METHOD ON THE AGING EVALUATION IN NUCLEAR POWER PLANT CONCRETE STRUCTURES

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ABSTRACT

In this paper, method on the durability evaluation in nuclear power plant concrete structures was investigated. In view of the importance of evaluating the degree of deterioration of reinforced concrete structures, relationships should be formulated among the number of years elapsed, *t*, the amount of action of a deteriorative factor, *F*, the degree of material deterioration, *D*, and the performance of the structure, *P*. Evaluation by *PDFt* diagrams combining these relationships may be effective. A detailed procedure of durability evaluation for a reinforced concrete structure using *PDFt* concept is presented for the deterioration factors of thermal effect, irradiation, neutralization and penetration of salinity by referring to the recent papers.

INTRODUCTION

Important reinforced concrete structures in nuclear power plant require aging management and evaluation, which comprise integrity evaluation assuming their use for decades ahead to confirm the effectiveness of the current maintenance program, as well as extraction of new maintenance measures as required. There has been an enormous accumulation of study results regarding the durability evaluation and deterioration prediction of reinforced concrete structures. However, durability evaluation of reinforced concrete structures generally involves the problems of a wide variety of external factors and a combination of reinforcing steel and concrete. In view of the importance of evaluating not only each material but also the composite body for evaluating the degree of deterioration of reinforced concrete structures, relationships should be formulated among the number of years elapsed, *t*, the amount of action of a deteriorative factor, *F*, the degree of material deterioration, *D*, and the performance of the structure, *P*. Evaluation by *PDFt* diagrams combining these relationships may be effective.

In this paper, a detailed procedure of durability evaluation for a reinforced concrete structure using *PDFt* concept is presented for the deterioration factors of thermal effect, irradiation, neutralization and penetration of salinity by referring to the recent papers.

THERMAL EFFECT

Current evaluation method

In the current evaluation method contained in the "Review Manual for Age-Related Technical Assessment "[1], the degradation of concrete is evaluated according to whether or not the temperature levels of concrete structures over the life span of the structure is less than reference levels (the reference levels of temperature of 90°C for concrete structures in designated areas and 65°C for structures elsewhere indicate the risk for thermal degradation.)

F-t diagram. Relation between the amount of action of a deteriorative factor, *F*, and the number of years elapsed, *t*

F_3 (subscript "3" represents the thermal deterioration) is the amount of action of a thermal deteriorative factor, which is related to the change of cement hydrates due to thermal effect. Relation between this factor and time t (year) is shown in the extrapolation formula (1).

$$F_3 = \alpha_3 \cdot t \tag{1}$$

Where, α_3 is the thermal deterioration coefficient for change of cement hydrates due to thermal effect. As on example, based on the chemical kinetics, this reaction can be shown as Eq. (2). Where, *a* and *b* is constant. *T* is temperature (°C).

$$\alpha_3 = a \cdot exp\left(-\frac{b}{T}\right) \tag{2}$$

D-F **Diagram. Relation the degree of material deterioration, *D,* and the amount of action of a deteriorative factor, *F***

The compressive strength of concrete has a tendency toward significant decreases in the early stages of exposure to a high temperature environment. Fig. 1 show test results of U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research Washington [2].

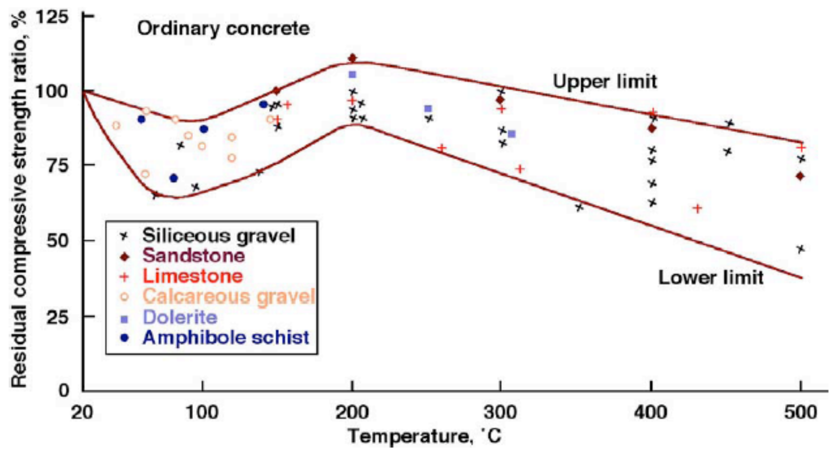

Fig. 1: Relation between the temperatures and the compressive strength reduction of concrete [2]

