IMPLEMENTATION OF METHODOLOGY FOR DETERMINATION OF IODINE THYROID BLOCKING EFFICACY AROUND KORI NUCLEAR POWER PLANT VIA LEVEL 3 PSA

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ABSTRACT

Iodine thyroid blocking (ITB) is an important protective action in the radiological emergency action plan. However, the efficacy of such protective action is highly dependent on the accident scenario and site-specific factors. It is important to be able to assess ITB with site specific factors to support decision-making over implementation of ITB. In this work, a new methodology for determination of the efficacy of ITB will be applied for the Kori nuclear power plant located in South Korea. In previous Level 3 PSA assessment, ITB has been applied as a general protection factor that is dependent on expert judgement and does not incorporate scenario specific nature of ITB. The new methodology will produce an ITB protection factor that is based on specific scenario and iodine biokinetic model. The methodology estimates ITB protection factors by utilizing scenarios of Level 3 PSA to obtain the timepoint of exposure to radioactive plume and coupling it with the user defined ingestion time of iodine tablet. This will allow for an assessment of radiological impact that is grounded on technical results, rather than relying on expert judgement, while providing insights for the implementation of ITB. Utilizing publicly available information for weather conditions and source terms, offsite consequence analysis was performed alongside the methodology to assess the impact of ITB. This work would hopefully provide insight to further enhance the implementation of ITB in the emergency protection zone of Kori nuclear power plant.

Keywords: Iodine thyroid blocking, Emergency protective action, Emergency planning, Level 3 PSA, MACCS

I. INTRODUCTION

Iodine thyroid blocking (ITB) plays an important role in limiting the impact on thyroid in the event of an accident. It is one of the protective actions in the radiological emergency plan and the implementation of ITB is particularly important for younger population groups [1]. ITB involves the ingestion of stable iodine tablets that saturate the thyroid organ and would lead to a reduction in the amount of radioiodine absorbed by the thyroid organ when exposed to radioiodine. While the implementation of ITB has been widely recognized and general recommendations have been provided such as provision of stable iodine tablets 24 hours prior to and 2 hours after exposure to radioiodine, implementation of ITB in practice is difficult due to inability to accurately pinpoint the timepoint of exposure. Coupled with limited research in the optimal implementation of ITB in emergency scenario, practical application of ITB has been proven to be difficult [2]. This could be due to the complexity surrounding the efficacy of ITB which are dependent on factors such as time of exposure to radioiodine and time of ingestion of stable iodine tablets that are hard to ascertain and predict in an emergency scenario. As a result, estimation of the impact of ITB has conventionally been dependent on expert judgement which has clear limitations.

Hence, this study demonstrates the use of an alternative methodology to quantify efficacy of ITB via Level 3 PSA [3] in the context of Kori nuclear power plant in South Korea. The study will estimate efficacy of ITB based on offsite consequence analysis and provide some insight to better support ITB implementation around Kori nuclear power plant. The applied methodology combines insights from an iodine biokinetic model [4] and results from Level 3 PSA to determine the efficacy and dose reduction factor for a hypothetical accident at Kori nuclear power plant. The distribution strategy of ITB was also considered by incorporating time delays attributed to the distribution of iodine tablets. With these results, the study will provide some recommendations to the implementation of ITB for Kori Nuclear power plant to enhance emergency planning around the vicinity of the nuclear power plant. The rest of this study is organized as follows. Section II presents a summarized methodology applied in this case study, and section III presents the simulation results with the illustration of the efficacy curve and dose reduction factor of ITB. Finally, section IV provides the conclusion to this study

II. METHODOLOGY

The study estimates the impact of ITB particularly around the Kori nuclear power plant with publicly available data. The methodology used combines iodine biokinetic model and Level 3 PSA. It consists of three steps which are atmospheric dispersion analysis, efficacy calculation and dose analysis.

