Developing Lead Rubber Bearing for Seismic Isolation of Nuclear Power Plants

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SUMMARY:
Seismic isolation systems are widely used at buildings, bridges and industrial plants all over the world. In particular, the need for seismic isolation systems for nuclear power plant facilities, as well as general structures, is growing globally in the aftermath of the Great East Japan Earthquake in 2011. In this study, cases of seismic isolation at nuclear power plant structures abroad and preliminary design techniques for seismic isolation systems were examined in order to secure seismic performance of nuclear structures against earthquakes. In addition, preliminary design for a seismic isolation system being developed in Korea for strong quake-prone regions was performed. The target nuclear structure is APR1400, whose natural isolation period, horizontal effective stiffness, design displacement and equivalent damping ratio were established in accordance with the ASCE7-10 design process, and laminated rubber bearings (LRBs) with material characteristics used in seismic isolation systems of general structures were applied to the preliminary design of the seismic isolator in this study. Based on our estimation of specifications and quantities of the seismic isolator required for nuclear structures, the developed seismic isolation system is deemed to offer sufficient applicability, and thus is expected to be used as reference when designing a seismic isolation system for nuclear power plants in the future.

Keywords: laminated rubber bearing, nuclear power plants, schematic design, APR1400

1. INTRODUCTION

A seismic isolation system is designed to separate a structure from its foundation soil at the time of an earthquake so that the size of external load on the structure is reduced by increasing the natural period of a structure through artificial means using seismic characteristics – strong short-period properties and weak long-period properties. Cases of application of such a system at general structures and bridges abound, but application to nuclear power plants has been extremely rare.

At the time of a nuclear accident, a nuclear containment building serves as the final barrier that shields the outside world from radioactive materials. In case of a strong earthquake, like the recent Great East Japan Earthquake, safety evaluation of such a containment building as well as other facilities is highly important. As the interest in the safety of nuclear power plants is increasing in the society, regions that have experienced earthquakes of over a certain magnitude are likely to require seismic design as well as seismic isolation design concepts when building nuclear power plants. Moreover, development of seismic isolation system technology is essential in order to satisfy more strict global regulations and standards involving seismic design for nuclear power plants. Against this backdrop, this study describes the current status of seismic isolation system development particularly for nuclear power plants to be built in areas with possibility of strong earthquakes.

2. SEISMIC ISOLATION APPLICATION TO NUCLEAR STRUCTURES

Seismic isolation systems are widely applied to bridges, industrial plants, etc., as well as general buildings all over the world. They are considered to be one of the most efficient methods to protect general structures and nuclear facilities from strong earthquakes. However, despite the importance of nuclear structures, there are only two cases of seismic isolation system applied to nuclear power plants: those in Cruas, France and the others in Koeberg, South Africa. This limited number of nuclear power plants equipped with a seismic isolation system is attributable to the design of structures with sufficient stiffness that allows resistance against low seismic input acceleration, and Jules Horowitz Reactor (RJH) in Cadarache, France is being built with the seismic isolation system already applied to the units in Cruas.

The first case of seismic isolator application to a nuclear power plant is located in Cruas, France, whose construction began in 1978 and operation started in between 1983 and 1984, with the capacity of 3,600MWe including the total power.

The reason why they chose to introduce a seismic isolation system to the nuclear power plants in Cruas, France was to maintain the existing design for other nuclear reactors that had already been constructed and designed by EdF in locations of weak earthquake occurrences (in general, the peak ground acceleration is 0.2g and the one at Cruas is 0.3g). For the same reason, the same seismic isolation system as the Cruas model was applied to two 900MWe PWRs in Koeberg, South Africa. The system in Cruas, France consists of 3,600 square neoprene bearings, and each system has 900 bearings with the dimension of 500x500x66mm. The system in Koeberg, South Africa combined neoprene with sliding systems so that the shear stress of existing neoprene induced by great shear strain can be shared.

More recently, new application of a seismic isolation system which is represented by the Jules Horowitz Reactors, after Cruas and Koeberg, is being built at the Cadarache Nuclear Centre site (France), and this system consists of 195 (size: 900x900x181mm) neoprene bearings manufactured by NUVIA, Freyssiner Group.

