Technical Paper http://dx.doi.org/10.7733/jnfcwt.2016.14.3.235

U.S. Policy and Current Practices for Blending Low-Level Radioactive Waste for Disposal

저준위 방사성폐기물의 혼합 관련 미국의 정책과 실제 적용

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(Received March 2, 2016 / Revised April 11, 2016 / Approved May 31, 2016)

In the near future, many countries, including the Republic of Korea, will face a significant increase in low level radioactive waste (LLW) from nuclear power plant decommissioning. The purpose of this paper is to look at blending as a method for enhancing disposal options for low-level radioactive waste from the decommissioning of nuclear reactors. The 2007 U.S. Nuclear Regulatory Commission strategic assessment of the status of the U.S. LLW program identified the need to move to a risk-informed and performance-based regulatory approach for managing LLW. The strategic assessment identified blending waste of varying radionuclide concentrations as a potential means of enhancing options for LLW disposal. The NRC's position is that concentration averaging or blending can be performed in a way that does not diminish the overall safety of LLW disposal. The revised regulatory requirements for blending LLW are presented in the revised NRC Branch Technical Position for Concentration Averaging and Encapsulation (CA BTP 2015). The changes to the CA BTP that are the most significant for NPP operation, maintenance and decommissioning are reviewed in this paper and a potential application is identified for decommissioning waste in Korea. By far the largest volume of LLW from NPPs will come from decommissioning rather than operation. The large volumes in decommissioning present an opportunity for significant gains in disposal efficiency from blending and concentration averaging. The application of concentration averaging waste from a reactor bio-shield is also presented.

Keywords: Low-level radioactive waste, Concentration averaging, Blending, Disposal, Decommissioning waste, Bio-shield

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우리나라를 포함한 많은 국가들에서 향후 원전 해체로 저준위폐기물이 대량으로 발생할 전망이다. 본 논문에서는 미국의 저준위방사성폐기물 처분 관련 규제 기준을 분석하고, 특히 원자력발전소의 운영 및 해체를 포함하는 전주기에서 발생하는 폐기물의 처분 옵션을 확장하는 방안으로 사용되고 있는 저준위방사성폐기물의 블랜딩에 대해 검토하였다. 2007년 미국 NRC는 미국 저준위폐기물 관리 프로그램에 대한 전략분석 결과, 방사선위험도와 성능평가에 기반한 새로운 저준위폐기물 관리 규제의 필요성을 제기하였는데, 특히 방사성핵종 농도가 다른 폐기물의 블랜딩을 처분에 대한 옵션을 다양화할 수 있는 안전한 방안으로 제시하였다. NRC는 블랜딩을 처분에 적합하도록 방사성핵종의 농도가 다른 저준위폐기물을 비교적 균일하게 혼합(mixing)하는 것으로 정의하였다. 2015년 2월 농도 평균과 포장에 대한 NRC BTP의 개정판으로 공표된 블랜딩에 대한 구체적인 기술요건을 분석하였고 국내 해체폐기물에 대한 적용 방안도 예시하였다. 대량으로 발생할 해체폐기물에 대해 블랜딩과 농도평균을 적용하면 처분 효율성을 향상시킬 수 있다. 바이오쉴드 콘크리트에 대한 농도평균 적용에 대해 예시하였다.

중심단어: 저준위방사성폐기물, 농도평균, 블렌딩, 처분, 해체 폐기물, 바이오쉴드

1. Introduction

1.1 Purpose and Background

The purpose of this paper is to look at concentration averaging or blending radioactive waste of varying concentrations as a method for enhancing disposal options for waste from reactor operations and more importantly decommissioning of nuclear reactors.

Decommissioning nuclear facilities means safely removing a facility or site from service and reducing residual radioactivity to a level that permits either of the following actions:

- Release the property for unrestricted use, and terminate the license.
- Release the property under restricted conditions, and terminate the license.

The objectives of waste management for decommissioning are to limit the generation and release of radioactive contamination and to reduce the volume of waste for storage and disposal. This limits human exposures, environmental impact, and the total costs associated with waste management.