II.A. Atmospheric Dispersion Analysis

In the first step, the atmospheric dispersion analysis will be conducted with MELCOR Accident Consequence Code System (MACCS) code [5] was utilized. MACCS is widely used in the nuclear industry and provides a good estimate of the offsite consequences. The analysis will be centered around Kori Nuclear power plant, a facility located in Busan, South Korea. This nuclear power plant is of interest as it has a significant population density around the plant and could benefit from the analysis of ITB implementation. For this study, the accident scenario will be limited to a hypothetical accident occurring in one of the pressurized water reactor of APR1400 design which result in release of radionuclides. Due to the limitations of publicly available data on the source term, a hypothetical accident source term would be used. The source term was assumed to be iodine-131 with 4.43E18 Bq and a release fraction of 0.1 [6], released over an hour. For this assessment, only iodine-131 was simulated as ITB only affects iodine radionuclide and significant amount in an accident release. Weather data over three years from 2021-2023 was extracted from the Korean meteorological agency website [7]. MACCS simulates the consequences by repeating the simulations with a series of weather sequences extracted from the weather data. In this instance, the results are an average of the 8760 scenarios in which weather sequences are created with each hour in the year as a starting point and the average results over three years are recorded for a conservative analysis. This allows for a probabilistic representation of the average consequences from a hypothetical accident.

The distances of interest were set to represent conventional distances in emergency planning such as 3.22 (2 mi) and 16.1 km (10 mi) [8, 9]. In addition, a range of distances provides an overall view of the impact of ITB for population at different distances. For each of this distance, an estimate for the average timepoint of radioiodine exposure for the population residing at that distance was obtained. Table 1 shows the timepoint of exposure for different population groups at the respective distance.

TABLE I. Timepoint of exposure for different population groups

Distance (km)	Timepoint of exposure (h)
2.5	0.35
3.22	0.45
5	0.71
7.5	1.08
10	1.48
12.5	1.90
15	2.32
16.1	2.51

II.B. Efficacy Calculation

Subsequently, ITB efficacy will be calculated based on the exposure timepoint from the previous step with insight from an iodine biokinetic model. The biokinetic model simulates the transport of iodine within the human organs as compartments which exchange radionuclides with each other. One output of iodine biokinetic model is the relationship of efficacy and administration time. Administration time, T_{Admin} has been conventionally defined as the timepoint of iodine tablet ingestion relative to the timepoint of radioiodine exposure and it can be related to the results from step 1. Administration time was divided into two parts which are the timepoint of ingestion of iodine tablets and the timepoint of radionuclide exposure both relative to the start of radionuclide release as shown in Eq. (1).

$$T_{Admin} = T_{Ingest} - T_{Expose} \tag{1}$$

The time of ingestion, T_{Ingest} is the timepoint in which a population group ingests the iodine tablet relative to the start of radionuclide release and is dependent on the user definition. Timepoint of exposure, T_{Expose} is the timepoint in which a population group is exposed to radioiodine relative to the start of radionuclide release and this is directly obtained from the prior step. With the calculated administration time, an estimate of the efficacy of ITB can be obtained based on technical analysis via Level 3 PSA. In addition, A variation of the formula was also introduced to address potential administrative delays associated with the implementation of ITB. The equation for administration time will then take the following form as shown in Eq. (2).

$$T_{Admin} = T_{Announce} + T_{Delay} - T_{Expose} \tag{2}$$

The timepoint of announcement, $T_{Announce}$ will be user defined and is based on the activation timepoint of the protective action by the governing authority. Timepoint of exposure remains the same and will be obtained from step 1. The time delay, T_{Delay} was used to represent the associated delays due to the distribution policy of iodine tablets. Two distribution strategies were considered which are pre-distribution and stockpile distribution. The pre-distribution strategy distributes the iodine tablets preemptively and the time delay is assumed to be zero. In the stockpile distribution strategy, the iodine tablets are stored in a central location and distributed in the event of an accident thus resulting in a time delay. The analysis for this part will focus on distance 3.22, 5, 10 and 16.1 km to provide an overall perspective of the corresponding strategies. The time delay will be set to 20, 40, 60 and 80 minutes as evacuation is expected to be completed within around 90 minutes [10]. This analysis allows policy makers to have a deeper insight of ITB and how the distribution strategies could potentially affect the effectiveness of ITB. These estimated timepoints will be used to calculate efficacies of ITB which will be used in the next step of the methodology.