Along with this, the International Thermonuclear Experimental Reader (ITER) at the Cadarache site is planning to adopt a seismic isolation system. The 4S (super safe, small and simple) nuclear reactor developed by Toshiba-Westinghouse is at the latter stage of development. The 4S nuclear reactor will be implemented in accordance with Japan Electric Association Guide JAEG 4614-2000 “Technical Guideline on Seismic Base Isolated System for Structural Safety and Design of Nuclear Power plants,” and guidelines for quality control, maintenance and management of the seismic isolator were prepared based on “Draft Technical Guidelines for Seismic Isolation of Fast Breeder Reactors [Forni, 2011].”

3. EFFECTIVENESS OF SEISMIC ISOLATION ON STRUCTURES

When a seismic isolation system is applied underneath a nuclear structure, the inertial forces occurring at the upper and lower structures diminish but the displacements increase, and the increased displacements are mostly accepted by the seismic isolator which is made to receive a large axial load at a large lateral displacement.

Fig. 3.1 shows a decrease in spectral demand, which is one of the benefits of seismic isolation. When the fundamental period of vibration increases from 0.1 second (general structures) to 2 seconds (structures with seismic isolation), the spectral demand decreases by over ten-fold. The 5% degradation spectrum in the figure is the design basis earthquake spectrum (DBE spectrum) for nuclear reactors at a rock site in the Eastern United States.

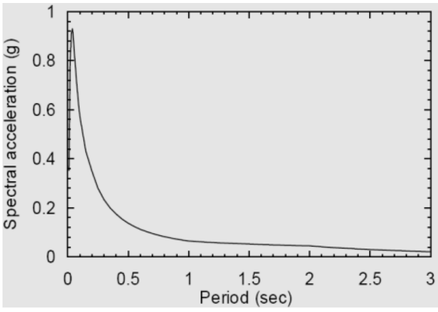


Figure 3.1. Design basis earthquake spectrum for a rock site in the Eastern United States

Hence, the following can be said about the effects of applying a seismic isolation system to nuclear structures: the seismic response of a structure can be limited to below 1Hz, the resulting working load, moment and displacement are reduced, and uncertain behaviors caused by seismic forces can be reduced by separating upper structures from ground motions. Also, criteria for seismic design of non-structural facilities are downgraded, making it possible to standardize a design process that is unrelated to characteristics of ground motions.

4. TARGET FOR SEISMIC ISOLATION AT A NUCLEAR POWER PLANT

Nuclear power plants must secure more complete and thorough safety against earthquakes in order to prevent radiation leaks. Another reason why securing seismic safety has particularly great significance is because seismic load can act as the most dominant design load at nuclear power plants as opposed to general structures due to the former's unique dynamic and structural characteristics as shown in Table 4.1 [Lee, Chang & Joo, 2000].

Table 4.1. Seismic behavior of Nuclear Power Plants

Structural Dynamic characteristics	Nuclear power plants	General structures
Seismic input for design	0.3g	0.12~0.14g
Return period	1000~10,000 years	50~500 years
Natural frequency	Nuclear reactor : 4.5Hz Auxiliary building : 7.5Hz Fuel building: 10.3Hz	20-story RC building: 0.5~1.0 Hz
Load	Seismic load is dominant	Wind load is dominant

The nuclear power plant structure to which the seismic isolation is applied in this study is Korea's own Advanced Power Reactor 1400 (hereinafter referred to as "APR1400"). It is an advanced pressurized water reactor (PWR) with capacity of 1,400MWe (3,983MWth). With enhanced safety, economy, and operational and maintenance-related convenience, APR 1400 extends the life of a nuclear reactor by 50% from 40 years to 60 years through performance improvements on major facilities including nuclear reactors. Also, it has much stronger seismic design standards which include application of 0.3g of safe shutdown earthquake (SSE) so that the structure can withstand stronger earthquakes. In addition, the design of APR 1400 is based both on reactor containment buildings and auxiliary building as joint foundations.