Based on the experimental formula of Abe et al. the proposed equation of the convergence value of compressive strength reduction of concrete D_u (-) is shown in Eq. (3) [3] (Fig.2).

$$D_u = (1 - 0.2\theta + 0.45\theta^2 - 0.0436\theta^3)exp(-0.413\theta) \qquad \theta = 1.5\frac{T-20}{100} \tag{3}$$

Where, T is Temperature (°C), T : 20 °C to 400°C.

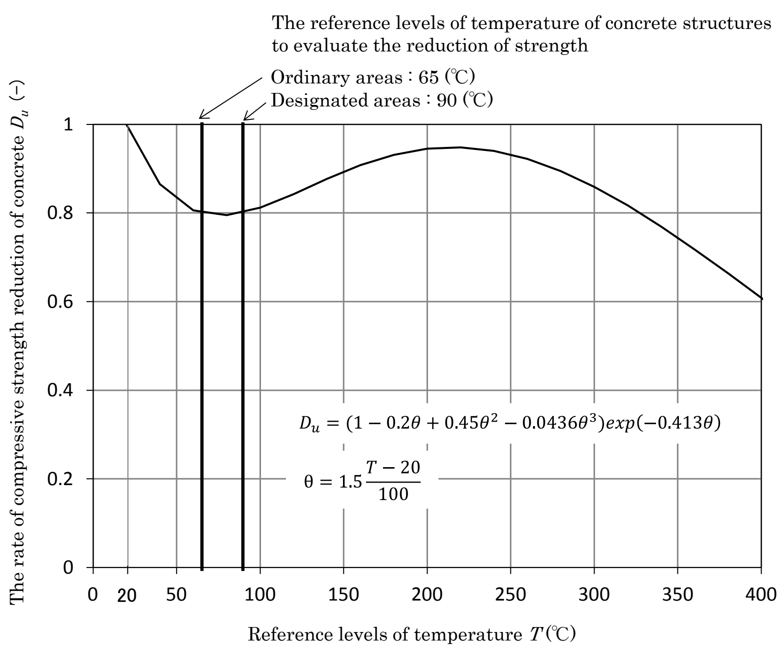

Fig. 2: The convergence value of compressive strength reduction of concrete [3]

Relation between the rate of compressive strength reduction of concrete D_1 (subscript "1" represents the compressive strength reduction of concrete) and the amount of action of a thermal deteriorative factor F_3 is shown in equation (4). Fig. 3 shows relation between the rate of compressive strength reduction of concrete and the amount of action of a thermal deteriorative factor.

$$D_1 = e^{-F_3}(1 - D_u) + D_u \tag{4}$$

Where, D_u is convergence value of compressive strength reduction of concrete depending on temperature (-).

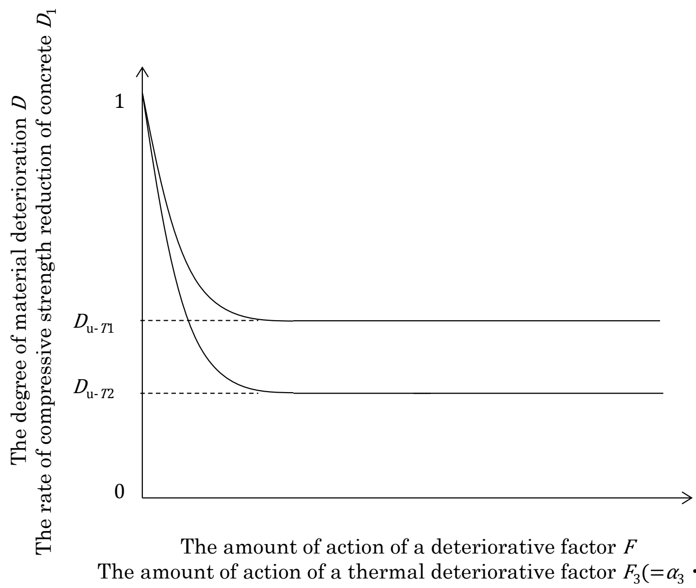

Fig. 3: Relation between the rate of compressive strength reduction of concrete and the amount of action of a thermal deteriorative factor

