Effects of Aggressive Groundwater on Concrete Structures: Operating Experience

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Effects of Aggressive Groundwater on Concrete Structures: Operating Experience

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ABSTRACT

This report presents a summary of the commonly referenced chemical components monitored for concrete systems, structures, and/or components (SSCs) subjected to aggressive groundwater, results from a survey with information on how utilities monitor groundwater, and actions taken by utilities in response to a change in groundwater conditions, particularly when chlorides exceed threshold values. The parameters to consider when performing an evaluation and durability modeling of an existing structure are covered.

Some of the most relevant documents and guidance for groundwater monitoring are in the U.S. Nuclear Regulatory Commission's Generic Aging Lessons Learned (GALL), International GALL, and GALL for subsequent license renewal. A summary of the values for chemicals in groundwater given in the available guidance and gaps in that guidance are presented in this report.

EPRI surveyed U.S. and international nuclear power plants about their groundwater monitoring activities. The survey data include the number of wells typically found on-site, frequency of sampling, and implementation of monitoring and trending used for groundwater monitoring of concrete SSCs.

Overall, the report is a valuable resource for utilities seeking information on the implementation of a groundwater monitoring program for concrete SSCs. The topic of groundwater monitoring will continue to be relevant for operating plants looking to extend their period of operation.

Keywords

Chlorides
Concrete
Groundwater
pH
Sulfates

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PRIMARY AUDIENCE: Engineers and inspectors interested in the inspection of concrete structures exposed to groundwater

SECONDARY AUDIENCE: Management staff interested in the inspection of concrete structures exposed to groundwater

KEY RESEARCH QUESTIONS

What are the thresholds established in the industry guidelines for concrete systems, structures, and/or components (SSCs) in contact with groundwater? What are the gaps in guidance related to groundwater monitoring for concrete SSCs? What processes are being followed by utilities around the world related to groundwater monitoring? What actions must utilities take when the threshold of aggressive chemicals is exceeded?

RESEARCH OVERVIEW

This report presents a summary of the commonly referenced chemical components monitored for concrete SSCs subjected to aggressive groundwater, results from an EPRI survey on actions performed by utilities to monitor groundwater, and actions taken by utilities in response to changes in groundwater conditions. The most relevant documents and guidance for groundwater monitoring include the generic aging lessons learned (GALL), international GALL (IGALL), and GALL for subsequent license renewal (GALL-SLR). The values for chemicals in groundwater presented in the guidance and gaps in that guidance are summarized. The relevant parameters to consider when performing an evaluation and durability modeling of an existing structure are presented.

KEY FINDINGS

- The threshold for chemicals in groundwater is the same for the main guidance documents in the nuclear industry, which are the GALL, IGALL, and GALL-SLR.
- Some of the gaps in guidance are the number of wells to be used, the proximity of wells to structures, and a specific sampling interval. The threshold for chlorides is debatable because a higher threshold might be supported by the conditions (low oxygen) to which the structure is exposed.
- Utilities that have experienced a change in condition at their site and that exceeded the chloride threshold in groundwater have performed modeling and/or changed the type of deicing chemicals used in winter. To perform modeling, it is important that representative material properties and concrete cover be as close as possible to the actual conditions in the field.
- Utilities seeking guidance based on what other utilities are doing regarding groundwater monitoring will find valuable information in this report.

HOW TO APPLY RESULTS

The report provides details on the number of wells and sampling frequency of monitoring wells as reported by some nuclear power plants, information that can help utilities as they develop groundwater monitoring programs for concrete SSCs. Utilities that exceed the thresholds for aggressive groundwater—particularly for chlorides—can consult the report to learn what mitigating actions and modeling other utilities have taken. The report includes information on the parameters to consider in models so that simulations can be as realistic as possible.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Learning and engagement opportunities related to concrete structures are available through participation in the EPRI Concrete Research Technical Advisory Committee. For more information, contact Salvador Villalobos, svillalobos@epri.com.