5. SEISMIC ISOLATION DESIGN

5.1. Preliminary Design of a Seismic Isolation System Based on ASCE 7-10

When designing a structure with seismic isolation, dynamic characteristics of the building as a structure with seismic isolation should be determined first in principle to meet target performance, followed by examination of safety and the target performance of the structure with seismic isolation by performing a time-history analysis on building models including seismic isolation members. The design is divided into the preliminary design using an equivalent static analysis and the final design through a dynamic analysis, and if the building satisfies certain criteria, the equivalent static analysis (ASCE 7-10, Session 17.41) or the response spectrum analysis (ASCE 7-10, Session 17.4.2.1) can be used directly in the design. While the analysis and design of a structure with seismic isolation should be based on actual deformational characteristics of a seismic isolator (ASCE 7-10, Session 17.5.2), the deformational characteristics of that seismic isolator cannot be identified accurately until experiments involving the seismic isolator to be used in an actual building are performed. Moreover, such a seismic isolator can be fabricated only after the variables to satisfy the target performance of the building are first determined through a design process.

Table 5.1. Damping Coefficient, B_D or B_M (Table 17.5-1 of ASCE 7-10)

Effective Damping, β_D or β_M (Percentage of Critical)	B_D or B_M Factor
≤ 2	0.8
5	1.0
10	1.2
20	1.5
30	1.7
40	1.9
≥ 50	2.0

Upon performing seismic isolation design, basic plans including design plans, location of the seismic isolation layer, response analysis and design method should be established first, and then appropriate design and maximum displacements in accordance with the target seismic isolation period should be decided. After that, the stiffness and damping ratio of the seismic isolation layer should be determined to distribute stiffness and damping performance to each seismic isolator. Table 5.1 shows damping coefficient of ASCE 7-10. The damping coefficient (B_D, B_M) is required when determining design and maximum displacements, and are related to the effective damping coefficient (β_D, β_M) of the seismic isolation system, and the damping coefficient other than those suggested in the table below shall take values of effective damping with linear interpolation [ASCE Standard, 2010].

When the target seismic isolation period (T_D), self-weight of the upper structure (W) and the damping ratio of the seismic isolation system (β) are decided, the design displacement of the seismic isolation layer can be calculated as follows from the relationship between the acceleration coefficient (S_{D1}) of the response spectrum and the response displacement.

$$D_D = \frac{g \cdot S_{D1} \cdot T_D}{4\pi^2 B_D}, \qquad \left(T_D = \sqrt{\frac{W}{k_{Dmin} \cdot g}} \right) \tag{5.1}$$

The effective stiffness of the seismic isolation layer can have the following equation induced from the relationship between natural period and stiffness.

$$K_{eff} = \frac{4\pi^2 W}{T^2 g} \tag{5.2}$$

The effective stiffness (K_{eff}) and the self-weight (W) are the total sums of the serial combination of stiffness and axial forces at each seismic isolator, and can be expressed as below:

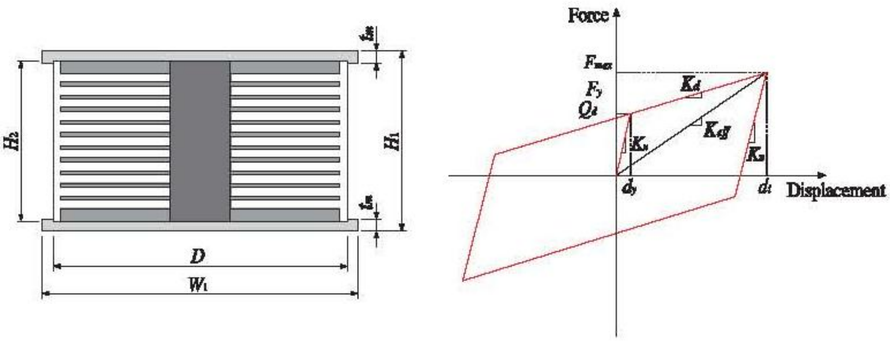
$$D_M = \frac{g \cdot S_{M1} \cdot T_M}{4\pi^2 B_M}, \qquad \left(T_M = \sqrt{\frac{W}{k_{Mmin} \cdot g}} \right) \tag{5.3}$$

The seismic isolation system for this study is established based on the force-displacement characteristics of each seismic isolator selected from the preliminary design and the effective stiffness (K_{eff}), seismic isolation period (T_D) and design displacement (D_D) are recalculated. Then design displacement (D_D) is determined through repetitive calculation by applying the trial-and-error method. Behavioral characteristics of seismic isolation are obtained by performing a type test. Here, in order to establish the best seismic isolation system, specifications of individual seismic isolators are modified through repetitive design modifications until the final design displacement (D_D) is determined.