Many countries including the U.S. and the Republic of Korea face a significant increase in low level radioactive waste from nuclear power plant decommissioning in the near future. This fact has been recognized by the NRC in its 2007 Strategic Assessment of the U.S. NRCs Low-Level Radioactive Waste Regulatory Program [1]. Korea faces a similar problem with the potential for large quantities of decommissioning waste. Korea recently announced that it will shut down its oldest reactor, Kori 1 in 2017. This will be the first reactor in Korea to transition from operations to decommissioning and it presents an opportunity to develop decommissioning technologies. This paper discusses concentration averaging as a method to reduce the volume of LLW for disposal that could be considered in planning for the Kori 1 decommissioning. There is not currently a VLLW disposal facility in Korea. The assumption is made that disposal costs for VLLW will be significantly lower than the disposal costs for LLW in the Wolsong repository. Thus concentration averaging and blending LLW may be highly beneficial from a cost perspective. There may also be potential source term reductions that result from this approach.

Radioactive wastes may are generated throughout the life cycle of a nuclear power plant. These wastes can be categorized as follows [2]:

- Operational wastes in the form of solids, liquids and gases
- Plant components resulting from maintenance, modification or life extension work (e.g. steam generators, pumps, valves, control rods, spent filters, etc.)
- Materials from the structure of the plant and equipment (e.g. metals and concrete that result in large quantities of waste upon decommissioning

Large quantities of materials will be generated during decommissioning and dismantling. A significant proportion of these materials will only be slightly contaminated with radioactivity. Due to economies of scale, recycling and re-use options are more likely to be cost effective for such large quantities of materials than for the relatively smaller quantities arising during operation [2]. These materials also present opportunities to manage waste more effectively by utilizing the approaches to concentration averaging and blending discussed in this paper.

2. Concentration Averaging and Blending LLW for Disposal

2.1 NRC Position on Blending

Blending as defined by the NRC is"the mixing of LLW with different concentrations of radionuclides, which results in a relatively homogeneous mixture that may be appropriate for disposal in a licensed facility. The types of waste may include those that are physically and chemically similar (such as ion-exchange resins from nuclear power plant systems). It could also include different waste types that can be made into a relatively homogeneous final mixture, such as soil and ash. Blending does not include placement of discrete wastes of varying concentrations into a disposal container, or the averaging of concentrations of radioactivity of a discrete component over its volume. Blending is confined to waste types that have physical properties that result in a homogeneous final waste form."[3].

The NRC's current position on blending is that large-scale LLW blending may be conducted when it can be demonstrated to be safe. The NRC allows blending based on risk and performance measures for public health and safety. NRC's decision-making involving blending is based on performance. Performance means that the blended waste must meet the limits on radiation exposures at the disposal facility and limits on how much the radioactivity concentration may vary (i.e., how well-mixed it must be) [3].

2.2 Branch Technical Position on Concentration Averaging and Encapsulation

Concentration averaging is the mathematical averaging of the radionuclide activities in waste over its volume or mass. The Branch Technical Position on Concentration Averaging and Encapsulation (CA BTP) provides guidance on appropriate volumes and masses to use in calculating average concentrations [4].

The regulatory requirements for licensing a low-level waste disposal facility in 10 CFR 61 describe a system for classifying low-level radioactive waste for disposal. Classification is based on the concentrations of certain radionuclides and 10 CFR 61.55(a)(8) specifically allows for averaging of concentrations in determining the waste class. The CA BTP expands on those regulatory requirements by describing acceptable averaging methods that can be used in classifying waste.

The NRC revised the 1995 CA BTP in February 2015. The revised version allows a risk-informed, performance-based approach to classifying low-level waste materials for disposal (as Class A, B or C) based on the radioactivity concentration of blended mixtures of waste. A summary of the major changes in the 2015 CA BTP is given in Table 1. A more complete list of changes can be found in Appendix B of Volume 1 of the revised CA BTP [4].