II.C. Dose Analysis

The estimated ITB efficacies from step 2 will be applied in MACCS code to estimate the impact of ITB. The MACCS simulation will focus on inhalation exposure for the thyroid organ over a period of seven days. This will simulate ITB impact in the early phase of the emergency. The key output from this step would be dose reduction factors which are defined as the ratio of the resulting impact with the protective measure against a scenario without protective measure in place. A dose reduction factor of 1 would imply that the protective action has no effect. The more effective the protective action is, the lower the dose reduction factor would be. The dose reduction factor for the WHO recommendation [1] would be approximately equal to less than 0.3 based on a standard iodine biokinetic model [4] and this would be used as a benchmark for the subsequent analysis. Through consideration of the different scenarios mentioned in the prior steps, different aspects of ITB can be analyzed and optimized in emergency planning.[11] In this study, the main objective would be to obtain the dose reduction factors for each of the population groups and provide recommendations for distribution strategy of ITB around the Kori nuclear power plant.

III. RESULTS AND DISCUSSION

III.A. Efficacy Curve and Dose Reduction Factors

ITB efficacy curves for each population group located at each distance were obtained and shown in Fig. 1. This provides an illustration of the efficacy of ITB against the time of ingestion of iodine tablet for population at different distances from the nuclear power plant. The origin point of this illustration also represents the timepoint where radioiodine is first released from the site. Hence a timepoint of ingestion at the origin point would indicate that the population consumes the stable iodine tablet at the same time as when radioiodine was first released from the site. The efficacy of ITB is expected to be high if it can be preemptively administered and the efficacy values diminish quickly after the timepoint of radionuclide exposure. Fig. 1 illustrates that each of the efficacy curve follows the typical ITB efficacy curve shape but the population at further distance experience shift of the curve according to the timepoint of exposure shown in Table 1. This is to be expected as a population located further from the release point would have more buffer time for the ingestion of stable iodine pills to obtain a high level of ITB efficacy.

This characteristic of ITB efficacy would results have critical impact to the implementation as delayed ingestion of iodine tablet would result in significantly diminishing impact. From this efficacy curve, the critical period for the change in efficacy falls within the 4 hours timeframe after the release of radionuclide. Coupled with the evacuation and emergency planning timeline, a reduced timeframe would provide more details on the key period for ITB implementation. Hence, subsequent analysis will focus on the time frame between 4 hours prior to the radionuclide release to 4 hours after the radionuclide release.

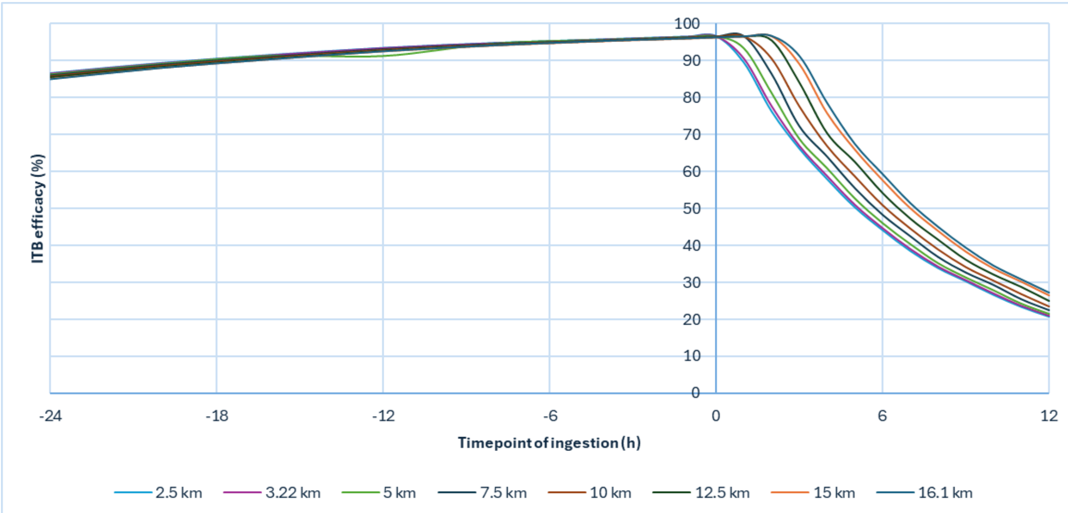

FIGURE 1. Efficacy curve for different population groups

Following the methodology, dose reduction factors were estimated from the offsite consequence analysis. The dose reduction factors for each group with respect to the time of ingestion of stable iodine tablets are shown in Fig. 2. The dose reduction factors were displayed in two categories which are divided based on the maximum distance of precautionary action zone. Radiological emergency planning typically consists of precautionary action zone (PAZ) and urgent protective action zone (UPZ). PAZ populations are required to evacuate immediately when prompted by the alert while UPZ population are required to take suitable protective action dependent on the results of detected radiation counts or predicted simulation result. The maximum boundary of the PAZ at the Kori nuclear power plant site is 5 km and the dose reduction factor will be characterized by being within PAZ and outside of PAZ.