IRRADIATION (NEUTRON RADIATIONS AND GAMMA RAY)

Current evaluation method

In the current evaluation method of "Review Manual for Age-Related Technical Assessment", the strength of concrete is evaluated according to whether or not the radiation levels over the life span of the structure are less than reference levels. The reference levels of 1.0×10^{20} (n/cm^2) for fluence of neutron radiation (Fig. 4) and 2.0×10^{10} (rad) for gamma-rays (Fig. 5) are obtained from the Hilsdorf's paper and are employed in assessing soundness of irradiated concrete [4].

F-t diagram. Relation between the amount of action of a deteriorative factor, *F*, and the number of years elapsed, *t*

The action of degradation factor F_4 (subscript "4" represents the irradiation value) is an integrated value of irradiation (neutron radiation and gamma ray), the equation can be expressed as follows:

$$F_4 = \alpha_4 \cdot t^n \tag{5}$$

Where, α_4 is a constant that is determined by such things as the relative position from the radiation source and other factors and n is constant.

D-F Diagram. Relation the degree of material deterioration, *D,* and the amount of action of a deteriorative factor, *F*

For example, if D_1 is assumed to be the rate of decrease in compressive strength of concrete, based on the Hilsdorf's paper, the regression equation can be expressed as follows:

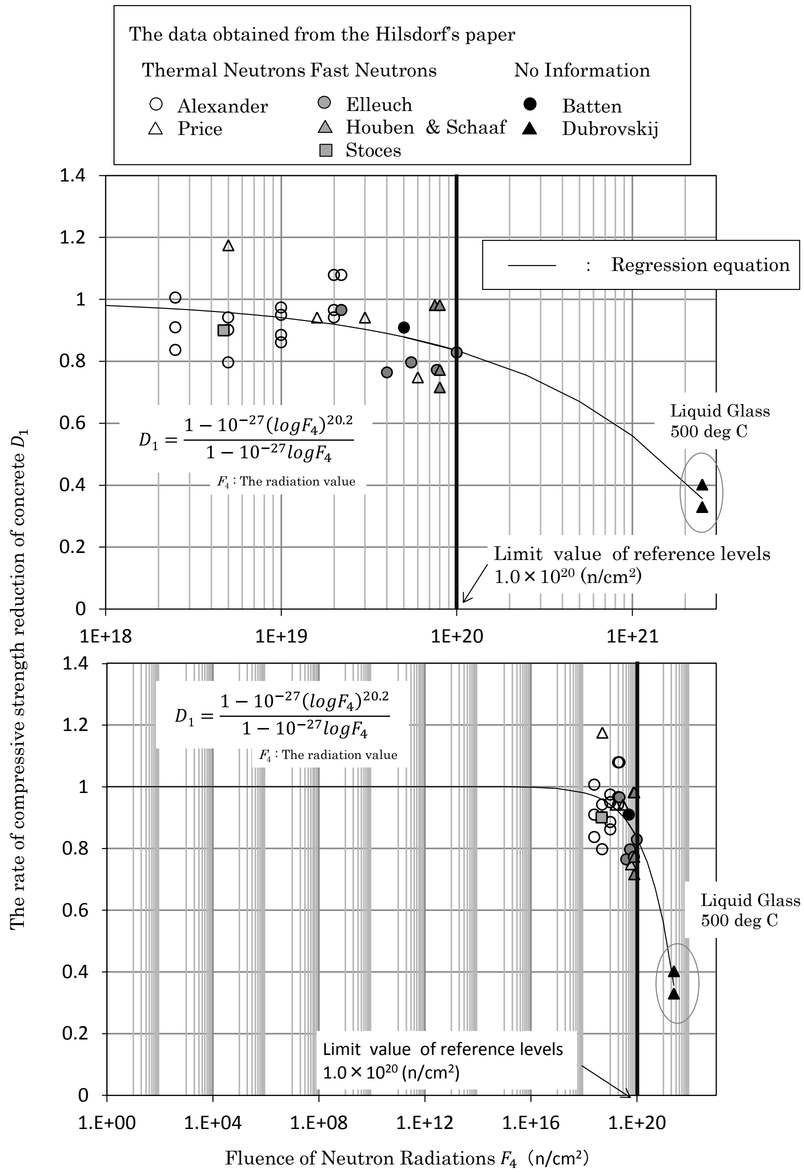

Fig. 4: Relation between the fluence of neutron radiations and the strength reduction of concrete [4]