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INTRODUCTION AND OBJECTIVE

This report presents a summary of the parameters monitored in groundwater under the U.S. Nuclear Regulatory Commission’s (NRC’s) Generic Aging Lessons Learned (GALL), the GALL for Subsequent License Renewal (GALL-SLR), and the International GALL (IGALL) that have an impact on concrete systems, structures, and/or components (SSCs). The report also includes the results from a survey related to the activities from utilities for monitoring groundwater and the use of the information for monitoring concrete SSCs.

Groundwater is regularly sampled and tested at every nuclear energy facility to monitor for tritium and other chemicals. Monitoring is performed through sampling wells from which water samples are collected that are later sent to a laboratory for testing and measuring the content of different chemical species in the water. Monitoring specific chemicals in the groundwater (such as sulfates and chlorides) can provide valuable information related to the susceptibility of buried concrete structures to a specific deterioration mechanism. The chemicals present in the groundwater may permeate the concrete, reaching the reinforcing or deteriorating the concrete paste and concrete that are available to protect the reinforcing steel.

Concrete deterioration is not only dependent on the environment to which the concrete is subjected but also to the properties of the concrete itself. A lower water-to-cement or cementitious ratio will result in concrete that is less permeable and will be less susceptible to deterioration. Therefore, the environment where concrete is placed, the properties of the concrete, and the cover of the steel reinforcement need to be considered when evaluating the remaining life of a structure.

The report is organized into five sections. This section presents an introduction, objective of the report, and background information on groundwater. Section 2 covers the deterioration mechanisms triggered by chlorides, low pH, and sulfates in groundwater and presents the guidance and gaps identified in this research. Section 3 gives the results of an industry survey on groundwater monitoring and lessons learned. Section 4 includes generic operating experience and some of the actions that utilities have taken under different circumstances of exposure to aggressive groundwater. Section 5 is a report summary with conclusions.

2

DEGRADATION MECHANISMS AND GUIDANCE

2.1 Degradation Mechanisms

The three chemical species in groundwater considered in this report are pH levels, sulfates, and chloride levels found in the groundwater under and around a nuclear power plant's concrete SSCs. In most cases, if through-wall leakage or groundwater infiltration is identified, leakage volumes and chemistry are monitored and trended for signs of concrete or steel reinforcement degradation.

Because concrete is highly alkaline, the below-grade concrete structures begin to deteriorate when pH levels in groundwater decrease below 6.5 [1]. These acidic levels are most harmful when they reach a pH of 3 or lower, when reaction rates significantly increase, creating water-soluble calcium compounds that are carried away by percolation. This form of dissipation in concrete begins on the surface and propagates inward as degradation increases.

Sulfate attack can be described as external and/or internal, depending on the source of sulfates. External sources of sulfates are typically found in groundwater, soils, brackish water, and sea water. Magnesium sulfates, specifically, are known for breaking down some of the chemical components within the concrete, generating damage and chemically attacking the concrete paste. Internal sources of sulfates are present in the concrete in the form of gypsum incorporated in the cement to control setting. The formation of ettringite from the dissolved sulfates can cause cracking in the concrete, which will allow other deleterious components to enter the concrete and continue or accelerate the deterioration process. This process involves physical damage due to the crystallization that can lead to internal expansion, cracking, loss of strength, and disintegration of the concrete, increasing porosity and permeability [2].

The third degradation method that will be analyzed in this study is chloride attack. Chlorides, in addition to oxygen and moisture, can cause corrosion and accelerate the corrosion process in reinforced concrete. This form of corrosion takes place in two stages, the first being initiation and the second being propagation. The initiation stage is dependent on concrete cover, chloride concentration, chloride diffusion coefficient, and type of cementitious material. Duration of this stage is directly correlated to the time required for chloride ions to penetrate concrete through the concrete cover and begin corroding the steel reinforcement. The propagation stage occurs throughout the continuity of corrosion, reducing the integrity of the steel reinforcement and resulting in concrete cracking, spalling, and, ultimately, loss of cross-section of the reinforcement.

For structures exposed to groundwater, the presence of chlorides is of highest interest. The environment to which the concrete is exposed is not the only factor affecting the durability of the concrete. The water-to-cement ratio, type of cement, and concrete cover to the reinforcement are only a few of the contributors to the deterioration of a structure. Exposure to acids in groundwater is less common and is typically experienced when acids are added to water in water-retaining structures for industrial processes or to control the chemistry of the water.