5.2. Design of Laminated Rubber Bearings for Seismic Isolation

In general, structures with seismic isolation extends the natural period of structures artificially by using seismic isolators, and are designed to exceed the predominant period of an earthquake. Bearings for the purpose of seismic isolation are designed by considering a target structure's self-weight, wind load and seismic load, and the ability to support the vertical load calculated from the combination of loads suggested in the design code must also be taken into consideration. Accordingly, the required dimension is calculated by using the design code for rubber bearings. In particular, in case of lead rubber bearings (hereinafter referred to as "LRBs"), it is very complicated to determine the thickness of the rubber layer and the lead diameter due to mutual relationships among different variables. If the height of the rubber layer is increased, the effective period extends, which leads to reduced seismic forces and increased displacements. The effective yield load takes the optimal value depending on the seismic load levels and ground conditions, and must satisfy wind load requirements. Safety with regards to buckling and material deformation of the seismic isolator must be reviewed at the maximum displacement suggested in the design code.

If an LRB-based seismic isolator has elasto-plastic behaviors as shown in Fig. 5.1, flexibility of rubber shifts the natural period of the structure which results in reduced seismic forces, and the plastic behaviors of lead absorbs seismic energy. Therefore, the most important element to consider when designing an LRB-based seismic isolator is to determine how to combine the rubber's flexibility, which minimizes the seismic forces and displacements transferred to the structure, with the size of lead core.



(a) Detail of LRB (b) Hysteretic behavior of LRB

Figure 5.1. Characteristics of LRB

In Fig. 5.1, K_u denotes the stiffness before yield of the LRB-based seismic isolator (first stiffness), K_d is stiffness after yield (secondary stiffness), K_{eff} represents effective stiffness, Q_d is characteristic strength of the lead core, F_y is initial yield force, F_{max} is the maximum lateral force, d_y is yield displacement of the lead core, and d_i is design displacement of the LRB-based seismic isolator. In general, seismic isolation design for structures is aimed primarily at extending the period of a structure. Therefore, when implementing seismic isolation design of a structure using the LRB-based seismic isolator, the stiffness before and after plastic deformation (K_u, K_d) of the LRB-based seismic isolator that can move the structure should be decided, and as for the size of the lead core for additional damping effect, use of a lead core whose yield strength (Q_d) is about 5% of the structure's weight is recommended [Ghobarah & Ali, 1998].

6. PRELIMINARY DESIGN

6.1. Case Study - Preliminary Design Of A Seismic Isolation System

For preliminary design of the seismic isolation system, LRB and RB, seismic isolators based on laminated rubber bearings were applied to the design sample in consideration of the weight of APR1400, and the natural seismic isolation period, effective lateral stiffness, design displacement and equivalent damping ratio of the system requirement characteristics and isolation system characteristics based on the preliminary design flow were compared and examined.

6.1.1 determination of response modification factor (R_I)
The response modification factor was decided to be 5.0 (special reinforced concrete shear wall) by applying Table 12.2-1 Design Coefficients and Seismic Force-Resisting Systems of ASCE 7-10.

$$R_I = \frac{3}{8}R \quad R_I = 1.875 \tag{6.1}$$

6.1.2 selection of seismic isolation bearings and determination of damping coefficient B_D or B_M.
The type of seismic isolator to be used is selected (single or mixed), and the appropriate level of damping for the chosen seismic isolator is selected conservatively. After that, the damping coefficient B_D or B_M is selected (ASCE 7-10, Table 12.2-1).

$$\beta_D = 20\%, \quad B_D = \frac{\beta_D - 10\%}{10\%} \cdot (1.5 - 1.2) + 1.2 \quad \therefore B_D = 1.5 \tag{6.2}$$

6.1.3 selection of target seismic isolation period T_D
The basic period of the seismic isolation system at design base-displacement is estimated and determined. The system for the target structure assumes T_D as 3.5sec.