$$D_1 = \frac{1-10^{-27}(logF_4)^{20.2}}{1-10^{-27}logF_4} \tag{6}$$

Where, D_1 is the rate of compressive strength reduction of concrete (-) and F_4 is fluence of neutron radiation (n/cm^2).

$$D_1 = \frac{1-10^{-23}(logF_4)^{21.6}}{1-10^{-23}logF_4} \tag{7}$$

Where, D_1 is the rate of compressive strength reduction of concrete (-) and F_4 is gamma ray dose (rad).

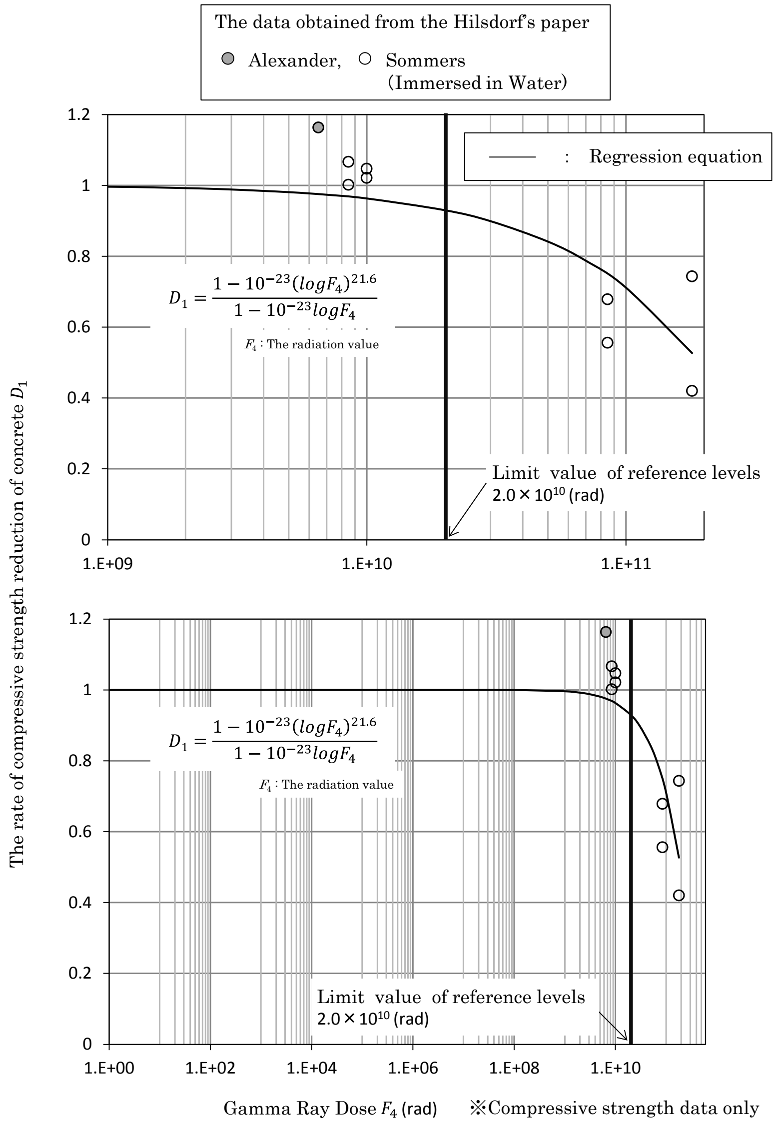

Fig. 5: Relation between the gamma ray dose and the strength reduction of concrete [4]

NEUTRALIZATION

Current evaluation method

In the current evaluation method contained in the manual [1], the degradation of concrete is evaluated according to whether or not the depth of concrete neutralization over the life span of the structure is less than reference levels.