2.2 Guidance

Maintaining the operability of safety-related SSCs is important in the nuclear industry. For this reason, multiple sources present thresholds and guidance related to thresholds of chemical components in the groundwater to which the SSCs are exposed. The GALL, its international version (IGALL), and the version for subsequent license renewal (GALL-SLR) are the most referenced documents for thresholds of chlorides, sulfates, and pH in groundwater. In addition to these documents, some utilities follow local jurisdiction thresholds as their limits for acceptance criteria, but only when the local threshold values are more conservative than the GALL documents. The thresholds established in each reference document are noted in Table 2-1.

Table 2-1
Guidance from different sources

Source	Acceptable Criteria
NRC Generic Aging Lessons Learned (GALL) [3]	pH > 5.5 Chlorides < 500 ppm Sulfates < 1500 ppm
NRC Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) [4]	
NRC International Generic Ageing Lessons Learned (IGALL) [3]	
Ministry of the Environment, Conservation and Parks: Soil, Ground Water and Sediment Standards (Canada) [6]	Chlorides < 790 ppm Sulfates < ND/ND
Canadian Standards Association: N288.7 [7]	Chlorides < 121 ppm Sulfates < 1280 ppm

2.2.1 Gaps in Guidance

There are variations in the thresholds adopted by utilities in different countries because they follow different guidance documents, as shown in Table 2-1. Typically, when variations exist, the most conservative values will be used. The guidance documents used most often are the GALL, IGALL, and GALL-SLR. Note that for these three documents, the threshold values for chlorides, sulfates, and pH in groundwater are the same.

Regarding the thresholds established in the GALL and IGALL documents, there are two categories—structures below the thresholds and structures above the thresholds. The threshold is important, but two other important variables are exposure to a chemical and changes in the value of chemical contents over time. Neither of these is addressed in the documents. For example, some plants have documented an increase in chloride content in the groundwater over time. The challenge in this situation is that when the structure was exposed to an environment below the thresholds, there was no aging management program to evaluate the condition or document and trend the exposure. Further, a change in the concentration of chemicals in the groundwater to a level higher than the threshold might trigger a change in processes and evaluation. For this reason, if the threshold is reached, it might be necessary to evaluate specific site conditions for the affected site and understand the exposure concentration and duration of exposure over time. The GALL documents address and recognize the exposure of concrete to a specific threshold of chemicals. However, the documents do not address the duration of the exposure and mitigation of the exposure.

Monitoring the chemical content of water provides insights into potential deterioration of the concrete. However, the properties of the concrete and the depth of cover to the steel reinforcement play a prominent role in the deterioration rate and likelihood of deterioration. In addition to monitoring the exposure conditions of the structure, it is important to understand the transport properties of the concrete to characterize its susceptibility to deterioration. For example, if a concrete structure with low permeability is exposed to a high concentration of aggressive chemicals, it is likely that due to its low permeability, the structure would be capable of maintaining its integrity for many years. In contrast, a concrete structure with high permeability might be susceptible to premature deterioration even in an environment with lower concentration of aggressive species. Therefore, while the environment is important, it is also important to have a baseline of the material properties and understand the susceptibility of the material to undergo deterioration.

For plants in an aggressive environment, which could be chloride or sulfate levels expected to be above the threshold, the material selection and structure design should include criteria to account for the effects of the exposure. For example, in a structure exposed to a high concentration of chlorides, a lower permeability or low water-to-cement ratio should be used during construction. In the case of a structure exposed to sulfates, a special cement and low water-cement ratio can be prescribed in the design to mitigate the effects of deterioration. Further, an aging management program should be used for periodic inspection of the structure and to identify any deterioration.

The GALL, IGALL, and GALL-SLR include the different thresholds, but a technical basis related to where or how a conclusion was drawn to obtain the thresholds was not found. For example, the threshold in chloride levels for groundwater has been established at 500 ppm. Note that although the concentration in the groundwater is important, exceeding this concentration does not necessarily mean that the structure will undergo corrosion. For example, 500 ppm is commonly considered to be the chloride content needed for corrosion initiation when the chlorides reach the steel reinforcement. However, a concentration of 500 ppm in the groundwater does not mean that the same concentration of chlorides is available at the level of the reinforcement. The progression of the chlorides will depend on the properties of the concrete on-site, oxygen concentrations, moisture conditions, and ambient temperature.