6.1.4 estimation of effective stiffness K_D of the seismic isolation system
The effective stiffness of the seismic isolation system for the selected seismic isolation period is estimated. Here, 4,903,000kN was applied as the total weight of the structure.

$$k_{Dmin} = \frac{4 \cdot \pi^2 \cdot W}{{T_D}^2 \cdot g} = 1{,}643kN/mm, \quad k_{eff} = 1{,}826kN/mm, \quad k_{Dmax} = 2{,}008kN/mm, \tag{6.3}$$

6.1.5 estimation of the minimum lateral displacement D_D
Before calculating the minimum lateral seismic design displacement D_D, the seismic design category is selected. Domestic seismic region coefficients and ground coefficients of KBC2009 were applied for the seismic design category. In the case of the US, S_S and S_1 which reflect a seismic hazard map are being applied.

$$D_D = \frac{g \cdot S_{D1} \cdot T_D \cdot sec}{4 \cdot \pi^2 \cdot B_D} = 265.2mm \tag{6.7}$$

6.1.6 calculation of the minimum design horizontal force
The following equation is used to calculate the locations of each seismic isolation system and the seismically isolated structure, or the horizontal force (V_b) of the structural system located at the bottom of the seismically isolated structure and the same horizontal force (V_s) of the structural system located at the top of the seismic isolation system.

$$V_b = k_{Dmax} \cdot D_D = 532{,}522\text{kN}, \quad V_s = \frac{k_{Dmax} \cdot D_D}{R_I} = 284{,}012\text{kN} \tag{6.8}$$

6.1.7 preliminary design of members at the upper structure

The optimal horizontal load is used for calculation at each layer of the structure. Here, the horizontal load is used to obtain the size of prestress force for the members of the upper structure.

6.2. Case Study – Preliminary Design Of The Seismic Isolator

For the preliminary design of the seismic isolator, the characteristic strength is decided by examining seismic displacements and reviewing effective stiffness. Once the seismic isolator is selected, the effective stiffness of the entire system is calculated, and then checked to see if it satisfies the range of the minimum and maximum effective stiffness. After evaluating the effective stiffness, characteristics of bearings – primary stiffness (k_1), secondary stiffness (k_2) and characteristic strength (Q_d) – are calculated by reflecting cross-section characteristics of the selected isolator. Also, a load-displacement history curve can be obtained for the seismic isolator by using the calculated characteristic value.

7. EXAMPLE – DESIGN OF SEISMIC ISOLATOR FOR APR1400

Seismic isolation design was performed by applying LRBs produced by Unison eTech for the target structure, APR1400. LRBs and RBs have the characteristics of materials generally applied to building structures. The laminated rubber applied here is natural rubber with 0.4MPa of shear modulus of elasticity ($G_{\gamma=100\%}$) and longitude of 40. As previously mentioned, the factor that affects the effective stiffness (k_{eff}) of LRBs the most is determination of the size of the lead core. To that end, JAEG 4614-2000 of Japan was used for the aspect ratio of the lead core applied to this design. The size and number of bearings were decided by assuming that the total weight of the target structure for seismic isolation as 5,000,000kN.

7.1. Design (1)

The values determined at the stage of preliminary design for the seismic isolator was reviewed. At the preliminary design stage, the target seismic isolation period (T_D) was set to be 3.2sec and the lateral seismic design displacement (D_D) was 243mm. Accordingly, the diameter of the seismic isolator could be determined first based on the target displacement. In other words, the secondary shape factor was initially set to be around 5.o and the outer diameter of the bearings was set to be over 1200mm. The individual vertical design load for a circular bearing with outer diameter of 1200mm, inner diameter of 250mm and surface pressure of 12MPa was calculated to be 12,982kN and the minimum required quantity of the target structure for seismic isolation based on the total weight was about 385.15. The effective stiffness of individual bearings according to the above conditions was 4.176kN/nm, and the overall stiffness of the seismic isolation layer was found to be 1,672kN/mm. Redesign was deemed necessary as the result was out of the range of the overall required effective stiffness (1,928-2,365kN/mm).

7.2. Design (2)

Because the stiffness of the seismic isolation layer calculated in Design (1) was found to be insufficient for the required effective stiffness, the effective stiffness of individual bearings was adjusted to a higher level for another assessment. The bearings used in Design (2) are circular bearings with surface pressure of 12MPa, outer diameter of 800mm and inner diameter of 200mm, and the individual vertical design load was calculated to be 5,654kN, while the minimum required quantity for the total weight of the target structure for seismic isolation was about 884. Based on the conditions above, the effective stiffness of individual bearings was 1.981kN/mm, and the overall stiffness of the seismic isolation layer was calculated to be 1,783kN/mm. Redesign was deemed necessary as the result was out of the range of the overall required effective stiffness (2,193-2,681kN/mm).