The older 1995 version constrained the concentration of

Table 1. Summary of Major Changes from 1995 CA BTP to 2015 CA BTP [4]

2015 CA BTP Change	Notes
Increase in Cesium-137 Sealed Source Activity Limits	The recommended constraint on the size of these sources for disposal has been increased from 1.1 TBq (30 Ci) to 4.8 TBq (130 Ci), based on new, more risk-informed analysis.
Demonstration of Adequate Mixing in Blended Low-Level Radioactive Waste	The 1995 CA BTP constrained the concentrations of inputs to a mixture of blended waste and therefore did not need to address the homogeneity of the final mixture. It included a "Factor of 10" concentration limit on waste blending which limited blending of waste streams with radionuclide concentrations to within a factor of 10 of the average concentrations in the blended product. The revised CA BTP specifies certain thresholds on radionuclide concentrations of waste streams that are blended together. Above these thresholds, licensees should demonstrate waste is adequately blended.
Alternative Approaches	The addition of specific guidance for licensees to use in proposing site- or waste-specific averaging approaches, rather than the generic approaches specified in the body of the CA BTP.
Risk-Informed Treatment of Cartridge Filters	In the 1995 CA BTP, cartridge filters—a waste type generated during the operation of nuclear power plants—were defined as discrete objects subject to certain averaging constraints on each filter. Each filter had to be radiologically characterized and fit within the specified averaging constraints of the 1995 CA BTP. The revised CA BTP allows for the treatment of such filters as blendable waste.
Risk-Informed Averaging of Other Discrete Waste Items	The 1995 CA BTP constrained the averaging of discrete items with its Factors of 1.5 (which applied to primary gamma emitters) and 10 (which applied to other radionuclides). The revised CA BTP ties the averaging factors to the class limit for radionuclide concentration.

certain waste types put into a mixture (e.g., ion exchange resins) to within a factor of 10 of the average concentration of the final mixture. The revised guidance for blending makes the hazard (i.e. the radioactivity concentration) of the final mixture the primary consideration for classification.

2.3 The Revised CA BTP Guidance for Blending LLW

2.3.1 Blendable Waste

The 1995 CA BTP did not use the term"blendable waste". It addressed two categories of waste, discrete items and wastes assumed to be homogeneous. The revised CA BTP introduces the term"blendable waste"to describe waste that is not treated as discrete items but which has unknown homogeneity. A waste stream is considered to be blendable if:

- The waste can be physically mixed to create relatively uniform radionuclide concentrations or
- The waste is not expected to contain durable items with significant activity

Examples of blendable wastes include contaminated soils, ash, ion-exchange resins, evaporator bottom concentrates, and contaminated trash [4].

2.3.2 Demonstration of Adequate Blending

Adequate blending is a requirement for the mixture of blended waste that provides assurance that the mixture of waste has a uniform concentration without hot spots. If blending is inadequate there may be volumes of relatively concentrated waste in the blended product. Demonstrating adequate blending can be based on process knowledge, reasoned conclusions, calculations, or direct measurements [4].

The revised CA BTP includes a standard for the homogeneity of blended wastes. Requirements for the blended product are given in the CA BTP Table 1. (See Table 2 below.)

There are two blending scenarios that are considered in the CA BTP. The first is a blended mixture from one waste stream and the second is a blend from multiple waste streams. If a waste package contains a single blendable waste stream, radionuclide concentrations for waste classification and a simple volume averaged concentration may be used.

If the multiple waste streams are blended and exceed the thresholds in CA BTP Table 1, then the requirements for demonstrating adequate blending must be met. Waste is adequately blended if there is reasonable assurance that there are no hot spots of waste ≥0.2 m^3 that have a sum of fractions >10 times the average concentration of the blended product for the specific radionuclides [4]. The sum of fractions is calculated as [3]:

$$\text{Sum of Fractions} = \sum_{1}^{n} \frac{\text{Concentration radionuclide n in most concentrated influent waste stream}}{\text{10 CFR 61 concentration limit for intended waste class for radionuclide n}}$$

Concentration limits for radionuclides are found in Table 1 and 2 of 10 CFR 61.55. A detailed explanation and example of determining the sum of fractions is provided in 10 CFR 61.55(a)(7) [3].

2.3.3 Ion Exchange Resins

As a result of the closure of the Barnwell facility in 2008, nuclear power plant operators started to look at blending ion exchange resins (IER) as an option to storage on-site [3]. Ion exchange resins are powdered or bead-shaped granular materials composed of polystyrene and divinyl benzene. Ion exchange resins remove impurities and improve the chemistry of process water that is used in NPPs. IERs are used for reactor water cleanup, pH adjustment, boric acid recovery, condensate polishing, spent fuel pool water cleanup, and removing contaminants from makeup water [5].