Thresholds for chloride concentrations do not account for the availability of oxygen, which is significantly different below and above the water table. The lower availability of oxygen below the water table limits the corrosion activity of the steel reinforcement, increasing the threshold at which chlorides can exist before corrosion initiation. The availability of oxygen in the concrete will be highly dependent on the state of saturation of the concrete. For concrete with high relative humidity, the oxygen will be available at lower concentrations because it only exists dissolved in the pore water within the concrete [8, 9].

The guidance documents present information regarding the thresholds for chemically aggressive species. However, there is no guidance on the number of monitoring wells nor the frequency of monitoring and testing of the wells for the use of the information for civil structures. The documents also omit the proximity of the well to the structures in question. As part of this research, we surveyed utilities about their approach to groundwater monitoring for civil structures.

3

INDUSTRY SURVEY AND LESSONS LEARNED

The objective of the survey was to collect data to understand the current practices in groundwater monitoring. Eleven utilities participated in a survey, more than half of them located in the United States. The questionnaire included the following questions, and respondents were asked to elaborate on the response:

1. Do you have groundwater monitoring wells? How many wells do you have? Do you monitor for chlorides, sulfates, and pH?
2. If yes, how long have you been doing this, and are you monitoring and trending the results?
3. Does your utility use the thresholds established in GALL, GALL-SLR, or IGALL (chlorides 500 ppm, sulfates 1500 ppm, pH 5.5)?
4. Have any of these thresholds been exceeded? If yes, what were the actions?

3.1 Summary of Survey Results

A breakdown of the results between U.S. utilities and international utilities is presented in Appendix A. The general practices used by U.S. and international utilities to monitor aggressive species in groundwater are as follows:

- The surveyed utilities use three to six groundwater monitoring wells to monitor civil structures, from a population of up to 70 monitoring wells per site.
- The groundwater wells used for monitoring civil structures are the closest to the structure in comparison to the general population of wells at a plant. A specific distance from the well to the structure was not provided.
- Quarterly, semiannual, and annual were the most commonly noted frequencies for monitoring for groundwater chlorides, sulfates, and pH.
- Data trending is being performed in most sites.

The information from the survey provides a general insight on the activities performed at different sites around the world. This information could also be used as a baseline for plants and sites that do not have a groundwater monitoring program for civil structures and that are seeking information on how to implement a groundwater monitoring program.

The groundwater monitoring activities for civil structures were noted to be associated with relicensing activities. Utilities applying for license extensions upgraded their programs to include a groundwater monitoring program for SSCs. This is only if the plant did not have a program in place. For utilities with an established program, the modification to the program included a shorter sampling interval and data trending.

3.2 Lessons Learned

All nuclear sites participating in the survey are equipped to monitor groundwater through various monitoring wells. Most utilities confirmed testing of groundwater for levels of pH, sulfate, and chlorides. Chloride monitoring has proven to be essential because all reported occurrences of exceeded thresholds found in this study were caused by elevated levels of chlorides. Chlorides, when permeating through reinforced concrete structures, can cause irreparable damage and put the power plant at structural risk. Fortunately, no significant structural damage was reported by any participants, but monitoring continues.

The most common standard for acceptable thresholds used throughout participating utilities are found in the GALL report. Some plants that operate outside of the United States use guidance other than parameters specified in the GALL reports when their local guidance is more conservative.

Long-term operations and relicensing of plants beyond their period of operation have triggered utilities to implement a monitoring and trending program for groundwater. In the case of plants that have exceeded the threshold, Section 4 of this report includes more information regarding the actions they have taken to manage the change in chloride concentration in the groundwater.

Groundwater monitoring for concrete SSCs has become a more common practice. However, there are some gaps in guidance as well as substantial variability in the way utilities monitor (number of wells, distance of the wells from the structures, and frequency of sampling). To benchmark utilities, more specific criteria and direction are needed.