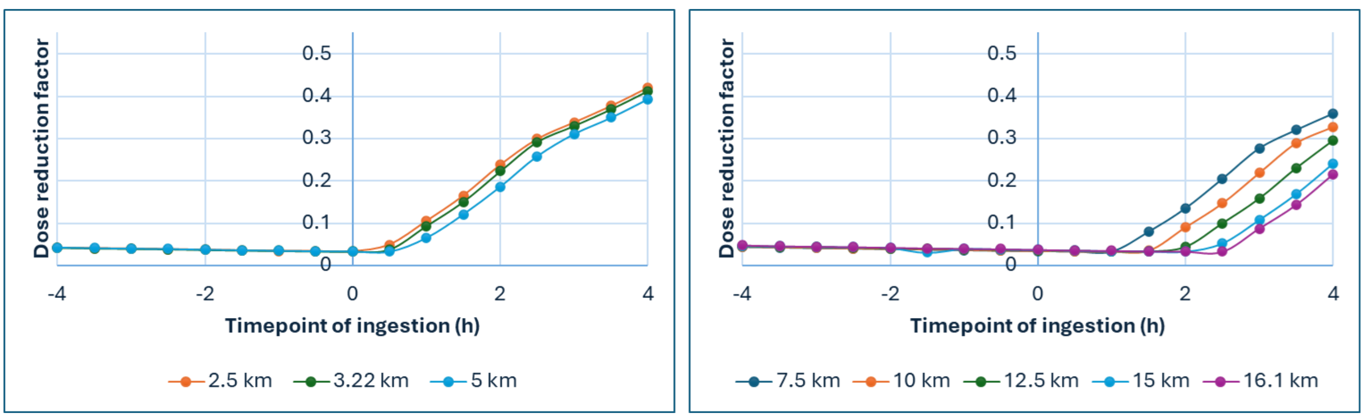

FIGURE 2. Dose reduction factor for different population groups within PAZ (left) and outside of PAZ (right)

Based on Fig. 2, population groups within the PAZ must ingest stable iodine tablet 30 minutes after release of radioiodine in order to obtain the highest level of protection from radioiodine. However, dose reduction factor would still be within the recommended range of less than 0.3, if iodine tablet is ingested within 2.5 hours from the release of radioiodine based on Level 3 PSA analysis of the average timepoint of plume exposure. Especially for the population at 3.22 km where thyroid dose can be reduced by 90%, if ITB is ingested within an hour of radionuclide release. For population groups outside of the PAZ till 16.1 km, Fig. 2 shows that best period of ingestion varies from 1 hour to 2.5 hours from release. For the population at 7.5 km and 10 km, optimal period of ingestion of stable iodine tablet for adherence to general recommendations is before 3.25 and 3.5

hours timepoint after release. For population groups at further distance that the one mentioned before, the recommended protective effect can be met as long as the tablet are ingested 4 hours after the release of radioiodine. This could indicate the merit of preemptive administration of iodine tablets and the incorporation of ITB into evacuation plans. With ITB optimal effectiveness heavily overlapping with emergency evacuation timeline and the possibility of accidental exposure during evacuation, it may be worthwhile considering the early administration of ITB, especially for vulnerable population groups.

III.B. Distribution Strategies

For practical application of ITB, the implementation of ITB was analyzed based on the distribution strategy. This is crucial as ITB effectiveness is time dependent. The time delay due to the distribution strategy would result in the delayed ingestion of iodine tablets and reduced effectiveness of ITB. The dose reduction factors for the distribution strategies were estimated with different delay time for different populations at 3.22 km, 5 km, 10 km and 16.1 km. The results are shown in Fig. 3.