7.3. Design (3)

Because the stiffness of the seismic isolation layer calculated in Design (2) was found to be insufficient for the required effective stiffness, the quantity of individual bearings was raised for another assessment. Bearings with the same specification as those for Design (2) were applied and the quantity was set as 1,024 (32X32). Individual vertical stress was examined for the circular bearings with 800mm in outer diameter and 200mm in inner diameter. The vertical load applied to individual bearings was 4,883kN and the design stress was 10.36MPa. Based on the conditions above, the effective stiffness of individual bearings was 1.921kN/mm, and the overall stiffness of the seismic isolation layer was calculated to be 2,029kN/mm. The range of the required overall effective stiffness is 2,193kN/mm minimum and 2,681kN/mm maximum, so the above result failed to satisfy the requirement.

7.4 Design (4)

Because all of the stiffness of the seismic isolation layer calculated in Design (1), (2) and (3) failed to satisfy the required effective stiffness, both the size and the quantity of individual bearings were readjusted for another assessment. In this design, bearings with 1100mm in outer diameter and 240mm in inner diameter were applied and the quantity was adjusted to 625 (25x25). In the 625 bearings, the individual vertical load was 8,681kN and the design stress was 9.59MPa. The effective stiffness of the individual bearings based on the conditions above was 3,290kN/mm, and the overall stiffness of the seismic isolation layer was calculated to be 2,056kN/mm. Accordingly, this result satisfied the required overall effective stiffness (minimum 1,928kN/mm and maximum 2,356kN/mm), and examination of the design effective stiffness of the seismic isolation layer within the required range found that the seismic isolation period (T_D) was 3.129sec and the minimum lateral seismic design displacement (D_D) was 237.38mm. When the secondary shape factor of the LRBs(ϕ=1100mm) used in this design was set as 4.5-5.0, the effective rubber thickness was 200-244mm, indicating that the seismic isolator can be designed with a stable shape, and that design characteristic at γ=100% could be reflected. Table 7.1 is a summary of results from Designs (1) through (4).

Table 7.1. Review on Design of seismic isolation system (with LRB)

Case	Number of isolators	D_o (mm)	D_p (mm)	K_{eff} (kN/mm)	T_D (sec)	D_D (mm)	Surface Pressure (MPa)	Decision
1	400	1200	300	1,672	3.470	263.23	12.00	N.G
2	900	800	200	1,783	3.360	254.90	12.00	N.G
3	1024	800	200	2,029	3.150	238.95	10.36	N.G
4	625	1100	240	2,056	3.129	237.38	9.59	O.K

5. CONCLUSION

In the aftermath of the earthquake off the Pacific coast of Tohoku in Japan and the subsequent tsunami in 2011, which caused a number of large-scale nuclear accidents at Fukushima nuclear power plants, the need for seismic isolation systems is growing globally. This study examined cases of seismic isolation at nuclear power plant facilities oversees and preliminary design methods of seismic isolation systems in order to secure seismic performance of nuclear power plant facilities at the time of an earthquake, and then performed preliminary design of a seismic isolation system for APR1400, a domestically-developed, new PWR with the capacity of 1,400MWe. For preliminary design of a seismic isolation system for nuclear power reactor structures, the weight of APR1400 was applied, and the natural seismic isolation period, horizontal effective stiffness, design displacement and equivalent damping ratio, etc. were established in accordance with the ASCE7-10 design process. Lead rubber bearings (LRBs), which are a kind of seismic isolators using laminated rubber bearings with material characteristics often used in seismic isolation systems for general structures, were applied to this study's preliminary design, and based on this, the specifications and quantity of the seismic isolation system required for nuclear power plant structures were calculated with sufficient applicability. To be fully adopted to the seismic isolation system for actual nuclear power plant structures, vigorous research is going on in Korea to develop the standards, analysis models and procedures for seismic isolation of domestic nuclear power plant structures, and the researchers of this study will develop an improved seismic isolator to satisfy new standards to be established in the future as a result of such research endeavors, while also demonstrating the seismic isolation design for nuclear power reactors and its performance, as well as its effect.

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