F-t diagram. Relation between the amount of action of a deteriorative factor, *F*, and the number of years elapsed, *t*

The amount of action of Oxygen as it affects the corrosion of reinforcing steel. However, it is difficult to measure this value, so the neutralization depth is used as an alternate value. The neutralization depth is represented as F_1, (subscript "1" represents the neutralization of concrete) which is the evaluation physical property. Generically, the neutralization depth can be expressed by the square root t theory as follows [5], [6] :

$$F_1 = a_1\sqrt{t} \tag{8}$$

Where, F_1 is neutralization depth (mm), α_1 is neutralization rate coefficient (mm/$\sqrt{\ }$year) and t is time (year).

D-F* Diagram. Relation the degree of material deterioration, *D*, and the amount of action of a deteriorative factor, *F

The rate of deterioration of materials evaluative physical property is assumed to be the rate of corrosion of steel reinforcing bars as outlined in the "Review Manual for Age-Related Technical Assessment". The rate of loss of steel reinforcing bars, D_3 (subscript "3" represents the corrosion of steel reinforcing bars), is the amount of corrosion of steel reinforcing bars as compared to their condition at the time of construction. Based on the corrosion experiments of Tomosawa et al. the Eq. (9) is proposed [7].

$$W_c = \frac{1}{38.1}(1.35T + 2.76H + 1.800O_2 - 163) \cdot \sqrt{t} \tag{9}$$

Where, W/C is rate of loss of steel reinforcing bars by corrosion (10^{-4}g/cm^2), T is temperature (°C), H is relative humidity (%), O_2 is concentration of oxygen (%) and t is elapsed time after neutralization reaches the steel reinforcing bars (day). The corrosion loss of steel reinforcing bars, W_c, and the square root t show a linear relationship. The rate of corrosion loss of steel reinforcing bars, D_3, is assumed to be Eq. (10).

$$D_3 = \beta_3 \cdot \sqrt{{F_1}^2 - {F_0}^2} \tag{10}$$

Where, D_3 is rate of corrosion loss of steel reinforcing bars (-), β_3 is environmental condition (temperature, relative humidity, concentration of oxygen et al.) and material (steel reinforcing bars, concrete) constant.

PENETRATION OF SALINITY

Current evaluation method

In the current evaluation method found in the manual [1], the deterioration of reinforced concrete due to penetration of salinity is evaluated according to whether or not the chloride concentration over the life span of the structure is less than reference levels, and whether or not cracks occur in the concrete.

F-t* diagram. Relation between the amount of action of a deteriorative factor, *F*, and the number of years elapsed, *t

For the action of the chloride ion F_2 (subscript "2" represents the penetration of salinity) this study uses the value of chloride concentration as show in Fig. 6. This evaluation uses the integrated value per annum in practice.

$$F_2 = \int_0^{t_n} C_t \, dt, \quad C_t \geq C_{cr} \tag{11}$$

Where, F_2 is amount of action of chloride ion (kg/m^3 year), C_t is chloride concentration (kg/m^3), t is time (year) t_n is evaluation period (year) and C_{cr} is critical chloride concentration of stainless steel corrosion(=1.2kg/m^3).

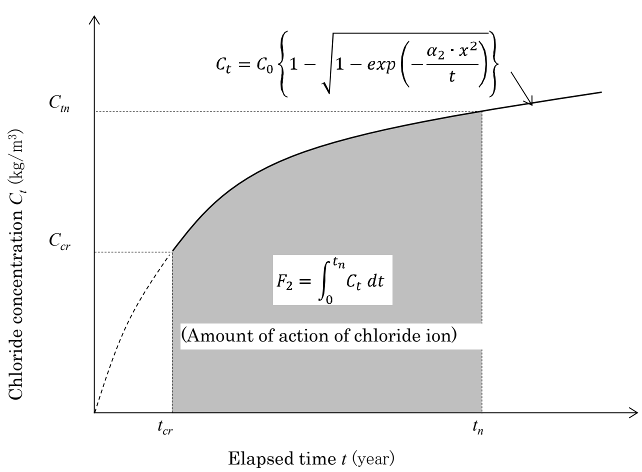

Fig. 6: The conceptual diagram of integrated value of chloride concentration F_2

The normally used equation for the prediction of the distribution of chloride concentration in concrete is Eq. (12), which is based on the diffusion equation [8], [9].

$$C_t = C_0\left(1 - erf\left(\frac{x}{2\sqrt{D \cdot t}}\right)\right) \tag{12}$$