Over time, the resins become loose effectiveness and must be removed and replaced. The spent IERs may contain

Table 2. 2015 CA BTP: Thresholds for Demonstrating Adequate Blending [4]

Characteristics of the Highest Concentration Input Waste Stream (Sum of Fractions)	Volume of Final Blended Product (m^3)*		
	Class A	Class B	Class C
<10	No limit	No limit	No limit
10 to 20	No limit	No limit	50
20 to 30	60	No limit	20
30 to 50	20	No limit	6
50 to 100	6	40	2

* For volumes larger than shown in Table 2, adequate mixing must be demonstrated.

significant quantities of radionuclides, including fission, activation, and corrosion products. Radionuclides that may be present include barium-133, cesium-137, cobalt-58, cobalt-60, iron-55, manganese-54, nickel-63, technicium-99, and zinc-65 (NRC, 2007). The concentrations of radionuclides in the spent IERs generally require these IERs to be managed as Class A, B and C LLW [5].

The annual volumes of spent IERs generated by NPPs vary by plant design, with boiling water reactor (BWR) plants typically generating more spent IERs than pressurized water reactor (PWR) facilities. The average total volume of spent ion exchange resins generated annually by commercial NPPs in the United States is about 2568 cubic meters. This is approximately 4% of the average total volume of LLW generated in the U.S. per year [5].

Blending of resin exchange ions that are Class B or C with a sufficient quantity Class A waste could result in a homogeneous mixture that could meet the concentration limits of Class A waste and therefore could safely be disposed at a lower cost. Because the volume of this operational waste is relatively low compared to the volume of decommissioning waste.

2.3.4 Cartridge Filters

Cartridge filters are found in a variety of nuclear power plant applications, including primary side letdown and

Table 3. 2015 CA BTP: Recommended Activity Limits of Primary Gamma Emitters [4]

Nuclide	Class A	Class B	Class C
^{60}Co	5.2 TBq	No limit	No limit
^{94}Nb	37 MBq	37 MBq	37 MBq
^{137}Cs	266 MBq	27 GBq	4.8 TBq

makeup water, steam generator blowdown, spent fuel pool and auxiliary cooling water systems. Previously in the 1995 CA BTP the filters could only be managed as discrete items for disposal. Each filter had to be radiologically characterized and managed within the specified averaging constraints. While that approach may still be used, the revised CA BTP also allows filters to be treated as blendable waste. Filters can now be part of a blended waste mixture classified based on its total radioactivity, rather than as individual items. This method is allowed because many filters do not present a gamma hazard to an intruder, based on their radionuclide concentrations. Cartridge filters that not to contain primary gamma emitters (cobalt-60, niobium-94, and cesium-137) with activity greater than the limits in Table 3 of the CA BTP may be treated as blendable waste [4].

2.3.5 Averaging of Other Discrete Waste Items

Discrete items are generally one of the following waste types: activated metals, sealed sources, cartridge filters, contaminated materials, and components incorporating radioactivity into their design. The 1995 CA BTP constrained the averaging of discrete items by applying factors of 1.5 for primary gamma emitters and 10 for other radionuclides. The factors applied to the average radionuclide concentrations in mixtures of certain discrete items, such as activated metals. The average radionuclide concentrations in a mixture volume average had to be less than the factor (1.5 or 10) times the maximum concentration for any item. The 2015 CA BTP ties the averaging factors to the class limit for radionuclide concentrations not the average of the mixture. The class limits are based on a maximum dose of 5 mSv/yr exposure to an inadvertent intruder. Thus the new method is risk-based because averaging is based on a dose limit. The NRC also changed the factor of 1.5 to 2 given the overall uncertainty in the estimate.

There are two approaches for averaging discrete items, using an activity limit or a concentration limit. For primary gamma-emitting radionuclides (^{60}Co, ^{94}Nb, or ^{137}Cs), the activity limits are provided in Table 2 of the CA BTP as shown above. One is for individual discrete items and the other is for mixtures of items belonging to a single waste type.