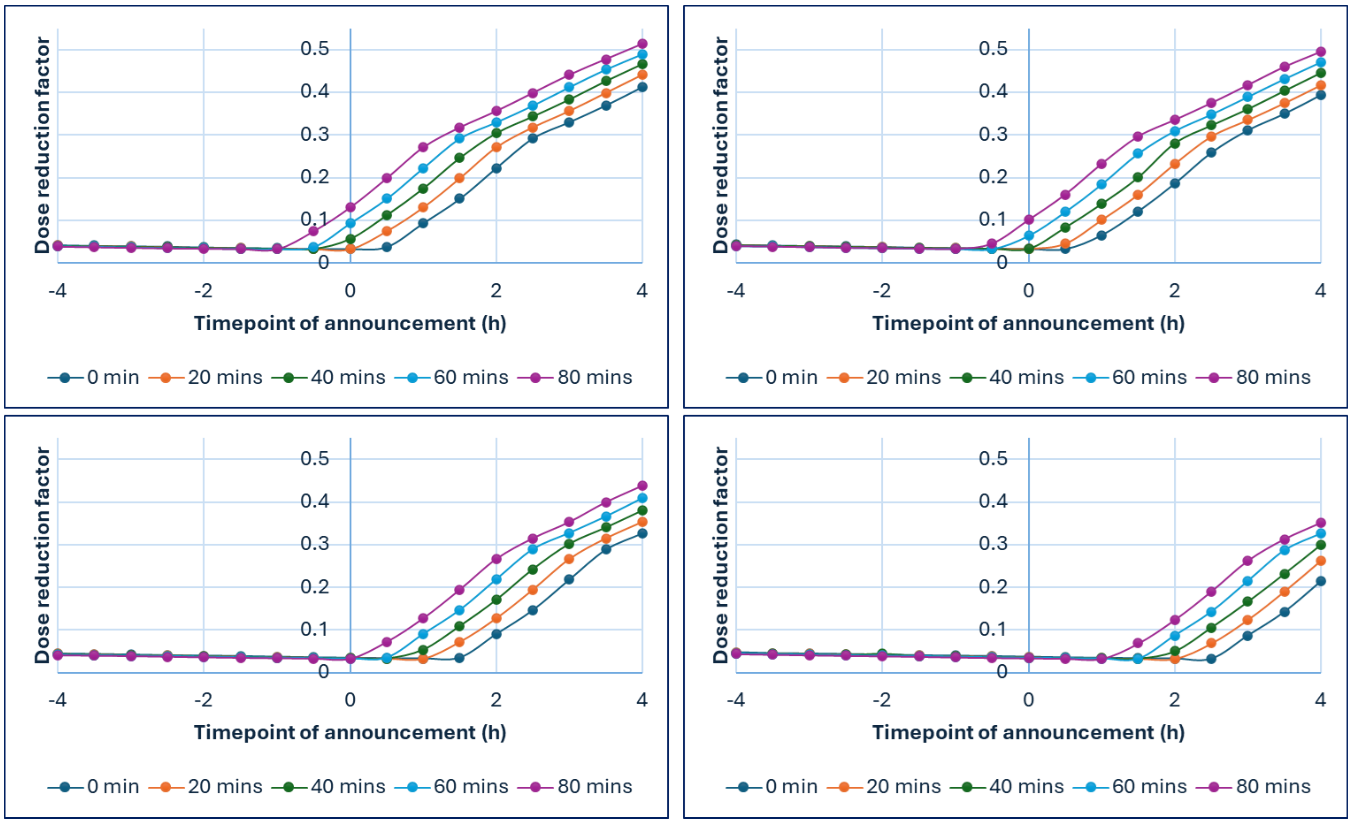

FIGURE 3. Dose reduction factor for different distribution strategies at different distance 3.22 km (top left), 5 km (top right), 10 km (bottom left), 16.1 km (bottom right)

As observed from Fig. 3, the time delay generally results in reduction in the effectiveness of ITB as can be seen by the increasing dose reduction factor with higher delay duration. Announcement of ITB must be implemented progressively earlier to achieve the same level of dose reduction compared to a scenario with lower time delay. Population closer to the Kori nuclear power plant will be more susceptible to the potential delays from the distribution strategy as optimal effectiveness of ITB involve implementation of ITB before the release of radioiodine. For the population group at 3.22 km to achieve 90% reduction in thyroid dose, announcement of ITB must be before the release of radioiodine for any time delays more than 60 minutes. Recommended effectiveness of ITB can be achieved by ensuring activation of ITB before 1.5 hour timepoint and 2.5 hour timepoint for 80 minutes and 0 minute time delay respectively.

