification

The qualified life is usually calculated using Arrhenius equations in the equipment qualification. In this section, the deduction of Arrhenius equation for the equipment qualification is demonstrated.

The solution of Equation (1) can be derived as the following where A denotes the pre-exponential factor.

$$t = \frac{1}{R} = \frac{1}{A}\exp\left(\frac{E_a}{kT}\right) \quad (4)$$

At the service temperature ($T_{service}$) and the accelerated aging temperature (T_{aiging}) of the equipment, Equation (3) is replaced with Equation (4).

$$t_{service\ life} = \frac{1}{A}\exp\left(\frac{E_a}{kT_{service}}\right)$$
$$t_{aging} = \frac{1}{A}\exp\left(\frac{E_a}{kT_{aging}}\right) \quad (5)$$

When organizing two equations in Equation (4) for $1/A$, the following equations is deduced.

$$t_{service\ life} = t_{aging}\exp\left[\frac{E_a}{k}\left(\frac{1}{T_{service}} - \frac{1}{T_{aging}}\right)\right] \quad (6)$$

The scientific meaning of $t_{service\ life}$ is the time to react at the service temperature. Thus, the thermal aging test is performed under the accelerated aging time (t_{aging}) and the accelerated aging temperature (T_{aging}). In other words, the equipment operability is qualified when the equipment operates without any faults under the accelerated thermal aging test.

2.2 Acceleration factor

The acceleration factor ($A.F$) defines the ratio between $t_{service\ life}$ and t_{aging} [1].

$$A.F = \frac{t_{service\ life}}{t_{aging}} = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{service}} - \frac{1}{T_{aging}}\right)\right] \quad (7)$$

If T_{aging} remains still, $A.F$ rises exponentially with increasing $T_{service}$ in Arrhenius equation while $A.F$ doubles every 10 degrees in 10-degree rule. In short, estimating the activation energy by comparing Equation (6) and the definition of 10-degree rule is the primary goal of this study.

2.3 Estimation for the activation energy

In this section, the estimation for the activation energy of an equipment qualified under T_{aging} is deduced. The ratio $A.F$ at ith and i+1th in Equation (6) should be greater than 2 according to the assumption of 10-degree rule. In short, the ratio $A.F$ by Arrhenius equation can be denoted as Equation (7) to comply with the assumption of 10-degree rule.

$$A.F(i)/A.F(i+1) = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{service}(i)} - \frac{1}{T_{service}(i+1)}\right)\right] \geq 2 \quad (8)$$

According to the definition of 10-degree rule, the difference between $T_{service}(i+1)$ and $T_{service}(i)$ is 10. Therefore, E_a can be deduced as the following.

$$E_a \geq k \cdot \frac{\ln 2}{10}\{T_{service}(i)[T_{service}(i)+10]\} \quad (9)$$

Since the service temperature ($T_{service}$) varies usually between 40~90°C in the nuclear power plant, the range of E_a can be calculated as the following.

$$0.61eV \leq E_a \leq 0.810eV \quad (10)$$

2.4 The optimal activation energy in 10-degree rule

In this section, the ratio of the acceleration factor ($A.F$) is shown with Equation (9) varying $T_{service}$ and E_a as the following table.

Table 1: Calculation of the ratio of the acceleration factor

$T_{service}$[°C]	E_a[eV]		
	0.610	0.800	0.801
40 ~ 50	2.012	2.502	2.531
50 ~ 60	1.930	2.368	2.394
60 ~ 70	1.857	2.252	2.275
70 ~ 80	1.793	2.151	2.171
80 ~ 90	1.736	2.062	2.081
90 ~ 100	1.671	1.984	2.001

As shown in Table 1, the ratio of the acceleration factor varies with $T_{service}$ and E_a as the following.

1) If the estimated E_a is 0.61eV, the ratio of the acceleration factor is lower than 2 when $T_{service}$ is higher than 50°C.
2) If the estimated E_a is 0.801eV, the range of $T_{service}$ falls outside the typical operational range (40 ~ 90°C) in a nuclear power plant even when the acceleration factor exceeds 2.

If the equipment - which has the service temperature exceeding 90°C - were tested under 10-degree rule, the optimal activation energy could be higher than 0.8eV. According to Equation (4), the higher activation energy indicates the service life. Therefore, 0.8eV is the optimal and conservative activation energy for the equipment tested under 10-degree rule.

3. Conclusions

In this study, estimating the activation energy of the equipment tested under 10-degree rule is deduced. According to the calculation results in Table 1, 0.8eV is the most optimal and conservative because:

1) if the estimated E_a is 0.61eV, the ratio of the acceleration factor is lower than 2 when $T_{service}$ is higher than 50°C,
2) if the estimated E_a is 0.801eV, the range of $T_{service}$ falls outside the typical operational range (40 ~ 90°C) in a nuclear power plant even when the acceleration factor exceeds 2, and
3) Considering the conservatism: the lower activation energy, the shorter service life.

However, the necessity condition for applying 0.8eV to equipment qualified under 10-degree rule is that the equipment should be qualified its operability during the thermal aging test by 10-degree rule.

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