Where, C_0 is chloride concentration at surface of concrete (kg/m^3), x is thickness of concrete cover (mm) and D is apparent diffusion coefficient (mm*2*/year). In Eq. (13) an approximation formula[10] is applied in place of the error function "*erf*" found in Eq. (12).

$$C_t = C_0\left\{1 - \sqrt{1 - exp\left(-\frac{\alpha_2 \cdot x^2}{t}\right)}\right\}, \quad \alpha_2 = \frac{1}{\pi D} \tag{13}$$

Where, α_2 is constant of the amount of action of degradation factor as related to the material properties. C_0 and α_2 are calculated using the distribution of chloride concentration values as measured at the determined evaluation periods. The amount of action of degradation factor, F_2, which represents the integrated value of chloride concentration around steel reinforcing bars, is expressed as Eq. (14):

$$F_2 = \int_0^t C_t\, dt \quad \left(= \sum_{t=0}^{n} C_t\, \Delta t\right) \tag{14}$$

Where, F_2 is amount of action of chloride ion around steel reinforcing bars, C_t is amount of chloride ion around steel reinforcing bars at evaluation time t (kg/m^3), t is time (year) and Δt is unit time (1year).

D-F **Diagram. Relation the degree of material deterioration,** ***D,*** **and the amount of action of a deteriorative factor,** ***F***

The rate of deterioration of material is D_3 (subscript "3" represents the corrosion loss of steel reinforcing bars) and is assumed to be the rate of corrosion loss of steel reinforcing bars. D_3 is the amount of corrosion of steel reinforcing bars as compared to their condition at the time of construction. D_3 can represent as follows:

$$D_3 = \int_0^{t_n} V_t\, dt \tag{15}$$

Where, D_3 is the corrosion loss of steel reinforcing bars (mg/cm^2), V_t is corrosion rate (mg/cm^2/year), V_t can be represented as Eq. (16).

$$V_t = \frac{1}{\sqrt{x}}(a\, C_t + b) \tag{16}$$

Where, a and b is constants. By substituting the Eq. (16) into the Eq. (15), the Eq. (17) is obtained, which is the relational expression of *D-F*. An example of the determination of the value of the constants a, b is as follows [11],

$$D_3 = \frac{1}{\sqrt{x}}(a\, F_2 + bt_n) \qquad a = 6.0, b = 0.4W/C - 31.7 \tag{17}$$

Where, *W/C* is water to cement ratio (%). If the diagram is to be determined by the measurement value, then the corrosion loss of steel reinforcing bars should use a multi-year measurement.

P-D **diagram. The relation between the performance of the structure,** ***P*****, and the degree of material degradation,** ***D***

The performance of the structure, P is assumed to be the width of cracks in the concrete surface. The relation between when cracks will occur in the concrete and the corrosion loss of steel reinforcing bars is shown as follows [12] :

$$D_u = -(0.19d + 0.06x + 2.0) \cdot ln(F_c) + 0.1d + 47 \tag{19}$$

Where D_u is critical corrosion loss of steel reinforcing bars to affect a crack in the concrete at a width of 0.1mm by FEM analysis (mg/cm^2), d : diameter of steel reinforcing bars (mm), F_c : compressive strength of concrete (N/mm^2). There exists a linear relationship between the corrosion loss of steel reinforcing bars and width of cracks in the concrete [13]. The relation between the corrosion loss of steel reinforcing bars, D_3, and width of cracks in the concrete, P_8 (subscript "8" represents the crack of concrete) is expressed as follows:

$$P_8 = 0.1\frac{D_3}{D_u} \tag{20}$$

ACKNOWLEDGEMENT

A part of this study was supported by a grant from the Japanese Ministry of Economy, Trade and Industry.

CONCLUSION

In view of the importance of evaluating not only each material but also the composite body for evaluating the degree of deterioration of reinforced concrete structures, relationships should be formulated among the number of years elapsed, t, the amount of action of a deteriorative factor, F, the degree of material deterioration, D, and the performance of the structure, P. In this paper, a detailed procedure of durability evaluation for a reinforced concrete structure using *PDFt* concept is proposed by referring to the recent papers for the deterioration factors of thermal effect, irradiation, neutralization and penetration of salinity.

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