4

OPERATING EXPERIENCE

The thresholds for groundwater chemicals noted in the GALL and IGALL are the most used across the industry. Three conditions can be found through groundwater monitoring: a concentration of chemical species known to exceed the threshold, a chemical concentration that remains below the threshold, and a change in the level of chemical species for which the threshold is exceeded. Regardless of the condition observed, the concrete SSCs are monitored under the Maintenance Rule or structures monitoring program for which opportunistic inspections are granted for underground structures. When there is a change in condition, further actions are necessary by the utility. This section briefly describes the most common actions for any of these scenarios.

4.1 No Change in Conditions and Structures in Aggressive Environments

There are structures that were constructed in a location where it was known that the threshold was going to be above the limit and structures where groundwater was expected and remained below the limit. In the case of structures that were known to be subjected to higher levels of chemicals in the groundwater, the design accounted for the presence of the chemical components. Design elements could include a lower water-cement ratio to reduce concrete permeability and a concrete cover to the steel reinforcement as required by the design code.

For structures that were known to be in regions where levels are expected to be below the threshold, groundwater monitoring and the structures monitoring program are important and should be maintained. Because the concrete was expected to be below ground, it is important that the structures have the necessary concrete cover as identified in the design and construction code.

No change in condition was reported in the survey for sulfate attack and low pH. These mechanisms are less common than chloride attack in nuclear concrete structures affected by chemicals in the groundwater. For sulfate attack, the main design parameter that helps with the durability of the concrete is a water-cement ratio that will prevent the mechanism from occurring or selecting a cement type that will mitigate the effects of sulfate attack. A water-cement ratio of 0.45 or lower has been shown to provide adequate permeability to prevent the effects of sulfate attack [2]. Further, a sulfate-resisting cement can be used to limit the deleterious effects of sulfate attack.

For the effects of groundwater low pH, data from the surveys indicate that the pH levels are typically above the threshold and that deterioration due to low pH has not been an issue. For some water-retaining structures in which injection of chemicals is used to decrease the pH of the water being stored, appropriate measures must be taken during the design stage to ensure that the change in pH will not affect the structure. This topic is not addressed in this report.

4.2 Change in Conditions

Changes in the level of chlorides in the groundwater can trigger further actions from the utilities to provide assurance that the reinforcement has not initiated corrosion. One response from the survey indicated that when high chloride levels were caused by chloride-laden deicing salt in cold climates, the mitigating action included changing the deicing chemicals to products that serve the same purpose but do not have chlorides. Some examples indicate the use of sand instead of deicing salts. In this case, the change in the threshold returned to a level below the threshold, and it was not necessary to perform an evaluation that would determine the time to corrosion initiation of the reinforcing steel.

The chloride levels in one of the survey responses were higher than the threshold established by GALL and IGALL. As an action, the utility evaluated chloride propagation through the concrete by using service life models [10]. There are multiple service life models that can be used to estimate the propagation of chlorides through the concrete. To get the most benefit from these modeling platforms, it is best to extract concrete cores and perform laboratory testing on the samples to obtain the inputs for the model. Using the data obtained from sampling will provide results that best represent the condition of the structure. In addition to concrete sampling, obtaining as-built results of the reinforcement depth will provide valuable information. Research indicates that concrete cover and concrete quality play critical roles in the corrosion initiation process [2].

Equally important is to understand the models and their intended use. Some models were developed for the propagation of chlorides under air exposure, and, therefore, the mechanics used to calculate the chloride thresholds might not be representative. In cases in which the model does not account for the underground/underwater environment, some adjustments and modifications to the models might have to occur to make them more representative of the actual exposure conditions. Also, note that there is variability between models, which might have to be considered when performing the analysis. The utility that responded performed service life modeling and obtained the time to corrosion initiation. The time to corrosion initiation was longer than the expected operating life of the plant.

In addition to modeling, a performance indicator can provide information on the effects of deterioration on the structure. Monitoring a performance indicator means that a component exposed to the same environment as the structure (or portion of the structure) in question can be inspected and monitored during the life of the structure to identify any changes that arise from deterioration. The notion is that if the performance indicator does not show deterioration, the remaining structure will have the same behavior. This approach has been adopted in other instances where monitoring for deterioration of inaccessible areas is critical. One response from the survey indicated that after a change in conditions and performing modeling, a performance indicator was used to continue monitoring the condition of the structure. Up to this day, the performance indicator has been used as part of the routine inspections to monitor the condition of the structure.