Individual discrete items may be classified based on the activity of their 10 CFR 61.55 radionuclides divided by the volume or weight of the item, as applicable. To classify a mixture of discrete items of the same waste type, simplified screening criteria may be used:

- If each item is less than 37 MBq, the activities may be volume averaged for the entire mixture.
- If any discrete item has an activity greater than 37 MBq, the entire mixture maybe conservatively classified as the same class as discrete item with the highest classification.

If the above screening criteria are not used, concentration-averaging constraints can be used for classifying a mixture of items belonging to a single waste type. If primary gamma-emitting radionuclides control the waste classification, more restrictive averaging constraints apply. If radionuclides other than primary gamma-emitting radionuclides control the classification, less restrictive averaging constraints apply [4].

2.4 Stakeholder Issues Related to Blending

Fifteen organizations representing a variety of interests submitted comments on the draft CA BTP during the revision process. They included Federal and State agencies and organizations, a nuclear power plant research organization, disposal and waste processing facility licensees, industry professional organizations, an advocacy group, and a waste services company. Several stakeholder questions and the NRC responses that are relevant for NPP LLW management are briefly discussed below [4]:

What is the difference between blending and dilution and will blending increase the disposal volume?

In the past, NRC has discouraged the blending or dilution of radioactive waste, without distinguishing between the two practices. The reason for discouraging was that simple dilution would increase the volume of waste for disposal resulting in more shipments and less efficient use of valuable disposal capacity. Blending two contaminated waste streams is not considered dilution and does not increase the disposal volume.

The NRC has recently made specific regulatory distinction between dilution and blending. Dilution means the mixing of clean and contaminated materials together for release to the general environment. Dilution increases the volume of waste through the addition of clean materials to a mixture, and enables the release of materials to the general environment where members of the public could be exposed to the hazard, however small. Blending involves the mixing of already contaminated materials containing different concentrations of radioactivity for disposal in a licensed disposal site.

Will blending classes of waste be used to lower the waste classification from Class B/C to Class A?

Several stakeholders expressed concerns with blending of LLW that lowers the waste class. These concerns include the perception that Class B/C waste would be disposed of in a Class A facility if these wastes were blended to Class A concentrations and potential safety impacts of disposing of blended waste at or near the Class A concentration limits which was not analyzed in the technical basis for NRC's disposal regulation in 10 CFR Part 61.

Any blended waste would have to meet the acceptance criteria and performance objectives for a disposal facility to ensure that public health and safety and the environment were protected.

Will blending result in poorly mixed waste with hot spots that could pose an increased risk for an inadvertent intruder?

The 1995 CA BTP constrained the concentrations of inputs to a mixture of blended waste and therefore did not need to address the homogeneity of the final mixture. It included a"Factor of 10"concentration limit on waste blending which limited blending of waste streams with radionuclide concentrations to within a factor of 10 of the average concentrations in the blended product. The revised CA BTP specifies certain thresholds on radionuclide concentrations of waste streams that blended together. Above these thresholds, it must be demonstrate that waste is adequately blended. The new approach is performance-based because no longer constrains concentrations of inputs to a blending process but instead specifies criteria that the output (i.e., blended waste) must meet to protect an inadvertent intruder from potential hot spots in the waste.

3. Decommissioning Waste

3.1 Decommissioning NPPs in Korea

Korea has 25 nuclear power reactors currently operating. Korea's reactor fleet consists of 21 PWRs and 4 CANDU reactors [6]. The first reactor to be decommissioned will be Kori Unit 1 which will be shut down in 2017. The decommissioning source term for PWRs has been studied [7] and a recent study has documented the Wolsong Unit 1 CANDU reactor source term [8]. This information is important for developing decommissioning and dismantling strategies and the corresponding regulatory guidance.

The decommissioning waste will represent a significant LLW disposal challenge due to activation of the massive components which include the concrete bio-shield, reactor vessel, reactor internals, and reactor coolant system. These components will have substantial amounts of activation products that were formed over the life of the reactor. The exact isotopic mix in the massive components of the reactor is to a large extent dependent on the particular decommissioning strategy and the time frame chosen for implementation. In any event, the massive components by their very bulk will require a different disposal approach than the reactor operational wastes. The approach that has been taken in the U.S. and other countries for the massive components is near-surface disposal. Especially VLLW is disposed in simple trench facilities with very simple packaging requirements.