For the 5 km population group, only the 80 minutes time delay scenario require the announcement of ITB to be coincident with the release of radioiodine to achieve 90% reduction in thyroid dose. Activation of ITB within the 1.5 hour timepoint would ensure the effectiveness of ITB falls within the recommended values. With evacuation of population around 5 km vicinity of Kori nuclear power plant expected to be completed within 1.5 hours, the preferred distribution strategy would likely be pre-distribution which would ensure that the effectiveness of ITB be maximized. ITB can potentially be coupled with evacuation to ensure that ITB will be activated in an accident scenario. In order to ensure the effectiveness of ITB for the population within the PAZ, ITB should be activated before the start of emergency evacuation. In the case of population group at 10 km, the additional distance provides sufficient buffer time for the implementation of ITB. Even with a time delay of 80 minutes, ITB can reduce thyroid dose by 80% when announced 1.5 hours after the release of radionuclides. For population at 16.1 km, dose reduction of 80% can be achieved if ITB is announced before 2.5 hours after release. Thus, this could suggest that both distribution strategies are viable at these distances if the time delay for stockpile distribution is kept at a minimum.

The above summarized the analysis of ITB implementation in Kori nuclear power plant based on the assumed source term. It should be noted that the analysis is based on a conservative source term and there may be variance in a potential accident. While the general recommendations of early implementation of ITB would still be valid for most scenario, there are certain limitations that should be considered. When considering the results, scenarios with significant time delay for the radionuclide release would result in a later exposure time. This tends to result in a greater time window for the implementation of ITB compared to the results shown in which release was expected to begin at the zero timepoint. In extreme scenarios where release of radionuclides was delayed by 24 hours would result in early implementation of ITB being ineffective as the efficacy is expected to only last for 24 hours.

IV. CONCLUSIONS

In conclusion this study assessed the impact of iodine thyroid blocking around Kori nuclear power plant via a methodology that utilized Level 3 PSA and insights from iodine biokinetic model. From the results, it is ideal for ITB to be activated as early as possible, especially for population in the vicinity of the nuclear power within PAZ. In order to ensure recommended effectiveness of ITB with dose reduction factor equal to less than 0.3, population residing within the PAZ must consume iodine tablets before the timepoint of 2.5 hours after the radionuclide release. However, to ensure dose reduction of 90 %, population groups within the PAZ should ingest stable iodine tablet within 30 minutes after release of radionuclides. Thus, it will be beneficial to consider the early administration of ITB, especially for vulnerable population groups. For population groups outside of the PAZ, the recommended dose reduction factor can be met, if the tablets are ingested 3 hours after the release of radioiodine.

In addition, analysis of the distribution strategies illustrates that pre-distribution strategy would be preferred scenario especially with the evacuating population at less than 5 km within PAZ. This is due to the time delays of stockpile distribution significantly affecting effectiveness of ITB. For a population at 3.22 km and stockpile distribution time delay of 60 minutes to attain 90% reduction in thyroid dose, the activation of ITB must be before the release of radionuclide. As such, it may be ideal to implement pre-distribution strategy and couple ITB with evacuation to ensure maximum effectiveness of ITB for the population within PAZ. For population at greater distance, stockpile distribution can be considered as the dose reduction factors can still be at an acceptable level, if tablets can be provided in a timely manner at least 1.5 to 2.5 hours after release for populations at 10 and 16.1 km.

This study showcases the analysis of ITB effectiveness which could be incorporated into emergency planning around Kori nuclear power plant. This is especially crucial for the PAZ population that are closest to the nuclear power plant and will be instructed to evacuate during the emergency. By considering the dose reduction factor with the evacuation timeline, it would be possible to minimize the dose exposure for the population in the PAZ. In order to maintain a 90% thyroid dose reduction, ITB should be implemented before the start of emergency evacuation. With more clarity of the implementation of ITB would also help to ensure that ITB will be activated in a timely manner during an emergency. This could potentially be used to support and enhance future emergency planning around the Kori nuclear power plant.

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