There were no reports of changing conditions in the levels of sulfates and pH in the groundwater.

5

CONCLUSIONS

This report covers monitoring of groundwater for concrete SSCs at nuclear plants. The available guidance documents through the GALL, GALL-SLR, IGALL, and other local codes and regulations have some similarities. However, there are gaps in guidance related to performing groundwater monitoring and addressing issues when thresholds are exceeded. The gaps include the following:

- Lack of specification on the minimum number of monitoring wells needed
- Lack of guidance on the distance needed from the monitoring well to an SSC
- No indications on appropriate monitoring frequencies

Results from the industry survey indicate that utilities use three to six wells for their analysis, the most common frequency of sampling is semiannual, and monitoring and trending have begun for plants seeking relicensing.

The threshold for chloride content in the water varies considerably among specific guidance documents, with GALL and IGALL reports using 500 ppm. This concentration (500 ppm) is typically found in the literature as the corrosion initiation threshold of chlorides at the rebar level. Note that the availability of oxygen in concrete plays an important role in the corrosion process. For underground structures with high relative humidity, the oxygen levels are low, and so the threshold for chloride levels might be higher. Also, it is important to obtain the material properties of the concrete and depth of reinforcing steel in the structure. When an analysis is performed, using representative properties is key for an assessment that is as close as possible to the actual conditions. For sulfates and pH, there were no reports of groundwater exceeding the threshold established by the guidance documents. These two deterioration mechanisms are not as prevalent as chloride ingress. In the case of sulfate attack, the issue is likely addressed by design. As for the change in pH, an acidic source would be needed to drop the values below the threshold.

The results from groundwater monitoring are evaluated first to determine whether there was a change in conditions from the previous measurement. Structures in areas where groundwater monitoring results do not show change in conditions are inspected under the Maintenance Rule or structures monitoring program. When a change in conditions is encountered, actions from the utility are required. These actions can take the form of mitigating the exposure of structures to a chloride-laden environment (changing deicing chemicals in the winter) and/or performing an easement of the structure through chemical transport modeling.

Groundwater chemicals can have an impact on the durability of structures. When utilities analyze the effects of chemicals from groundwater in concrete structures, appropriate thresholds and material properties should be considered, depending on the exposure of the structure. Exposure under high relative humidity and low oxygen levels will increase the threshold of chlorides at the level of the reinforcement for corrosion initiation, which will likely allow a longer operating life of the structure.

6

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A
SURVEY RESULTS

A.1 Reporting from U.S. Plants

The findings from the survey of utilities in the United States are summarized as follows:

- Responses accounted for 17 units distributed across nine sites. All but one site reposted having wells for monitoring chloride, sulfates, and pH for civil structures. The one site that did not monitor is near the ocean, and the concentration of chlorides was expected to be high and designed accordingly.
- Each site could have as many as 70 wells; typically, three to six wells are used to monitor chloride, sulfates, and pH for civil structures. Two utilities reported non-well locations used for monitoring groundwater.
- The wells used for monitoring civil structures are the wells closest to the structure. A specific distance was not provided.
- Half of the respondents have experienced chloride values above the threshold.
- Chloride levels above the threshold were reported to be associated with weather events, that is, abnormally high volumes of rainfall or use of chloride-laden deicing salts during cold weather.
- The time at which sampling began ranges from 30 to 5 years ago.
- The frequency of sampling ranged from quarterly to every five years.

A.2 Reporting from International Utilities

- Six utility participants provided input. Results from some of them could represent a group of sites. Responses were received from one point of contact for each of the six utilities that responded.
- A median of 19 wells were reported to be available per site. Two utilities with plants near the ocean did not have wells to monitor civil structures.
- Utilities that reported wells did not provide specific information related to the number of wells used for civil structures.
- Three utilities monitor for pH, sulfates, and chlorides.
- The time at which sampling began ranges from 15 to 25 years ago.
- The frequency of sampling ranged from semiannual to every five years.
- Une utility reported the case of one plant that exceeded the chloride levels. The problem was associated with deicing salts.

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