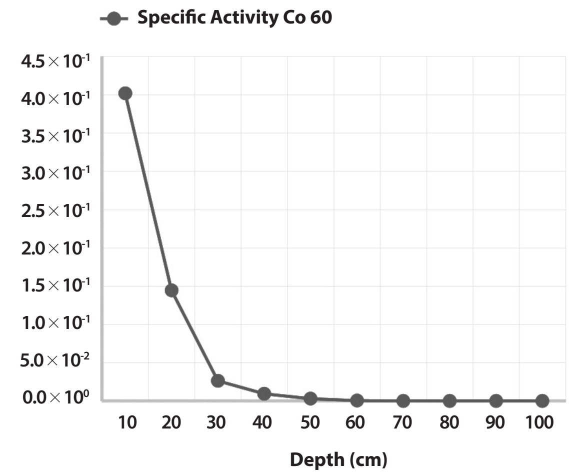

Fig. 1. Specific Activity (Bq/g) of Co 60 vs. Depth in Bio-shield of Wolsong Unit 1 [8].

3.2 Bio-shield Concrete

The concrete bio-shield is a one of the massive reactor components that undergoes neutron activation during reactor operation. It surrounds the reactor vessel and its thickness depends on the specific reactor type and design. The bio-shield has a wide distribution of specific activity with an exponential decline in concentrations that varies with depth (distance from the reactor vessel). The wide distribution of specific activities makes the bio-shield concrete amenable to the concentration averaging approach for classification. An activation model is used to calculate the expected levels of long-lived neutron activation products in the bio-shield concrete. Fig. 1 shows an activation calculation result from an activation model for a bio-shield concrete from the Wolsong Unit 1 CANDU reactor [8]. The graph shows the results for the ^{60}Co specific activity (Bq/g) as a function of depth of penetration (cm) in the bio-shield. For this concrete material the full bio-shield model average specific activity was 6.8×10^{-1} that would result in classification as VLLW. What is important about this result is that it shows the depth-varying specific activity in the bio-shield concrete. Similar results from earlier studies at Pacific Northwest Laboratory for PWR bio-shield concrete [7] showed higher levels of activation than for the Wolsong Unit 1 CANDU reactor. This is expected from the higher neutron flux in the PWR as compared to the CANDU reactor. The depth variation in specific activity could be averaged using the concentration averaging approach to optimize waste classification for disposal.

Earlier research showed that a wide range of compositional variation exists in concrete reflecting geologic differences in the quarry sites used for the aggregate and variability in the impurities in the concrete [7]. The activation patterns in the bio-shield concrete studies showed that a complex isotopic mixture is possible due to the differences in geochemical composition of the concrete samples. Of the bio-shield concretes studied the highest activation was less that the LLW upper limit with maximum activation occurring between 10 and 20 cm depth from the inner surface for most isotopes due to neutron activation in the concrete. Much of the mass of bio-shield concrete is of considerably lower levels of activation. In general the bio-shield would be sectioned at the depth corresponding to the clearance level. The remainder will meet clearance level for disposal as non-radioactive waste.

These results suggest that the bio-shield concrete from decommissioned reactors could be managed for disposal using concentration averaging to VLLW after sectioning the activated part of the bio-shield.

4. Conclusions

The NRC's current position on blending is that large-scale LLW concentration averaging and blending may be conducted when it can be demonstrated to be safe. The NRC allows concentration averaging based on risk and performance measures for public health and safety.

LLW concentration averaging and blending is an approach to waste management that can give greater flexibility for disposal options for NPP waste from the entire life cycle of the plant which includes operational wastes and most importantly large quantities of decommissioning wastes.

Concentration averaging could be applied to the concrete bio-shield to potentially facilitate disposal in a simple trench facility as opposed to the LLW disposal facility. It is assumed that disposal costs would be significantly lower for a simple trench facility for VLLW as compared to disposal as LLW. There are other potential advantages to near-surface disposal as LLW. The ability to dispose of much larger sections of the bio-shield as VLLW could reduce the final disposal volume. The exact isotopic mix in the massive components of the reactor is to a large extent dependent on the particular decommissioning strategy and the time frame chosen for implementation.

Acknowledgements

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1305009).

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